Probing and perturbing the oligomerization of membrane protein utilizing nanoparticle plasmon coupling and Deep learning

Dr. Abu S. M. Mohsin, Associate Professor
BracU,EEE, 66 Mohakhali,Dhaka-1212,Bangladesh

Challenges: Membrane proteins are the first line of communication between the extracellular environment and the cell interior. This communication in cellular systems is largely under the control of complex spatial and temporal networks of macromolecular interactions called signaling pathways [1]. Traditional biochemical tools such as yeast-two-hybrid [2], co-immunoprecipitation [3] together with gene [4] and protein arrays [5] provides critical information on the constituents of interaction networks. Recently it has been known that the activation of epidermal growth factor receptor (EGFR) occurs via dimerization [6,7,8] or higher order oligomerization however the precise geometry, stoichiometry, and relevance to signaling pathways is not known at this time [9].
More recently several state-of-the-art fluorescence based non-destructive, non-invasive super resolution imaging techniques has been used in lateral micrometer and sub-wavelength range to track and analyse the biological molecules, interaction and oligomerization. However, due to the photo blinking and photo bleaching property of fluorophore and destructive nature of imaging these techniques cannot be utilized in live-cell imaging or to examine dynamic information about the uptake or aggregation. In order to investigate the oligomerization of membrane protein and subsequent activation pathway we proposed to use plasmonic nanoparticle and deep learning-based image segmentation technique in human cervical carcinoma (HeLa) cells. Plasmonic nanoparticle will be used as multifunctional probes and nano-spacers in a model cell system to investigate the organization of membrane proteins and to determine how receptor spatial arrangement influences cell behavior. The findings of this study will be helpful in spatial structuring, receptor organization and cellular function and drug delivery. Most importantly, the novelty of our work lies in the presentation of a pioneering technique that allows in-vitro cellular studies of membrane protein interaction in a non-destructive setting under the diffraction limit.
Proposed Project: The aim of the project is to determine the role of spatial organization on the function of membrane proteins. The objective of the project is as follows: **(a)** Investigate the light matter interaction of nanoparticle& structure using analytical models (Mathmatica/Matlab) & numerical methods (Lumerical-FDTD).**(b)**Probe the spatial organization of membrane proteins (EGFR). (c)Control the spatial organization of membrane proteins**. (d)** Determine how receptor spatial arrangement influences cell behaviour.
Expected Outcome: Expected outcome from aim 1: Investigate the light matter interaction of single particle and cluster on the 10-100 nm scale. We will provide evidence how the shape, size and geometry of the particle influence the plasmonic property. **Likely Impact from aim 1:** The results will be useful for understanding the fundamental properties of plasmonic nanoparticles and structures and employ them in several applications. This will help to investigate monomer-dimer transitions at the molecular scale. We expect to have one peer reviewed paper from these findings.

Expected outcome from aim 2: We will probe the spatial organization of membrane proteins (EGFR) using nanoparticle as a probe or nanospacer. We will demonstrate perturbation of spatial organization through the creation of clusters of different size, spatial extent and geometry. **Likely impact from aims 2:** The impact from this study will be high because it will address the issues of creating clusters with defined size and geometry directly. We expect to have one peer reviewed paper from these findings.
Expected outcome from aim 3: We will determine how cellular function is linked to spatial organization of membrane proteins._**Likely impact from aims 3:** The concept of spatial organization appears to be important for polyvalent ligand-receptor interactions where ligand-mediated receptor cross-linking brings components into molecular contact. However being able to ascertain the role of different sizes and geometries has been challenging because of the numerous species on the cell surface. Our novel approach will provide the link between spatial structuring, receptor organization and cellular function. We expect to have one peer reviewed paper from these findings.

The proposed project will help to address SDG 3-Good Health and Wellbeing, SDG4 Quality education and SDG 9 Industry, Innovation, and Infrastructure and help to create skilled workforce for Industry 4.0.

Efficient Models for Photonic Functional Devices for Future Optical Communication
Category: Information
Summary

The continuous growth of the telecommunication market has led to a huge demand of high-density low-power high-speed nanoscale systems. Recently, the excessive demand on mobile and communications networks during the COVID-19 pandemic adds pressure to the network, which affects service quality and levels. This rising demand can create a ripple effect as companies across various sectors are in the ongoing shift to remote work and implement remote-work plans. Therefore, we should put a lot of research efforts to investigate the future of ICT amid the challenges.

The global photonics market is estimated to rise from USD 802.5 billion in 2021 to USD 1267.3 billion by 2028 according to Fortune Business Insights™. According to its latest research report titled “Photonics Market, 2021-2028”, the optical communication technologies are listed top of “Key Market Trends”. Because photonics, as a new technology, can help address some of the challenges facing ICT. For instance, plasmonics, as a promising branch of photonics, is playing a vital role in the realization of many devices and systems beyond the diffraction limit penetrating a wide range of applications from telecoms, integrated optics, sensing, and others. However, understanding the physical effects behind plasmonic devices is still a challenge and needs much more considerable effort to deeply understand light-matter interaction enabling plasmonic effect. On the other hand, silicon photonics shows promise to realize a wide range of photonic devices for future ICT applications. However, modeling such high-index-contrast nature between silicon and surrounding materials is still a challenge facing numerical techniques to be able to capture the correct rapid variation of the field at the interfaces.

In this regard, this proposal will focus on developing new powerful computational modeling tool for fundamental physical understanding and correctly analyzing photonic devices with high-index-contrast like in plasmonics or even silicon photonics. This proposal aims at:

- Demonstrating a study for the physical explanation of the challenges facing existing modeling techniques of such high-index-contrast structures.
- Recommending the best techniques for each photonic device and based on its physical nature in both classical and quantum regimes.
- Developing more accurate and efficient numerical modeling techniques based on semi-vectorial/ full-vectorial modal analysis and bidirectional beam propagation method for 3D photonic devices.

This proposal can lead to the following outcomes:

- New efficient computational tool capable of accurately characterizing and design both 2D and 3D photonic devices such as couplers mandatory for future ICT.
- 1-2 publications in high impact factor open access OPTICA journals (targeting Opt. Express).
- Participating in one international conference.

This proposal will give me a good opportunity to extend some of existing open research possibilities related to my PhD, and future work may include other extensions to solve the following problems:

- Coupling my quantum solver with Poisson solver to be able to apply external bias (V=x) to characterize more features of modern quantum devices.
- Making use of the parallel implementation of my algorithm to speed up the analysis.

Global Modular Microscopy (G-ModMicro)
Executive Summary

Global Modular Microscopy (G-ModMicro) is an ambitious project that will leverage optical technologies, additive manufacturing and low-cost innovations for making diagnostics affordable, tackling the key problem of disparate healthcare capabilities globally. A step-change in research and diagnostics will be a direct result of the current proposal to make advanced microscopy hardware accessible at a fraction of the cost of proprietary systems. G-ModMicro was designed to bridge the gap between microscopy technology access and diagnostic needs, with a focus on developing countries. The proposal is shaped through conversations and existing collaborations with pathologists in Visakhapatnam (India), microscopy needs for malaria diagnostics in Malawi and Tanzania (Africa), as use cases, and researchers in the UK.

The proposal outlines the novel development of hardware for three techniques – confocal microscopy, structured illumination microscopy (SIM) and stimulated emission depletion (STED) – as a step towards solving an ever-present imbalance of hardware access due to high costs. Simultaneously, the project will build strategic partnerships to deploy currently available and subsequent novel hardware in pathology labs in India and Africa with a focus on cancer and malaria diagnostics, respectively. Building on the OpenFlexure project[1], this proposal will innovatively design imaging hardware using additive manufacturing, novel light sources and in-house electronics to build all-inclusive and openly accessible microscopy systems.

G-ModMicro suite brings together a complete range of 3D-printed microscopy hardware and a bill of materials that enables users to build and apply multiple microscopy techniques to research and diagnostics. The suite of tools has thus far adopted the OpenFlexure project as a template for (1) bright field microscopy, applied to machine learning-based classification, (2) epifluorescence microscopy with bespoke components (Figure 1) for zebrafish imaging[2] and (3) polarised light microscopy for imaging malarial parasites in tissue samples from Malawi, in collaboration with parasitologists at the University of Glasgow. This research has received prior support from the University of Glasgow Knowledge Exchange Fund, Engineering and Physical Sciences Research Council (EPSRC) Impact Acceleration Accounts (IAA), SPIE, IEEE Photonics Society and the Institute of Physics. Subsequent support through this Award will see both additional research and development, and deployment in the UK, India and Africa (the latter is in progress with the University of Glasgow Research and Innovation team).

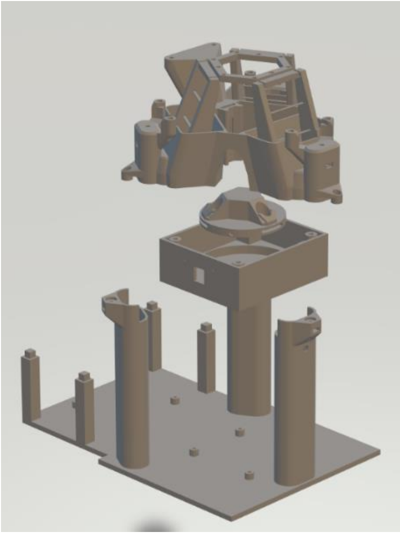


Figure 1 – G-ModMicro's epifluorescence microscope costs £150 per unit, fully equipped with an objective, filters and light sources.

G-ModMicro will provide the global community, irrespective of the economic standing, access to dependable hardware. This will directly enhance the capabilities of research institutions, and improve capabilities and reduce diagnostic waiting times in healthcare.

[1] https://openflexure.org/

[2] Our system costs £150 vs. standard systems that can cost between £2,000 to £40,000

Executive summaries

Name of Challenge Project: "**Design and Development of Cost and Energy Efficient TWDM Optical Wireless Link for High Speed Reliable Communication**".

Category: Information

Problem Statement/Objective: To Design and Develop Flexible TWDM Optical Wireless Link for Reliable, Cost Effective and Energy Efficient Connectivity. The designed link is expected to enhance the reliability of the high speed wireless link with low cost and power requirements.

The major objectives of the proposal are: -

- To simulate and analyze the performance of 20 Gbps and beyond optical wireless link at different geographical locations.
- Evaluation of the bit error performance (BER) of the designed link for real time variable network conditions and various parameters.
- Designing and development of 20 Gbps and beyond test bench link for physical network connectivity.
- FPGA implementation for real time effective resource allocation and link switching.
- Reliability, cost and power effective analysis of developed TWDM optical wireless link bench.

Outcome(s) and deliverables

- Designed and developed 20 Gbps link is expected to provide the high speed, energy and cost efficient reliable broadband wireless connectivity.
- The implementation of FPGA in the designed link is expected to utilize the available central office resources effectively and can allocate the bandwidth dynamically as per real time requirements and network conditions.
- The complete project report with the technical details
- Research papers having potential to get published in the Optica journals and conferences.

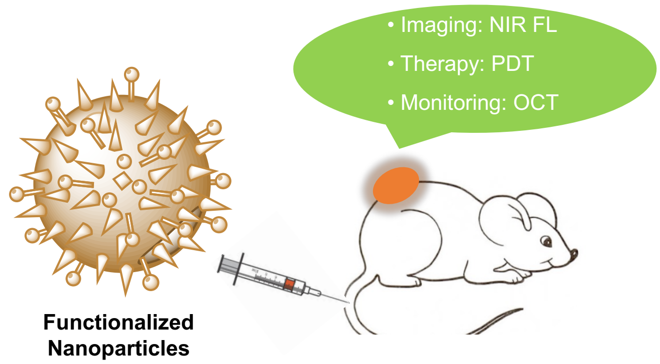
Impact

- The proposed and designed link can provide the reliable wireless broadband connectivity to the rural areas and can overcome the technological gap between the rural and urban communities and therefore can reduce the population density fluctuations.
- Dissemination of the major findings of the project with the industry, academia and research personals through symposia and spread the knowledge to the scientific community.
- The delivered major findings and technical aspects will help the telecom operators to provide the reliable, energy efficient and cost effective connectivity to the rural areas and can boost the rural development.

Executive Summary of Research Proposal

FUNCTIONALIZED NANOPARTICLES FOR CANCER DIAGNOSIS, THERAPY, AND MONITORING USING OPTIC TECHNOLOGIES

We propose an all-in-one approach to cancer research using optical technologies in this proposal. New organic-based nanoparticles will be developed as biomarkers for NIR fluorescent imaging. Photodynamic therapy will be used as a treatment option. Finally, optical coherence tomography (OCT) will be used to track the progress of the therapy.



Premature clearance by the reticuloendothelial system (RES) and insufficient penetration into the tumor frequently impede the effective delivery of actively targeted nano constructs to deep tumor sites. A recent pre-targeting strategy based on the administration of a polyethylene-glycol (PEG)-coated nano-carrier to the tumor-bearing subject has been designed to overcome these shortcomings. This PEG-coated nanocarrier has the ability to (i) evade RES capture and clearance, (ii) increase nano-drug accumulation in tumors via the enhanced-permeability-retention-effect (EPR), and (iii) enhance the performance of photosensitizers via drug-loaded-PEG-nano-carrier.

We hypothesize that the PEG-coated nanocarrier will enhance the photophysical properties including photo-stability, biocompatibility, singlet oxygen quantum yield, and fluorescent quantum yield of our synthesized photosensitizer. In addition, the nano complex is expected to evade RES and immunosurveillance and the near-tumor-vasculature and is capable of penetrating deep into the tumor, which can be seen by fluorescent imaging. After that, the light will be given to activate the photosensitizer of the complex to generate singlet oxygen that harms cancer cells. Moreover, the progress of tumor ablation will be non-invasively monitored via OCT.

The OCT setup will be a custom-built frequency domain OCT (FD-OCT). The high-speed spectrometer will be built to detect two bands of the spectral interference signal, namely at approximately 850 nm light wavelength for high-resolution imaging of superficial skin and 3D cell culture and at approximately 1300 nm light wavelength for deep imaging at low resolution beneath the skin surface. OCT system will enable non-invasive real-time 3D imaging of 3D culture cells and/or artificial skin to track the development of skin cancers as well as to track the progress of PDT treatment.

The goal of this work is to create a research network between Thai researchers and researchers from other countries such as the United States, Malaysia, and China. In terms of wellness and healthcare, this project will have a significant impact on society. The outputs and outcomes will include the graduation of at least two students, the production of two well-trained post-docs, at least three international publications, and the filing of one patent application. Furthermore, a strong bond will be formed among the researchers. Finally, and most importantly, the international network will foster the development of deep technology and platform knowledge.

Name of the Project: Piloting an affordable and real-time Water Assessment System (WAS) for detection of fecal coliforms in drinking water

Category : Environment

The Problem:

- 40% of water consumed globally is not tested,
- an estimated 2 billion people globally use drinking water contaminated with feces,
- >829,000 people (with >297,000 children) die each year from diseases transmitted via fecal-oral route because of fecal contamination of water,
- traditional approaches to testing water for fecal contamination require infrastructure (>30k$), testing-time (>18 h), training (~2Y post high-school) and/or expensive consumables (~5$/test), so are not conducive for implementation in the developing countries where such tests are mostly needed.

Our solution: A reagentless system, based on our unique flat Fresnel lens working in the deep-UV, to detect fecal contamination in water based on native fluorescence of tryptophan-based proteins synthesized by the fecal coliforms

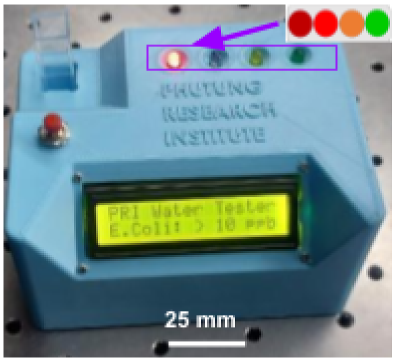


Fig. 1: A prototype WAS model with simple traffic light indicators and a LCD display to indicate level of fecal contamination.

Capabilities:

- Real-time (<1 min), low-cost (<$300 for a basic system), portable (< 1000 cm^3 ; < 1 kg) and user-friendly (basic traffic-light indicators according to WHO risk categories)
- 96% sensitivity to detect fecal contamination
- Detection of other contaminants in drinking water

Applications to real-world issues: early-warning detection of fecal contamination in resource-limited settings

Outcomes of the proposed project: By the end of the project, we will have piloted 20 beta models (Technological Readiness Level-8) WAS devices with >6 community-managed water user groups, >6 households, >2 municipalities in Nepal, and > 6 food and water-related industries in Nepal. While doing so, we will have:

1. obtained >18 early adopters paying a discounted price, and obtained a rating of >7/10 from the users based on their overall experience with our device,
2. adapted our system designs according to the corresponding user's key requirements,
3. improved the method of manufacturing the optical system on our premises in Nepal using a low-cost polymer process, with a performance comparable (within 10%) to those made using methods requiring high-end lithography,
4. improved methods to manufacture electronics and assemble the whole system to yield 99% consistency in performance across all devices,
5. secured ~$200,000 of seed funding for a new company to scale up and expand the sales in the countries around the globe (focused on developing countries).

Long-term Impact

- Reduction of water-borne diseases, especially in developing countries, improving lives and livelihood of billions of people around the globe,
- Direct economic impact on the country of Nepal, and to its scientific, R&D and innovation ecosystem.
- Acting as a role model by giving confidence to other researchers and entrepreneurs.

Collaborators/Advisors: Prof. Thomas Kraus (Nanophotonics), Prof. Marcel van der Horst (Electronics design), Mr. Arjan Rensema (New Business Development), Prof. Prof. Annelies Bobelyn (Product Design).

Executive summary for proposal to the 20th anniversary challenge in the field of environment:

Tunable dual-comb spectrometer for real-time high sensitivity multi-species environmental sensing

One of the major challenges today is the emission of greenhouse gases and air pollutants by industry, intensive agriculture and traffic in urban environments leading to global warming and health issues with enormous costs for society. In order to be able to take appropriate measures, a suitable data basis must be created. Since the currently known trace gases are harmful even at very low concentrations in the parts-per-billion range, highly sensitive measurement methods are required. With modern instruments, such measurements are relatively easy to perform as point measurements. But precise multispecies large-area measurements are still not very widespread. However, such measurements are of particular importance in order to study the exact relationships between emissions and their environmental effects and to identify main sources.

The problem can be addressed with open-path dual-comb spectroscopy measurements. These high-precision time-resolved multi-species measurements have been successfully demonstrated for the detection of methane leaks, agricultural monitoring and urban pollution monitoring.

So far, however, such measurements have been extremely costly and mostly limited to proof of principle experiments, since the underlying optical system, consisting of two stabilized optical frequency combs, is complex and expensive. Furthermore, the measurements have so far suffered from limited sensitivity. This is due to the fact that attempts were made to measure a broad optical spectrum simultaneously in order to achieve a good species selectivity. Also, these first measurements were predominantly performed in the near-IR at 1.6 µm where the trace gases show only relatively weak absorption features. This in turn has forced long integration times on the minute to hour scale and integration distances on the km scale.

Here, we propose a setup superior to these systems, which has a simpler architecture and at the same time offers higher performance. The performance gain can be achieved by sequential narrowband measurements in the mid-IR optical spectrum (2 µm to 5 µm), the molecular fingerprint region of trace gases, at identical total integration times. We access this regime by a combination of a low-noise single-cavity dual-comb solid-state pump laser operated at 1 µm in combination with a wavelength tunable single-cavity dual-comb optical parametric oscillator (OPO) for highly efficient frequency conversion into the mid-IR. At the core of this system is our special recipe for the realization of low noise, solid-state single-cavity dual-comb lasers. We spatially multiplex the optical cavity by the insertion of a biprism that allows for the coexistence of two slightly detuned but mutually coherent frequency combs in the same cavity. Further we transfer the same concept to the OPO cavity to obtain a synchronously pumped single-cavity dual-comb OPO. This allows us to realize a wavelength tunable system with optical frequency combs in the mid-IR pumped by a simple to realize dual-comb laser at 1 µm with excellent noise performance in free-running operation. The low intensity noise and timing noise of the laser is crucial for dual-comb measurements for two reasons: Measurements are typically shot-noise limited and high sensitivity will be obtained through a coherent averaging approach.

In the framework of this project, we will design and assemble a mechanically optimized and portable prototype system of the proposed tunable dual-comb spectrometer, validate it under laboratory conditions and apply it for open-path environmental sensing.

Benjamin Willenberg, Ultrafast Laser Physics (Prof. Keller), ETH Zurich

Project Proposal Optica Foundation 20th Anniversary Challenge

Applicant: Dr. Carlos Doñate Buendía, University of Wuppertal, Germany

Category: Health **Anticipated total duration of the project: 24 months**

Stereolitography 3D printed bactericidal dental parts by laser generated Ag_2WO_4 nanoparticles additivation

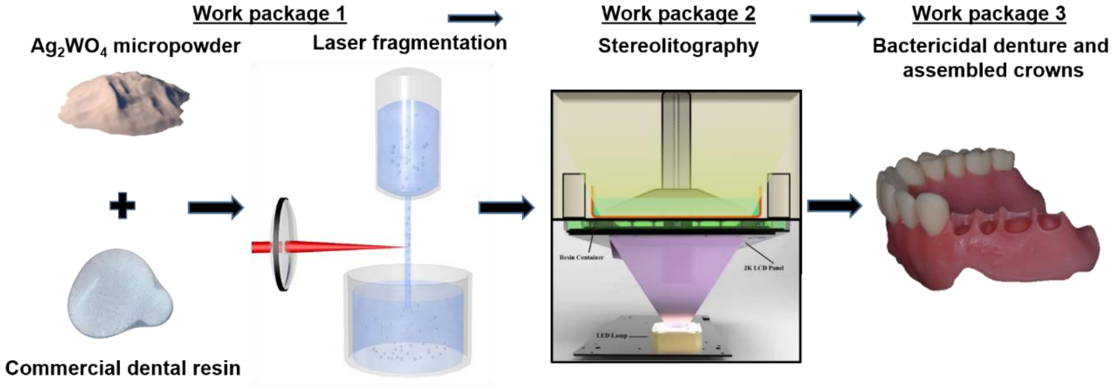
The proposed project addresses a fundamental problem in nowadays society, universal health access. Specifically, dental health costs limit its access to low-income population and countries, resulting in reduced well-being, sickness, and even death. Implants, crowns, and dentures costs still represent a barrier for their extended employment. One of the sources of the high costs comes from the necessity of fabricating custom dental prosthetics for each patient, not allowing serial production. To overcome this limit, a photonics-based 3D printing technique as stereolitography (SLA) is proposed to produce dentures and teeth crowns with complex custom geometries and low production costs.

Another problem linked to dental prosthetic is the proliferation of bacterias and the risk of infection. Dentures and crowns represent a reservoir of microorganisms that can derive into stomatitis or infections. In fact, 70% of dentures wearers suffer from denture stomatitis. To treat infection problematics, antibiotic protocols are developed. However, this solution is limited due to the emergence of antibiotic resistant superbugs. To address it, the employment of laser irradiated Ag_2WO_4 particles exhibiting bactericidal properties is proposed.

Overall, in the current project a complete photonics based approach is proposed to produce dentures and crowns with bactericidal properties by the formulation and SLA printing of resins containing laser generated Ag_2WO_4 particles with enhanced bactericidal properties.

The proposed methodology can be explained in three steps represented in the scheme below. First, the irradiation of Ag_2WO_4 particles dispersed in two dental resins, a flexible one to produce dentures and a hard one to produce crowns. The irradiation is carried out by laser fragmentation in liquids (LFL), and it enhances the Ag_2WO_4 bactericidal effects, as shown in preliminary work from the applicant. Then, the Ag_2WO_4-resin is employed for SLA after detailed characterization of the Ag_2WO_4 particle stability in the resin, the viscosity and wettability. Finally, the produced dentures and crowns are characterized by tensile, hardness, bactericidal, and biocompatibility tests to evaluate their suitability for in-vivo applications.

The proposed approach aims to overcome the current main drawbacks of dental prosthetics. On the one side, high costs that difficult general population access to basic dental health treatments. On the other side, infection and bacteria proliferation and the subsequent loss of patient well-being and extra dental health treatment costs.



Hybrid Optoelectronic Memory for Dual Electronic and Photonic In-Memory Computing

PI: Carlos A. Rios Ocampo | University of Maryland College Park

The Challenge (Category: Information)

In-memory computing has emerged as the optimum architecture for high-throughput matrix-vector multiplications. This approach breaks the processor-memory dichotomy in von Neumann computers by performing co-located computing and storage. In-memory computing on a photonic platform furthers the performance by enabling ultra-fast speeds and wavelength multiplexing, which has been demonstrated using optical pulses to write and perform scalar-scalar multiplications—work pioneered by the PI. However, this approach poses serious scalability challenges when considering architectures with thousands of memory elements due to the complexity of routing writing pulses on-chip. Optoelectronic memories that can be written electrically (i.e., leveraging standard electronic packaging) and read out optically are necessary to guarantee seamless scalability. However, such a memory remains a critical missing link. This proposal aims to fill this gap by creating an innovative optoelectronic memory based on photonic integrated circuits with embedded phase-change materials and a three-terminal electrical scheme. Furthermore, we aim to demonstrate the most versatile device that can be written and read with both optical and electrical signals. This way, we propose an in-memory computing paradigm that carries high-throughput parallel computation in both domains, thus avoiding electro-optical conversions, having continuous communication between parts, and mutually enhancing their performance. This proposal's scope matches OPTICA's interest in driving new scientific discoveries and breakthroughs to transform our world by enabling faster and more energy-efficient ways to compute large volumes of information.

Overview and Objectives

The *overall objective* of this proposal is to develop a transformative hybrid optoelectronic memory (HOEM) based on phase-change materials (PCMs) for advanced photonic-electronic hardware accelerators. Our *central hypothesis* is that, unlike current PCM-based technology operating either optically or electrically, our HOEM will create innovative systems that integrate both into a single device, merging the best performance metrics from both domains. Photonic PCM architectures have advantages in bandwidth, throughput, heat dissipation, no drift, and multiplexing over their electronic counterpart. The latter benefits from mature, scalable CMOS fabrication and demonstrated memory architectures (exemplified by Micron/Intel's 3D Xpoint), enabling volume manufacturing and interfacing with ASIC logic units and DACs/ADCs – inexistent in the optical domain.

This project pursues a unique cross-disciplinary approach spanning optical material synthesis and processing, device design engineering, and scalable photonics manufacturing, which builds on our group's know-how and PI's accumulated experience in combinatorial PCM synthesis, photonic devices, foundry fabrication, and in-memory computing. The team will validate the central hypothesis by completing *two main tasks*: **1) optical materials innovation**: we hypothesize that Ge-Sb-Te PCMs alloyed with Sn, Ti, or Ag will achieve optimal optical and electrical performance. **2) device engineering, manufacturing, and testing:** we hypothesize that HOEM devices can be built using three electrical terminals on SOI waveguides with embedded PCMs for simultaneous optical and electrical signal processing. Developing a HOEM is the first step towards a long-term vision: a hybrid photonic-electronic in-memory computing processor.

Expected outcomes

Our expectations for a one-year seed funding are ambitious, given our accumulated experience in this type of device and material. We anticipate: **1)** finding at least one optimum PCM alloy for simultaneous electrical and optical operation. **2)** demonstrate a high-yield device fabrication process for vertical vias in HOEM, including the crucial third electrode for electronic readout. **3)** experimentally demonstrate a HOEM using the alloy found in (1). We aim to achieve mixed-mode operation of the HOEM resulting from electrothermal Write and simultaneous optical and electrical read. **4)** demonstrate repeatable multilevel response in the optical domain, a crucial property for in-memory computing, and study the drift in both optical and electrical readout. Moreover, we expect insightful exchanges and fruitful collaborations from other scientists in the OPTICA network participating in the 20th Anniversary Challenge.

Digital Holographic Microscopy (DHM) is a potential candidate to diagnose malaria without prior staining of the blood sample, thanks to its essential feature of visualizing and quantifying transparent samples. As a result, numerous applications of DHM in medicine and biology have been reported. One of the DHM versions, Digital lensless Holographic Microscopy (DLHM), is the simplest imaging method to recover information from microscopic samples. DLHM is instrumental in the point of care malaria diagnosis considering its portability-oriented developments. This technique allows the numerical retrieval of the complete optical complex wavefield scattered by the specimens, thus providing numerical refocusing of individual objects and phase information of transparent sample, as required in the malaria diagnosis scenario established before.

As with any other digital holography implementation, DLHM is a two-step technique: holograms of the studied sample are recorded in a digital camera, and further numerical processing allows the retrieval of its information in a plan-by-plane fashion. A simple instrument comprising a digital sensor and an illumination point source is required in the recording stage—notwithstanding its simplicity, significant efforts to enhance the technology in various aspects are continuously reported. Nevertheless, the implementation of portable devices with polarization sensitivity is required to extend the use of this imaging technique in point-of-care malaria diagnosis. Regarding portability, the main challenge is the development of new light sources that fulfill the requirements of DLHM but are cost-effective and mechanically stable. As for the polarization sensitivity of the technique, the challenge is to avoid using bulky setups that require computationally intensive reconstruction methods. In the literature can be found different proposals addressing the latter challenges, however, in practice, all these proposals are cumbersome, expensive, challenging to align, difficult to manufacture, or mechanically unstable. To solve these disadvantages, we have proposed a holographic point source to provide high spatial coherent illumination sources for DLHM without using micrometer pinholes. Moreover, we have reported the insertion of two linear polarizers in the typical DLHM system (LD-DLHM) to enhance disease diagnosis by quantifying the linear diattenuation response of the samples. As a result of our contributions, we have opened the path to portable devices without using bulky setups at a reduced cost and with high optical efficiency that also allows quantifying the polarization response of the studied samples. Nevertheless, in this proposal, we aim to develop specialized point of care platforms for the accurate in-situ diagnosis of the disease and its study. To do this, we propose three developments.

(1) A mechanically stable, low-cost point source DLHM illumination with high spatial coherence using only off-the-shelf elements.
(2) A full Muller-matrix polarization-sensitive DLHM system with a reduced number of polarizing elements and simple numerical processing that runs in affordable embedded computer systems.
(3) A miniaturized DLHM 3D printing-based device comprising the first two developments.

Integrated Photonic Neuromorphic Processor Enabled Intelligent, Energy-Efficient Signal Processing for the Next-Generation Communication Systems

The Internet is vital in the modern society and global economy. In handling today's optical communication systems, digital signal processing (DSP) chips have adopted advanced CMOS technology nodes and approached the limits of semiconductor technologies in terms of power dissipation and density. Even so, DSP chips still must avoid using powerful but computationally expensive algorithms, in order to maintain their power dissipation below the thermal dissipation limit. In the coming decade, DSP needs to handle 10x more data traffic, and correspondingly, their energy per bit must be reduced by 10 times. However, as semiconductor technologies evolve at the end of Moore's law, DSP will find it increasingly difficult to satisfy future demand.

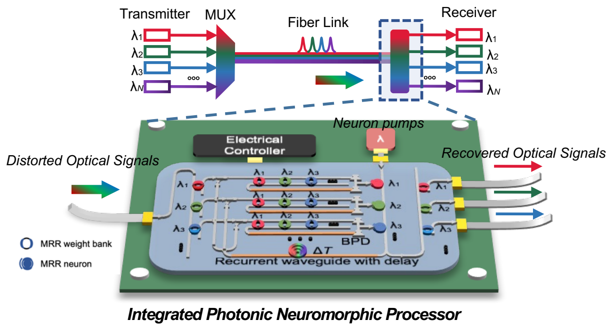


Figure: Proposed fiber communication link with photonic neuromorphic processor.

Therefore, to support continued internet traffic growth, it needs a paradigm shift in signal processing technology that can improve both energy efficiency and processing capability. This project proposes to develop such solutions by investigating a novel integrated photonic neuromorphic processor, which leverages the strengths of intrinsic properties of photonics, deep learning architectures, and integrated photonic technologies. Our approach promises to bring 10x higher energy efficiency and 1000x less processing latency. Meanwhile, the processor offers the capability of compensating for various transmission impairments, which DSP fails to achieve due to its limited bandwidth.

The proposed photonic neuromorphic processor is a system-on-chip that emulates the recurrent neural network (RNN) model using integrated photonic devices and waveguides. However, our neuromorphic processor is **NOT** simply a faster substitute of software RNN for the same operations (in contrast to some research on photonic AI accelerators). Instead, **our solution builds on our discovery of the strong analogies between the physics models of the proposed photonic neuromorphic processor and that of the fiber transmission systems.** By exploiting such analogies, our photonic neuromorphic processor, with only a small neural network, can advance signal processing beyond what is presently feasible by DSP. **The improvement lies in three aspects. First**, our photonic neuromorphic processor, with only N photonic neurons, can simultaneously process N channels, resolving dispersion, intra-, and inter-channel fiber nonlinearities in the transmission system. These capabilities are uniquely enabled by the wide bandwidth of photonics and, therefore, promise to break the nonlinear Shannon limit. **Second**, our photonic neuromorphic processor can process optical signals in their native form and photonic domain. This avoids prohibitive energy consumption and speed overhead in analog to digital converters (ADCs) and substantially reduces power consumption. **Third**, our photonic neuromorphic processor leverages photonic devices designed for optical communications and, thus, can always offer a processing speed matching the fiber communication line rate in the future.

This project will develop a practical and scalable photonic neuromorphic signal processor, built on our proposed architecture and prior research on integrated neuromorphic photonics. Three major tasks will be completed. (1) We will design a novel photonic system-on-chip that allows processing multi-dimensional communication signals in their native form and in the photonic domain. (2) We will explore the optimized photonic platform and photonic-electronic integration methods to realize practical and scalable photonic neuromorphic processors. This will be done by leveraging our prior research and cross-stack collaborations. (3) We will address a common concern in the optical signal processor: the reduced signal-to-noise ratio (SNR) caused by the device loss. To do that, we will conduct a novel joint design of the communication system and photonic neuromorphic processor at the system level. (4) We will experimentally demonstrate the optimized processor and communication link, showing that the photonic processor can address distortions across wide channels while offering energy advantages over DSP approaches. The success of our project will provide a fundamental solution for meeting the future communication demand by delivering faster, more energy-efficient, and more powerful signal processing technologies.

Executive Summary

Dispersion engineering of light for new optical sensing and metrology technologies

(Category: Information)

Dr. Chen-Ting Liao
Senior research associate, JILA, University of Colorado, Boulder, Colorado 80309, USA

Dispersion relationship engineering in materials and structures enables the desirable photonic properties, facilitating modern advances in metamaterials, plasmonics, and photonic slabs for optical sensing. Indeed, the design of coherent or optical transfer functions of materials and systems dictates the information and functionalities an exit optical field can carry. However, this is, in fact, an incomplete picture of a generic sensing principle that ignores the role of the optical illumination itself. As evidenced by the recent success of structured light for super-resolution imaging, enhanced sensing, and telecommunications, the holistic picture of optimized total dispersion relation must take optical illumination into account. In particular, exciting discoveries and creations of nontrivial, spatiotemporally sculptured light show that the nonlinear dispersion relations of light wave packets can elicit novel material properties. Over the past few years, the research has been primarily focused on the fundamental properties of such light, including its propagation, diffraction, refraction, and transmission. Little attention has been devoted to its great potential for parameter monitoring capabilities that can eventually corroborate with the material- and structure-based dispersion relation engineering for enhanced laser-based optical sensing.

By utilizing and optimizing the emerging field of space-time wave packets of light, this proposed project aims to address this knowledge gap and the demanding need to further enhance the existing parameter estimation and monitoring capabilities. Various novel space-time wave packets have been generated and studied recently, including toroidal pulses, baseband x-shaped space-time wave packets, time-varying and spatiotemporal orbital angular momentum of light. The goal of this project is to systematically investigate these space-time wave packets by theoretically and experimentally characterizing how the non-separable degrees of freedom of light can be utilized as a probe for parameter monitoring. Inspired by the analogous concept of dispersion engineering of materials, this project will design, develop, and test the sculptured dispersion relation of structured light pulses that reside on the light cone. The focus will be using sculptured laser pulses in a form that would further enhance nanomaterial, metastructure, or nanophotonic-based sensing applications.

The potential outcome of this project could be transformative as the spatiotemporal tailored illumination are largely under-exploited in laser-based sensing as of today. The potentially new optical sensing mechanisms could improve existing sensing capabilities for a broad range of applications in the future, ranging from materials and semiconductors research and development to environmental, biochemical, and biological sensing and monitoring.

Thermo-mechanical and chemical properties of cornea with hybrid Raman-Brillouin spectroscopy.

Introduction: The mechanical and chemical properties of the cornea are linked to ocular diseases and therapeutic procedures. Brillouin microscopy is a novel and emerging non-contact spectroscopic sensing technology that enables the measurement of viscoelastic properties of a material. Raman micro-spectroscopy on the other hand is a powerful non-invasive optical tool for bio-photonic research and sensing applications targeting the chemical properties of tissues.

Purpose and Impact: Collagen cross-linking using combined riboflavin/UVA treatment has been shown to increase the biomechanical rigidity of the cornea and has been used successfully for the treatment of progressive keratoconus. From morphological and biochemical investigations, a different degree of cross-linking for the anterior and posterior stroma by the treatment is suggested. The present study will seek to better evaluate this effect by testing the thermomechanical behavior.

Methods: In this project, we will present a hybrid spectroscopic technique for cornea thermal-mechano-chemical properties and microstructure analysis that combines Brillouin and Raman spectroscopies with confocal microscopy into a single bio-imaging modality. This hybrid integrated approach to bio-sensing enables probing mechanical and chemical properties of the cornea simultaneously in a non-contact and non-invasive fashion with micrometer spatial resolution using a single laser probing source. Additionally, corneal anisotropy will be tested at different collagen orientations of the cornea. An automated data analysis technique will be developed for fitting the data which will allow fast and accurate spatial integrated mapping of Brillouin and Raman spectral peaks (position, linewidth, and intensity). Spectral images at different temperatures will be further analyzed using machine learning algorithms for extraction of correlated mechano-chemical information of diseased and healthy cornea with micron-scale spatial resolution.

EXECUTIVE SUMMARY

Preeclampsia affects approximately 4.6% of pregnancies and is the second leading cause of maternal mortality. It is characterized by elevated blood pressure and evidence of end-organ dysfunction, and the majority of deaths are considered preventable with early diagnosis and treatment. Unfortunately, the signs and symptoms of preeclampsia (1) are not specific to preeclampsia, (2) often represent late-stage disease, and (3) require laboratory evaluation, which may not be readily available in rural and low-resource settings. Luckily, a few alternate cardiovascular parameters have been identified that can accurately diagnose preeclampsia. Preeclampsia patients have increased arterial stiffness measured via the augmentation index (AIx) compared to normal and chronic hypertensive patients. AIx effectively measures the speed of the reflected systolic pressure wave, which returns faster in stiffer arteries and results in an increased AIx. In addition, patients with early-onset preeclampsia, which has higher morbidity and mortality and requires distinct patient management, have higher systemic vascular resistance (SVR) than patients with late-onset preeclampsia. Current AIx and SVR measurement tools require either invasive catheterization or specialized equipment with a trained operator. A low-cost, non-invasive, point-of-care (POC) device for measuring AIx and SVR is needed to enable improved preeclampsia screening for earlier diagnosis and improved pateint outcomes.

The light-based time varying measurement performed in pulse oximetry, photoplethysmography (PPG), has shown potential to measure AIx and SVR non-invasively. PPG sensors are small, wearable, and inexpensive, enabling widespread use and continuous monitoring. Furthermore, near infrared wavelengths can be used to minimize influence of skin color which has been shown to affect the accuracy of visible wavelength PPG data. Unfortunately, PPG suffers from poor signal-to-noise ratio (SNR) and thus is not used clinically for diagnosis of cardiovascular indicators beyond heart rate. The poor SNR of PPG may be overcome by using speckle phlethysmography (SPG), which measures changes in blood velocity. SPG creates a similar periodic signal as PPG during the cardiac cycle but with significantly higher signal contrast. Preliminary data collected by our group in swine suggest that AIx and SVR may be extracted from SPG data with higher SNR than PPG, overcoming a key barrier for use as a POC diagnostic.

We developed a custom wearable SPG sensor and conducted a feasibility study in a swine model (n=2) of controlled volume hemorrhage. We compared our SPG-based SVR against an invasive gold standard SVR measure and achieved a correlation coefficient of 0.91. As PPG-based AIx has already been validated to show strong correlation, we compared our SPG-based AIx against PPG-based AIx from high SNR PPG waveforms and achieved a correlation coefficient of 0.8. Based on this preliminary data, *we hypothesize that high fidelity AIx and SVR parameters can be non-invasively extracted from a miniaturized, high SNR design of our wearable SPG sensor for POC diagnosis of preeclampsia.* We will test our hypothesis as follows:

Aim 1: Validate the ability of a miniaturized wearable SPG sensor to extract accurate SVR and AIx values in patients. Aim 1a: Construct miniaturized high SNR SPG sensor: The current SPG sensor will be redesigned to have a wristwatch footprint, 24 hour battery life, bluetooth data transfer, and a second camera to increase SNR. Aim 1b: Validate miniaturized SPG sensor's performance in patients with intra-arterial catheters: The newly miniaturized SPG sensor will be tested in 40 patients undergoing intra-arterial catheterization procedures from which gold standard SVR and AIx values will be extracted to compare against SPG–based SVR & AIx values.

Upon successful completion, we will launch testing of the device in pregnant patients in high and low resource settings. Our wearable SPG sensor will be the first device to provide non-invasive and operator independent POC assessment of AIx and SVR for early detection of preeclampsia and identification of early-onset preeclampsia. The sensor has been specifically designed to be a simple, quantitative, continuous monitoring tool, with the goal to reach underserved patients with the greatest preeclampsia burden.

Germania Glass-based Optical Fiber and Light Source Technology for Green Photonics

The broad objective of the proposal is to develop exceptionally novel optical fiber and light source technology for the mid-infrared wavelength region by integrating novel fiber design, material (Germania glass), and fabrication technology. The important chemical compounds such as CO_2, NH_4, CO, N_2O, and CH_4 display strong absorptions in this wavelength region. Therefore, optical fibers and light sources operating in this wavelength region are critical tools for applications such as efficient high-power fiber lasers, high-power beam delivery, spectroscopy, imaging, material characterization, sensing (environmental, gas, and illicit drugs), monitoring (pollution, industrial, and food control), medical diagnostic, and security.

This proposal will establish novel outside vapor deposition (OVD) technology to fabricate optical-grade pure Germania and Germania-Silica glass rods and tubes. The Germania glass inherits the properties of the Silica glass such as good mechanical strength, lower susceptibility to moisture, lower reflection coefficients, higher power damage threshold, easy handling, and processing, therefore, outperforms the other competitive glasses such as ZBLAN and Chalcogenides.

The pure Germania and Germania-Silica glass rods and tubes will allow the fabrication of different kinds of fibers. For fiber lasers, a Silica-Germania cladding with a Silica core will allow a high number of rare-earth ions and other dopant ions such as phosphorus and aluminum. This combination will demonstrate large-core fiber lasers with low NA leading to high power, high efficiency, photodarkening resistance, and good beam quality with thermal stability. For passive fibers, a fluorine-doped layer between pure Germania core and cladding can offer effective single-mode operation for a large effective area. The development of these Germania fibers will lead to the demonstration of the fiber couplers, which are mandatory for an integrated (free from bulk optics) optical device. This project will also form the basis fabrication of the hollow-core negative-curvature fibers using fabricated Germania tubes. The Germania glass in cladding will increase the low-loss transmission window up to 6 µm, which is limited up to 4 µm for Silica glass.

These paths-breaking development will open doors for novel light sources in 2 to 3 µm which can be extremely useful for several applications such as early forest detection, medical diagnostics, pollution monitoring, gas sensing, etc. The project can dramatically scale the utility of fiber optics technology and can demonstrate products suitable for commercialization. On the scientific front, this project will provide a novel tool to researchers for advanced scientific discoveries and building new instruments.

EXECUTIVE SUMMARY

DEVELOPMENT OF TUNABLE MULTI-COLOR LASER FOR SENSING: CASE STUDY FOR HYPERSPECTRAL DETECTION OF WATER CONTAMINANTS

Access to pollution free water is essential for humans and animals alike. It is from this point of view that photonic spectroscopic technologies have gained increased attention for water quality and environmental monitoring applications. The photonic technologies have the capability of detecting dissolved contaminants in clear water samples by way of inspecting optical water clarity. However, most of the well-established spectroscopic techniques such spectrophotometry used in ongoing research at University of Eldoret require expensive instrumentation and are un-affordable. Therefore, the key motivating factor of this proposal lies in the ultrafast, sensitive optical detection of low levels of pollutants in clear water samples using a simple and cost-effective all-optical approach . Our long-term goal is to develop a multi-wavelength visible laser source generated through wavelength conversion for varied applications in water quality assessment, environmental monitoring and basic research. However, development of a tunable, multi-wavelength visible laser source remain unexplored and this proposal is an attempt to bridge the existing gap. We firmly believe that such a visible laser, once integrated in an optical communication system can find wide range of applications among them, water quality assessment. For instance, it is well known that the presence of contaminants in clear water sample causes optical absorption and/or fluoresces at certain wavelengths since most known substances have specific absorption spectra. Therefore, it is possible to tell the type of contaminant through their spectral 'fingerprints' because they can show strong absorption at particular wavelengths when a laser light interacts with the contaminated sample. Notably, some of the pollutants can be toxic even a low concentration and often difficult to detect.

The specific objectives are designed to provide a detailed design, fabrication and deployment of the multi-wavelength visible laser source for sensing applications. The specific objectives are to:

1. Design a step-chirped PPLN waveguide for tunable wavelength conversion in to the visible spectral range.
2. Investigate the tunability and wavelength broadening of the waveguide device.
3. Fabricate and characterize the compact monolithic multi-wavelength device.
4. Apply the generated wavelengths for detecting water contaminants in a laboratory set up.

Implementing this proposal will strengthen and broaden the applications of multiwavelength visible lasers to solve societal challenges such as in health and environmental monitoring just to name a few. For instance, an all-optical sensing system when used for water quality assessment can contribute to mitigation measures against water pollution, decrease waterborne illnesses and improve the quality of life. It is also expected that, upon completion of the project, the future career prospects of the participants will be enhanced. The project is expected to train two (2) MSc and one (1) PhD students. The research team will participate in scientific conferences, symposia and publish research findings in peer reviewed journals.

Multi-core Polymeric Optical Fiber Sensors for Atraumatic Smart Cochlear Implantation

Category: Health

Hearing loss is a growing global health issue which affects people of all ages. Latest statistics from the World Health Organization, affirms that globally, an estimated 1.5 billion people (1 in 5 people) suffer from hearing loss with a projected rise to 2.5 billion by 2050. It has downstream effects on speech recognition, cognitive development and leads to an increased risk of dementia. Surgical involvements such as cochlear implantations have the capacity to alleviate this burden. Cochlear implantation is the current well-established standard of care to treat the hearing-impaired suffering from severe to profound sensorineural hearing loss. A cochlear implant (CI) consisting of an electrode array (EA) is implanted into the inner ear (cochlea) bypassing the missing or defective sensory receptors by directly stimulating the auditory nerve and thereby, restoring hearing in deaf patients. This extremely delicate surgical procedure involves high precision and complex navigation. The quality of hearing restored to a deaf patient depends on accurate positioning of the EA while preserving the cochlear membranes. New bone formation that occurs inside the cochlea as a result of electrode insertion trauma, not only negatively impacts the hearing performance but also makes future explantations and re-implantations of CIs difficult. The typical lifetime of CIs is just over 20 years, so, replacement of old implanted CIs will be required several times over a young individual's life. Existing technological electrodes end up at an undesirable (traumatic) intracochlear location up to 50% of the time. Yet current approaches on cochlear implantation have significant shortcomings: lack of any visualization of the intracochlear structures during implantation which requires precise positioning in order to preserve the delicate cochlear structures and absence of feedback on insertion forces with blind insertions guided only by the clinician's tactile feedback.

With polymeric optical fibers (POFs) anticipated to revolutionize the biomedical sensing industry due to their intrinsically beneficial properties, in this project, we propose the application of a ZEONEX-based low loss multi-core polymeric fiber consisting of four cores inscribed with fibre Bragg grating (FBG) sensing arrays which can be integrated internally inside a CI. These smart CIs can provide real-time feedback to clinicians when navigating CIs during cochlear implantation surgical procedure with minimum insertion trauma thereby, promoting hearing preservation. Apart from extreme flexibility and low stiffness levels, ability to withstand temperatures exceeding 120 °C, absence of any risk of fiber breakage even under low bending radii, chemical inertness and insensitivity to humidity offered by these ZEONEX-based POFs which are fundamental requirements in the manufacturing process of cochlear implants emphasize their compelling candidacy. Feedback from the FBG arrays that will be inscribed in these proposed ZEONEX MCFs can be used to derive a multitude of forces (eg. tip force, lateral force, frictional force) experienced by the CI inside the constricted cochlea during insertions as well as its shape at specific localities. Insertion trials already carried out on CIs integrated with ZEONEX single core polymeric FBGs inside the cochlear phantoms permit contact force detections of these CIs in the scale of millinewtons with investigations inside human temporal bones anticipated to be conducted at the Royal Victorian Eye and Ear Hospital, Melbourne in late 2022.

Ongoing collaborative research with world leaders of cochlear implant technology places us in a unique position to pioneer the development of smart cochlear implants. Industrial collaborative experience brought in by the investigators paves the way for clinical translation of these research outcomes ensuring that new diagnostic approaches truly benefit the hearing impaired. Hence, adaptation of this technology provides a direct course to the next generation of CIs and we believe its virtues will complement lifetime implanted-hearing conditions.

The Optica Foundation 20th Anniversary Challenge
Category: Environment
Title: Spectral radiance mapping to characterize the ecological impacts of light pollution
Name: Dorukalp Durmus
Affiliation: Pennsylvania State University

Executive summary:

The challenge

The accessibility and growing demand for electric lighting have a large-scale impact on natural habitats. Unfortunately, the electric light at night (LAN) can cause negative consequences, such as disrupting ecosystems, confusing migratory patterns, altering predatory-prey relations, causing stress, and interrupting the entrainment of circadian rhythms of many species. The negative effects of LAN (aka "light pollution") is often quantified using photometric and colorimetric measures. Despite the complexity of spectral impact of light sources on the environment, research suggests that light source spectra influences arachnida, aves, instecta, mammalia, and reptiles in predictable manners. However, ecological research studies still use photometric (i.e., illuminance, luminance) and colorimetric (i.e., correlated color temperature) measures, which are based on human visual sensitivity. In addition, photometric and colorimetric measurements are performed using either spot measurements or satellite images. While these measurement methods have merits, they have limitations in accurately evaluating the ecological impacts of light pollution.

Proposed project

Characterizing the impacts of light pollution on several species requires a holistic measurement approach in spectral and spatial dimensions. The proposed research project aims to characterize optical radiation using a spectral imaging radiance colorimeter and assess the outcomes compared to spot (e.g., handheld spectroradiometer) and remote (satellite) measurements. A test field in central Pennsylvania will be identified, and light pollution of a large field of view will be characterized using radiance imaging colorimeter to simulate realistic field conditions. The variation between the traditional and proposed measurement methods will be evaluated, and a new metric for light pollution will be developed using the data generated in this project.

Intended outcomes

The results of this project will help characterize the unintended consequences of light pollution that captures the effects on the environment beyond just humans. New light pollution metric and measurement methods comparison will be disseminated to relevant bodies, such as the Council for Optical Radiation Measurements, the International Commission on Illumination, and International Dark-Sky Association. The project aims to reach a transformative impact on project development where designers and engineers can quantify the impact of lighting systems and mitigate any potential offence. The development of a holistic light pollution metric will also help ecological researchers find acceptability thresholds and guide outdoor lighting standards and recommendations, such as Model Lighting Ordinance (MLO), LEED Sustainable Sites program, the International Commission on Illumination (CIE) recommendations, and standards, such as the Australian New Zealand Standard AS/NZS 4282:2019 Control of the obtrusive effects of outdoor lighting.

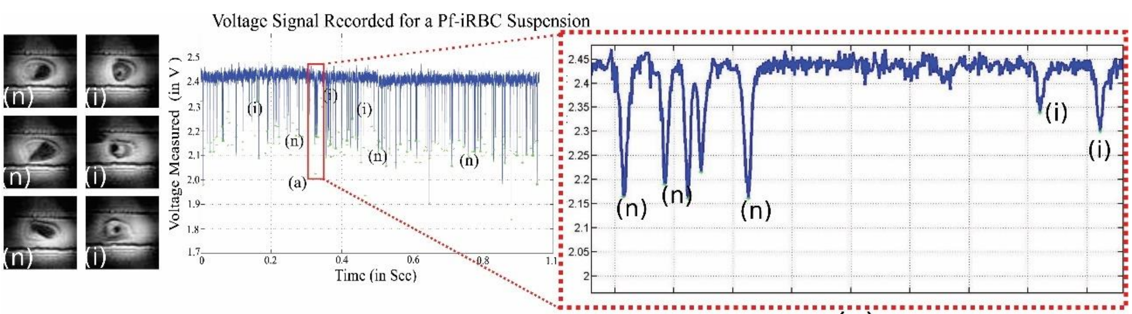
20th Anniversary Challenge (Optica Foundation)

Name of Challenge Project: Artificial Intelligence enabled smart Optical Absorption Point-of-Care device for Malaria screening

Executive summary:

Background: For the larger interest of the needy design and development of Point-of-Care (PoC) diagnostics is the critical requirement of the health care industry. The requirement of rapid, sensitive detection and reliable solution with minimal human intervention is the front runner objectives of the research and innovation. The aim of the present research proposal is to develop an indigenous smart PoC instrument for screening/ detection of the malaria. The monitoring and screening of malaria transmission is possible with the advancement of the technology in view of malaria eradication.

Scientific Rationale: The microvascular system is responsible for the transfer of oxygen and nutrients and the removal of the waste products generated by the tissue it serves. Here, the main role of the erythrocyte/ Red Blood Cells (RBCs) is the transmission of hemoglobin (oxygenated) and nutrients through microvascular system. As we know that the malarial parasite targets RBCs such as infect inside the RBCs and reduce the hemoglobin concentration by degrading it as hemozyme. As a result, there will be changes in the level of hemoglobin present in normal RBC and malarial infected RBCs. So, this information can be utilized to develop a point of-care device to differentiate between malarial infected and normal RBCs at single-cell high-throughput by differential light absorption in microfluidic channel as observed in any flow cytometry. The proof-of-concept and primary results shown briefly in the figure below.



Novelty: The present malaria diagnosis instruments including clinical microscopy, PoC, Rapid (**qualitative info**.) testing devices use standard signal/image processing algorithms. PoC devices integration with AI models for automatic malaria screening/ testing may give more promising results. Current proposal aims in development of an AI-enabled PoC device for Realtime analysis at single-cell high-throughput (quantitative info.). The primary objective of the study involves development of smart PoC device for malaria screening. The secondary objective of the study includes proper design of experiments for clinical validation and testing, Develop the novel AI based algorithm and comparison with state-of-the-art techniques

Methods: The major principle involved in development of device is to study the light (near UV) absorption properties of malaria infected and healthy/normal blood cells. Predominant features are automatically extracted from the output signal of the sensor using signal processing algorithms and trained with artificial intelligence algorithms for classifying malaria and non-malaria cells. Novel reinforcement learning techniques will be incorporated and further tested.

Expected outcome: Low cost and portable Smart point-of-care Instrument for malaria screening and research publications in high reputed journals along with patents. Custom design and developments of flow-focusing microfluidic devices which are used for identifying cell morphology, deformability, blood flow velocity. Development of GUI based algorithm for malarial parasite detections, finding the stages of infection, quantitative information of infected cells from overall assessed sample. Development of this type of product help in early screening of malaria endemic zone which help towards the eradication of malaria.

Integrated NDIR gas sensor based on mid-infrared silicon photonics

Executive summary

Floria Ottonello-Briano

The technology that I developed in my PhD is currently in the technological “valley of death” and I want to lift it out of it. I successfully demonstrated the use of mid-infrared (mid-IR) Si photonic waveguides for optical gas sensing, as a path to dramatically reduce NDIR sensor size, power consumption, and cost. Miniaturizing optical gas sensors is crucial to enable the extensive and accurate measurement of greenhouse gases (GHGs), which negatively affect climate change and air quality. Optical gas sensors, which rely on the absorption of light by the analyte gas molecules, offer a superior performance in terms of selectivity, sensitivity, speed, stability, and lifetime, compared to other types of sensors. However, their widespread adoption is still limited due to high power consumption, size, and cost. In fact, despite the advantages, their development has been hindered by the lack of suitable optical components for the mid-IR spectral range, where the optical sensing of GHGs with a high selectivity and sensitivity is optimal. Nevertheless, recent advances in light sources, detectors, and integrated photonics for the mid-IR are now accelerating the development of on-chip optical gas sensors based on photonic waveguides.

In this project, I aim at demonstrating the first integrated mid-IR gas sensor based on silicon photonic waveguides and low-cost, low-power-consumption active components. The system will comprise a Si photonic chip and off-the-shelf mid-IR LED light source and photodiode detector with integrated optical filter. The main goal of the project is to show the compact integration of all components into a working gas sensor prototype for NDIR CO_2 detection. The main challenge of the project is to achieve a sufficiently efficient coupling from the light source to the photonic circuit and from the circuit to the detector.

Although the proposed prototype still uses discrete off-chip components, it is the crucial step towards a fully on-chip integrated system. Once demonstrated, the system will attract resources to be advanced further. The proposed technology will lead to a reduction in size and cost of one order of magnitude compared to current commercial NDIR sensors, enabling the adoption of optical gas sensors in an increasingly broad range of applications, in particular air quality monitoring for environmental, health, and safety purposes, with a positive impact of people’s and Earth’s well-being.

Executive Summary for:

Noninvasive High-Resolution Imaging through Living Tissue with Single-Shot Synthetic Wavelength Holography

Florian Willomitzer, Wyant College of Optical Sciences, University of Arizona, USA

What is proposed? This proposal seeks to develop a *computational camera* that can *image through dynamic scattering media* with *high resolution*. The camera is primarily proposed for medical imaging applications through living (moving) tissue. The proposed noninvasive technique only uses light in (or close to) the optical wave band and works with standard off-the-shelf camera technology – theoretically even with mobile phone camera sensors. The technique leverages the huge potential of carefully designed optical systems paired with sophisticated algorithms. If successful, the camera could become part of a new wave of computational imaging devices that will represent key technologies in our near future.

Why is this important? Over the last decades the field of medical imaging has spawned several seminal inventions which can be found in every hospital nowadays. Prominent examples include Optical Coherence Tomography (OCT), Computed Tomography (CT), Ultrasound, or Magnet Resonance Imaging (MRI). However, recent years have seen a growing interest in medical imaging techniques which enable to look inside the human body, *but are non-invasive* and can be facilitated in a *small form factor*, i.e., possibly even operated in a hand-guided fashion. In other words: Cameras that allow to image small structures (such as capillaries, lesions, tumors, etc.) through scattering media, such as tissue and bone.

What is the problem? The proposed plan to develop such a camera builds up on the recent publication of the PI's research group, which used "Synthetic Wavelength Holography" (SWH) to image through scattering media and around corners with a demonstrated resolution up to 800μm [1]. However, the current SWH approach relies on the *acquisition of sequentially captured images* (at different optical wavelength) and is *extremely susceptible to motion*. Even the slightest movement of object or scatterer between two captured images leads to a complete loss of information, which makes imaging through living (i.e., moving!) tissue impossible with the current method. Moreover, the current SWH technique relies on expensive modulation/imaging hardware, such as acousto optical modulators and specialized lock-in cameras.

What is the solution? This proposal outlines a solution for the aforementioned problems of the current SWH method. The solution draws inspiration from established optical metrology principles and allows for *single-shot (!)* SWH measurements with the same or similar quality as shown in [1]. This means that all required information can be captured *with one single camera image* in a very short exposure time (<1ms in our preliminary experiments). Moreover, the proposed approach allows to swap expensive and specialized imaging hardware with standard off-the-shelf camera technology that can be found in every smartphone nowadays.

Who cares (impact)? If successful, the proposed technique of "Single-Shot-SWH" could have immense impact on future academic research as well as today's billion-dollar industries. This impact goes far beyond potential applications in medical imaging (e.g., to noninvasively monitor the beating heart through the chest). Potential examples from other industries include self-driving cars that use the technique to analyze hidden scenes around corners or through fog, hand-guided industrial inspection devices that detect defects around corners in confined spaces, novel cameras for first responders that image through smoke or turbid water, or next generation VR/AR headsets that show the user obstacles or hazards which are hidden from his direct view.

Why should this proposal be granted? The proposed technique significantly advances the state-of-the-art and our fundamental understanding of limits. Moreover, the work represents a critical first step to put the PI's long-term research vision into practice and would eventually enable him to apply for follow up funding. Due to the risks involved in the initial "Single-Shot-SWH" demonstration (which would provide the basis for larger multi-year grants) the proposed project may be difficult to be funded from other sources.

OPTICA | Formerly OSA

Foundation

20th Anniversary Challenge

Use photonics. Find a solution. Change the world.

Application Dates

07 Jul 2022 - 15 Sep 2022

Executive Summary of “hardware and software enablers for future optical access networks”
Contact: Gaël Simon, Philippe Chanclou
The access network recently witnessed an important increase, through the massive deployment of Fiber To The Home (FTTH). The industry is already working on the definition of the optical technologies which will replace the currently deployed technology, the G-PON (gigabit passive optical network) standard, offering higher than ever throughputs. Those future technologies will enable, beside the throughput increase, to answer the constantly evolving customers’ uses. The success of G-PON and the coming XGS-PON technologies and similar permitted to imagine new use cases for those technologies, in taking advantage of their robustness, their low energy consumption, or their low-cost for mass production in other network segments. This is the objective of the “ETSI-F5G” organism, which aims to “extend the FTTH paradigm to a Fiber to Everywhere”. In parallel, the rapid development of mobile networks (5G’s deployment started; 6G’s main directions emerge) requires the fiber infrastructure to evolve toward antenna sites. Mobile network transport and associated specifications induce important constraints on optical segments in terms of throughput (10x more in 6G than 5G), and latency (10x less in 6G than 5G). This is emphasized by the interest in solutions as “Cloud Radio Access Network”. The later splits the radio network functions and creates new interfaces, often requiring high bitrates, as the x-Haul. The objective of this project is to identify technological solutions allowing to answer to previously presented stakes, and to identify their strength and weaknesses, while insuring interoperability of the future systems working at 100Gbit/s. The current optical transmission technologies for access network employ Non-return to Zero modulation format, for the sake of simplicity and cost. However, the need for high bitrate interface come at a price, which imposes to reevaluate the solutions and to assess the need for a technological rupture. It could mean to choose PAM4, coherent detection “regular” or simplified, the use of Frequency Division Multiplexing, Wavelength Division Multiplexing, NRZ at higher bitrate,… In any case, those solutions must adapt to the multiple access topology of the FTTH. The energy consumption must also be carefully monitored, and so must be the ability to maintain interface’s interoperability, avoid the dependency to a vendor, and make the optical fiber passive infrastructure viable.

Multi-contrast OCT + AI-based image processing supported by optical segmentation for minimally invasive assessment of bone quality (MOSOS)

Application for the Optica Foundation 20th Anniversary Challenge: Health category

Executive summary

Osteoporosis is a disease that causes progressive deterioration of the mechanical competence of bone resulting in an increased risk of fractures. Up to now, it is mostly characterized by the loss of bone mass or microstructural changes. However, changes in the material composition and properties of the bone tissue altogether lead to reduction in bone strength and increase in risk of fracture due to the more fragile skeleton. The methods currently used for clinical diagnosis of osteoporosis primarily consist of measurements of bone mass and density. However, changes in bone mass only account for approximately 15% of fracture risk, and in several diseases affecting the skeleton, such as type 2 diabetes (T2D) and glucocorticoid-induced osteoporosis, the correlation between bone mass and fracture risk is low. This fact makes it difficult to predict risk of fracture and thus determine when to initiate proper treatment to prevent future fragility fractures. Fractures put a strong burden on the health system, cause considerable risk for patients, and the prevalence is on the rise worldwide due to the aging population and the increase in associated disorders impacting bone quality such as T2D. Early fracture prevention is of paramount importance to reduce health care costs and prevent individual suffering. Hence, there is a high unmet need for new tools to assess bone quality in vivo.

The MOSOS project aims to provide proof of principle that optical coherence tomography (OCT) is such sought-after method for assessing early fracture risk in vivo. OCT is an imaging modality that uses infrared light to generate label-free cross-sectional images of tissue microstructure. Unlike existing diagnostic methods, OCT has sufficient spatial resolution necessary for segmentation of cortical or trabecular bone compartments. Additionally, OCT has the potential to assess bone quality directly through the modeling and extraction of optical properties, which are directly correlated with material properties and sub-resolution microstructure of the tissue. So-called multi-contrast OCT incorporating structural information and optical properties will aid in the identification of new optical biomarkers of fracture risk.

Until now, OCT imaging in hard tissues such as bone has been challenging due to the limited penetration depth of light in highly scattering tissues. We have recently developed a new embodiment of OCT, spatial offset OCT, which leverages the role of multiply scattered light to enhance contrast at depth in highly scattering tissues. As an added benefit, spatial offset OCT improves contrast between mesoscale tissue structures acting as “optical segmentation” to improve identification of regions of interest in tissue.

By combining the multi-contrast OCT and spatial offset OCT images as inputs to a deep learning algorithm, the MOSOS project will develop an innovative tool for assessing bone quality and fracture risk without the use of ionizing radiation. The MOSOS project holds promise to build a robust and cost-effective technique that can be used in a range of settings (outpatient clinics, general practitioners, etc.). If the hypothesis in this project is confirmed, MOSOS might disrupt the assessment of bone health.

TITLE: Optimization of Windows for Energy Efficient Buildings: Non-imaging optics for ultra-cool surfaces

CATEGORY: Environment

OBJECTIVES:
The objective of the proposed project is to a) investigate efficient materials emitting in the atmospheric window and b) develop optical designs to direct this radiation towards space. Broadband directors of infrared radiation are required towards this end, and this project aims in investigating their designs based on suitable materials and windows exhibiting cooling at sub-ambient temperatures. Promising results reported multi-degree outdoors cooling by utilizing imaging optics. The throughput of several classes of non-imaging optics e.g. the compound parabolic, is superior compared to their imaging counterparts. The rational design of optics exhibited very efficient concentrators. By reciprocity, these thermodynamically ideal optics make for excellent directors. Many of these designs were inspired by nature and the bio-mimicking approach lead to many serendipitous discoveries. The advent of efficient evolutionary algorithms for the optimization of such designs can greatly speed up the development of efficient designs. Consequently, the core of the optimization based on advanced algorithms will be developed during this project. In this work dielectrics and polymer composites for radiative cooling will be investigated. On one hand, the extensive experience in one-dimensional deposition will enable wide-area cool surfaces. On the other hand, composite materials from recycled products can add value towards a circular economy of these much needed products.

INTENDED OUTCOMES:
The proposed research will develop advanced algorithms for optimization of one-dimensional filters and cool micro-structured materials for wide-area surfaces such as windows and buildings, based on non-imaging optics. In addition, benefits to industrial sectors such as building, windows, manufacturing, as well as automotive and space are expected via the transfer of the developments based on non-imaging optics and photonics. Training of personnel in developments of algorithms, film deposition and additive manufacturing during this project, will further aid the transfer of knowledge. Involving and training master's students during their final year projects will further expand the reach of optics and photonics, as well as arming them with skills for further professional development and job security. The results of the project will be published in reputable journals and disseminated in international conferences and workshops organized by Optica. 4 journal publications and 4 conferences presentations are expected during this project.

APPLICATION TO REAL-WORLD ISSUES:

The proposed research intends to progress the application of radiative cooling materials in wide-area surfaces to address the issue of urban heat island. This will be accomplished by replacing existing surface materials with these developed during this project, based on non-imaging optics and optimized one-dimensional structures. Real-world applications of the developed materials can take place in buildings, roofs or windows. In this way, the extensive experience of the industry in one-dimensional deposition, as well as the excellent radiative properties of non-imaging optics can be utilized towards enabling wide-area cool surfaces. Moreover, the use of recycled materials in the design will take some of the burden to the environment by the accumulation of leaching materials either escaping or buried underground in the absence of better alternative solutions.

Executive Summary of Proposal:

Single-shot, **I**sotropic and **M**iniaturized **D**ifferential **I**nterference **C**ontrast (SIM-DIC) Microscopy Based on Computational Flat-Optics

Dr. Guangwei Hu (guangwei@stanford.edu)
Early-Career Member of Optica and SPIE
Nanyang Assistant Professor (Starting Jan 2023)
School of Electrical and Electronic Engineering
Nanyang Technological University, Singapore

In our daily life, we care about our health and the environment on the earth. In the healthcare and biomedical technologies, we need to image the biological samples, including cells, tissue slices and many others; in many areas on this planet and in many working spaces, people and other living creatures are facing challenging problems such as air pollutions (due to $PM_{2.5}$ dust micro/nanoparticles), microplastics in the sea and others. It is important to image those tiny samples with optical microscopy, and to track their movements in real time and in three dimensions.

However, most of those matters are transparent in the visible spectrum, being hard to be seen in most microscopies based on the optical absorption variances. There are existing techniques such as differential interference contrast (DIC) microscopy to record the refractive index change and the associated phase difference for imaging purpose. DIC features the merits of high spatial resolutions, outstanding contrast, optical sectioning capability, cost effectiveness, and pseudo-3D relief type of image. However, the conventional system is bulky (use 4f system) and can only obtain the information in one dimension, not the others, which is known as problem of "orientation sensitivity".

In this proposal, we will use the flat-optical elements, i.e. metasurfaces, to innovate the traditional DIC microscope and develop the *single-shot, isotropic and miniaturized* DIC (SIM-DIC) microscopy. Our single-layer metasurface is made of millions of *deeply subwavelength, thin* (~300 nm) and *COMS-compatible* Si nanostructures and can perform the multiple functionalities including the focusing phase, the polarization multiplexing, and the edge detection (i.e. the first-order derivative mathematic operations). Moreover, our system is a 2*f* compact system and has the powerful capabilities of mapping the full and isotropic contours of moving transparent microparticles and bio-samples in three dimensions. Most importantly, it can be designed into a simple and flexible module as an add-on portable device for our daily consumer electronics such as cellphones and others.

Beyond those technological values, the proposed project will lead the innovation of conventional photonic technologies via fusing the emerging platforms such as computational flat-optics. Our designed important system is highly integrated, low-cost, portable, flat and multifunctional for various high-end applications, including bio-imaging microscopy, wearable healthcare devices, environmental monitoring (of air pollution, microplastic pollution and etc.) and others.

Executive Summary

Coherent large bandwidth laser sources, e.g., supercontinuum sources, with a flat spectral profile are needed for a large plethora of optical devices. For example, they are used in sensing devices to detect substances, medical devices such as optical coherence tomography (OCT), and security devices like ones employed in airports or at events.

Wide-bandwidth low power coherent laser sources are also integral in telecommunications where the demand for more information channels – at lower powers is increasing as the size of global information exchange is ever increasing. Currently, all these devices need large pump powers for the coherent wide-bandwidth source used within them. This makes them expensive, bulky and large, which makes them expensive, not portable or robust and constrained to highly controlled environments such as laboratories.

We have an approach and prototype product that can significantly downscale the cost and size of supercontinuum laser sources, by significantly lowering these power requirements. Enabling these sources to be on microchips or in fibers while producing high-quality flat spectra relevant for applications. We plan to provide large bandwidth coherent sources on chip or fiber to device manufacturers that rely on this source technology, i.e. we want to make our technology practical to solve problems in all three categories: Health, Environment, and Information.

At the core of our approach, we rely on sign-alternating the waveguide dispersion, such that the supercontinuum process remains ongoing and thus highly efficient with pump power. By alternating between anomalous and normal dispersion segments, spectral clamping mechanisms are bypassed such as the shaping of the pump pulse to solitons that stagnate generation (in anomalous segments) or the loss of peak power that occurs in normal dispersion segments. The soliton profile is disrupted by the placing of the normal dispersion segments along the propagation and the anomalous dispersion segments recompress the temporally broadened pulses coming from the normal dispersion segments – thus, keeping spectral generation ongoing. Furthermore, the spectral bandwidth is generated primarily within the 1/e range (achieving greater than 1000nm) instead of the -30 dB range found in conventional supercontinuum lasers.

Our approach is well suited for the integrated photonics setting such as in CMOS-compatible silicon nitride where the high-index contrast enables dispersion engineering simply by modulating the waveguide width. The reduction in pump power is now achieved with our technology, from the nanojoule pulse energy level to 9 picojoules ranges to a factor of thousands and can enable handheld or integrated wide-bandwidth lasers where the possibility did not exist. We have proven our technology through the construction of an integrated chip, described in a submitted publication and even in fiber waveguides. Furthermore, the output pulses from our devices are experimentally demonstrated to be non-linearly compressed by a factor of ten to approx. 20 fs. This makes our technology highly suitable for low-power pulse compression as well and can be used for timing distribution in optical networks.

We are at the TRL 5 technology level, with a functioning and demonstratable prototype. We have published in high-profile scientific magazines, participated in conferences (Laser and Photonics Reviews, Photonics, Optica Conferences) and our technology has been covered by popular science media outlets (e.g., Laser Focus World, AZO Optics, engineers online Netherlands, etc). With the grant, we would like to collaborate and offer a complete product to all major industries that would benefit.

Handheld MEMS-SOA Silicon Based Gas Analyzer for Real-time, Cumulative and Wide-Band Environmental Monitoring in Smart Cities

Assoc. Prof. Dr. Eng. Haitham Omran

OSA Early Career Professional

Laboratory of Micro Optics, Faculty of Information Engineering and Technology (IET), German University in Cairo, Egypt

Human activities are the main cause of Earth's environmental changes [1]. Effects like global warming caused by increasing carbon dioxide (CO_2) and methane (CH_4) emission from fossil fuel, human waste and agricultural activities have disastrous effect on humankind [1, 2]. Rising see levels and extreme weather triggered by environmental changes affects the existence of many communities and even nations across the globe [3, 4]. Limiting the global warming and pollution to the target levels requires continuous, wideband, cheap and accumulative monitoring solutions for CO_2, CH_4 and other climate forcing emissions [1-4].

This proposal aims at contributing to achieve the global warming 2°C target limit implying a cumulative carbon emissions limit of the order of 500 GtC [1]. The target to be achieved by continuous, cumulative and smart monitoring of climate forcing gas emissions (e.g. CO_2, CH_4) using a flexible use case handheld micro-electro-mechanical-system semiconductor-optical-amplifier (MEMS-SOA) Silicon based gas analyzer with cloud connectivity for Internet of things (IoT) smart cities. The analyzer core engine is an experimentally verified MEMS-SOA swept laser connected to a small gas cell [5-7]. The MEMS is constructed from two deeply-etched Si/Air Bragg mirrors attached to an electrostatic comb actuator allowing the tuning of the swept laser over 100 nm bandwidth with up to 0.2nm resolution depending on sweep speed [6, 7]. The absorption spectrum of gases in the near-infrared is used for quantitative and qualitative monitoring of the environment climate forcing emissions [5]. The device smart IoT and cloud connectivity allow real-time and accumulative monitoring which is crucial for correct environmental assessment and decision-making. The device will have a flexible use case by working in two gas sampling modes; an in-device near gas cell mode and long-fiber far gas cell mode for difficult to access locations (e.g. factories, mining cites and gas pipelines) enabled by a detachable gas cell head.

At the end of the project, the team will demonstrate a working prototype of a packaged handheld MEMS-SOA gas analyzer in the near-infrared spectrum. The package is to include all functional parts including the MEMS-SOA swept laser core module, control electronics, power supply, gas flow control and detachable gas cell head. We will demonstrate practical sensing of climate forcing gas emissions (e.g. CO_2, CH_4) in the range (1500 nm – 1600 nm) with up to 0.2nm resolution. The device will have IoT connectivity for smart cities environmental monitoring. We will develop a mobile app with cloud connectivity allowing device control, real-time monitoring and cumulative data logging for fast and accurate analysis and long-term decision-making based on cumulative sensing in IoT smart cities.

A Colorimetric Optical Nose for Hazardous Gases
In this proposal, we would like to **develop a colorimetric optical nose for hazardous gases in industrial manufacturing environments**. Target gases include five volatile organic compounds (methylene chloride, isopropyl alcohol, formaldehyde, chloroform, and toluene) and five toxic industrial chemicals (ammonia, chlorine, hydrogen chloride, hydrogen fluoride, and nitric acid) with different concentration ranges of permissible exposure limit (PEL) and immediately dangerous to life or health (IDLH). This system consists of colorimetric indicator arrays as sensing components and image sensor arrays as signal conditioning components vertically assembled as an artificial olfaction system.

- In **signal generation**, **more than ten gas-reactive porous nanostructures**, including nanofibers and nanoparticles, will be developed to generate optical fingerprint-like patterns against individual gases. This can enhance the detectable concentration less than IDLH and PEL for multiple gases.
- In **signal processing**, gas-induced optical changes, e.g., emission wavelength, dyes' color, and transmitted light, are quantified and amplified in photocurrent signals, establishing **the data library on gas-fingerprint patterns** in terms of types and safety levels of hazard. In addition, the evaluation index of optoelectrical behaviors can be determined for post-processing.
- In **pattern recognition**, an unknown gas X can be determined by a newly defined pattern recognition algorithm based on a relative gas coefficient $d_g = \sum_{n=1}^{N} |\log a_n / X_n|$.
- The colorimetric optical nose separates sensing and signal conditioning components, allowing quick, accurate identification of gases with thresholds and amplifying the quantified current changes for post-process and commercial viability on-site workplaces.

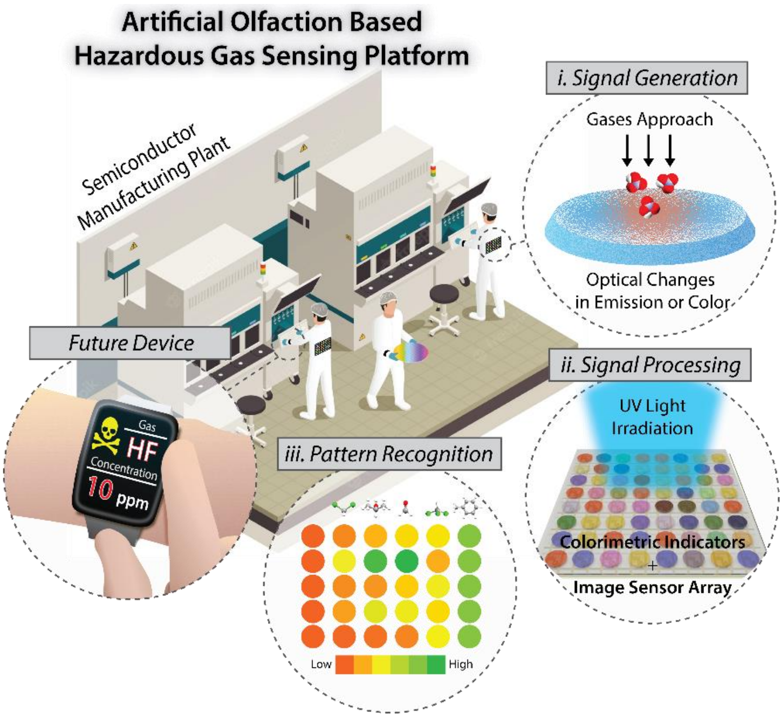


Figure 1. Schematic illustration of a colorimetric optical nose for hazardous gases.

Title: Multimodal Imaging of Genetic Drug Delivery in Airway Cell Populations.
Category: Health

Cystic fibrosis (CF) is a genetic disease caused by mutations of the cystic fibrosis transmembrane conductance regulator (CFTR) gene. CF patients experience dysregulated epithelial ion gating and severely impaired mucociliary clearance. The advent of highly effective CFTR modulator therapies has increased the expectancy of the CF patient population substantially. Nevertheless, there remain a portion of CF patients carrying mutations that are not treatable by the available CFTR modulators. Therefore, the field is moving towards alternative treatments based on genetic therapies that could benefit the entire CF patient population. Drug developers are seeking a mechanistic understanding of the drug's interaction with the microenvironment of CF airways and its subsequent impact on airway physiology.

This drug development process is fraught with numerous uncertainties, and there is an unmet need for optical imaging technologies to inform on the functional delivery (i.e., ability to both reach targeted cells and restore healthy physiological function) of investigational genetic therapeutics. Currently, the use of mRNA-based therapeutics to correct CFTR mutations is one of the most hotly pursued approaches, and they are tested on Cre reporter animal models. When CFTR mRNA enters the targeted cells of the reporter animal, Cre-mediated recombination occurs, and the cells express fluorescence proteins. Presently, the efficacy of genetic treatment is determined via fluorescence cell sorting and cell sequencing. Unfortunately, these methods provide little insight into the drug's effectiveness in restoring healthy airway physiology and how that evolves over different time points of the treatment. *The overall goal of this 2-year proposal is to overcome this drawback by developing a multimodal imaging platform based on micro-optical coherence tomography (μOCT), dynamic μOCT (DμOCT), and confocal fluorescence microscopy (CFM).* The rationale is to leverage μOCT, DμOCT, and CFM for co-localized *in situ* assessment of airway physiology via characterization of airway mucociliary transport system, identification of cell populations in the airway epithelium, and monitoring functional delivery of genetic therapeutics, respectively. This imaging platform will enable correlative studies that are particularly aimed at 1.) understanding which cell types the therapeutics have been delivered to, and 2.) if correction of the underlying CFTR defect is effective in modifying the course of CF disease, especially in the presence of epithelial damage.

While our lab has extensive experience in developing CFM and μOCT for investigating airway physiology, the development of DμOCT for robustly identifying airway cell types is in its relatively early stages. Year 1 will be spent focusing efforts on developing multiple aspects of the DμOCT technology for increasing accuracy in distinguishing airway cell types. We anticipate that the same hardware for performing DμOCT will be capable of performing μOCT imaging of the airway physiology. Subsequently, we will integrate CFM imaging capabilities to the DμOCT/μOCT system in year 2 and ramp up efforts to test investigational CF genetic therapeutics on Cre reporter cell models.

Although μOCT has subcellular optical resolutions that make it conducive for imaging airway functional microanatomy, it lacks cellular contrast due to minute differences in refractive indices between cells. To enhance contrast and, more importantly, to delineate cell types in the airway models in a label-free manner, we propose to advance a technology termed DμOCT, which itself is an extension of μOCT. Instead of using information from a single snapshot image, the current form of DμOCT utilizes temporal information extracted from μOCT videos of metabolically active cells to enhance the image contrast of cells. We will advance DμOCT by developing methods to extract temporal signatures in μOCT that are specific to major cell types in the airway epithelium, thus enabling us to distinguish cell types in the airway without having to stain tissues. This capability will be critical for identifying which cell types the drug compounds have been delivered to via co-localized detection of fluorescence signals in Cre reporter mouse models.

The range of information that can be acquired in our proposed multimodal imaging platform will enable researchers to gain mechanistic insights into why certain investigational therapeutics work or not. Those insights are critical for understanding how to further optimize the efficacy of an investigational drug. For example, our imaging platform allows investigators to determine functional delivery across mucus barrier, characterize drug uptake by various cell types, and enable monitoring of long-term treatment effects on epithelial remodeling and restoration of healthy airway physiology. The ability to answer these questions will potentially improve the relevance of pre-clinical studies and allow for a more realistic assessment of the drug's clinical impact on CF patients' health.

Executive Summary

Name of the proposal: Mechanistic insight of ultrasound neuromodulation unveiled by local optoacoustic stimulation and super-resolved voltage imaging

Category: Health

Ultrasound neuromodulation is a next-generation technique for neural stimulation, but its real-world application such as the treatment of neurological disorders has been challenging due to the fundamental technical limitations and controversies on the molecular mechanism. Specifically, there is a critical need for improving the spatial resolution of the ultrasound neuromodulation and precision measurement of the ultrasound effects at the sub-cellular level.

The objective of the proposed study is to develop a panel of novel technologies to overcome these challenges in both stimulation and imaging. The specific aims are:

Aim 1. Demonstrate neuromodulation and membrane potential imaging with single-cell resolution.

Aim 2. Examine the mechanism of neuromodulation at the single-cell level.

By completing the proposed aims, we expect to develop a high-precision neuromodulation and membrane potential imaging platform and establish a systematic mechanism of the spatiotemporal profiles of ultrasound neuromodulation. Technically, we will develop an optoacoustic-based ultrasound stimulation device with sub-micron spatial resolution, which is capable of stimulating neurons at the single-cell level without any genetic modification. We will also develop a molecular fingerprint-based imaging system, namely stimulated Raman scattering voltage imaging, which allows quantitative mapping of membrane voltage at sub-cellular levels. With these technical innovations, we expect such a multi-modality platform will allow us to tackle the fundamental challenge in the ultrasound neuromodulation technique by providing a comprehensive mechanism. The new insight will be the *foundation for designing the next-generation neuromodulation device* for disease-specific applications in the clinical setting.

EXECUTIVE SUMMARY

Design and fabrication of a fiber optic accelerometer based on surface plasmon resonance for environmental monitoring

Accelerometers have several uses in the science and engineering fields. Fiber-based accelerometers largely employ various schemes based on Fiber Bragg grating (FBG) with cantilever beam structure, diaphragm or spring-mass structures. The main purpose of environmental monitoring is to manage the environment and minimize adverse impacts on it. To achieve this, effective environmental monitoring tools are needed. Photonic crystal fibers (PCFs) are a new class of optical fibers that allow their structural parameters and geometries to be tuned to realize tailored designs and properties [1]. Sensors based on PCFs are light in weight, very small in size, and immune to electromagnetic interference. In recent decades, the surface plasmon resonance (SPR) sensing technique has attracted tremendous research attention due to its real-time monitoring capabilities and high sensitivity [2]. SPR in PCF is currently well developed to achieve highly sensitive and robust sensors with high resolutions [5], [6], [7] for measuring parameters such as refractive indexes [8], temperature [9], and pressure. The response of the SPR in PCF can be controlled and improved through the variation of the geometrical structure and selective filling of the fiber cladding with plasmonic nanostructures such as nanowires, nanorods [10], etc.

The sensitivity and resolution levels of current accelerometers are not enough for several environmental monitoring applications. However, SPR in PCF technology can be applied to achieve higher accelerometer performance. Therefore, the main objective of this research is to design and fabricate a highly sensitive plasmonic fiber accelerometer based on surface plasmon resonance for environmental monitoring. The design methodology to be adopted in this research is based on the finite element method (FEM), which is well implemented in the Comsol Multiphysics® software. The plasmonic accelerometer will be fabricated via the stack-and-draw technology. The coating or infiltration of plasmonic materials will be accomplished by the plasma-enhanced chemical vapor deposition (PECVD) process using facilities at the University of Cambridge, UK.

The proposed plasmonic fiber optic accelerometer based on surface plasmon resonance is expected to be highly sensitive, compact, and low-cost. It can be integrated into existing environmental monitoring systems for acquiring seismic data and predicting hurricanes, volcanic eruptions, wind, and so on. It is also expected that the new plasmonic accelerometer will improve the efficiency of a wide variety of smart devices and equipment, including electronics, automobiles, robots, prosthetics, and so on.

DNA-assembled quantum-dot spatial barcodes with imaging flow cytometry for hundreds of analytes in liquid biopsy

Research challenge

More than a quarter of people worldwide will ultimately be affected by cancer[1], and cancer treatments are often more successful when the disease is detected early[2]. The analysis of blood for circulating tumor cells (CTC) or cell-free nucleic acids called "liquid biopsy" has opened new avenues for cancer diagnostics, including early detection of tumors, improved risk assessment and staging, as well as early detection of relapse and monitoring of tumor evolution in the context of cancer therapies[3]. However, the common detection methods for liquid biopsy can only process a few analytes simultaneously at a low throughput, making it challenging to find the optimal panel of biomarkers according to different objectives (e.g., accurately identify different tumors) due to the low detection efficiency. <u>A massively parallel detection, high-throughput, and easy-to-operate liquid biopsy modality providing precise measurements of hundreds of specific circulating biomarkers will be a tremendously enabling tool for the researchers and doctors to comprehensively analyze the cancer development and further effectively discover the right panels for various objectives.</u> This is the research challenge we propose to undertake here.

Proposed project

This proposal is to combine DNA-assembled quantum-dot spatial barcodes and imaging flow cytometry for simultaneous detection of hundreds of analytes in liquid biopsy. The proposal has three aims.

1) To construct DNA-assembled quantum-dot spatial barcodes (QD barcodes). Quantum dot beads of different colors are connected in a line via DNA strands, which will offer a huge number of individual signatures (e.g., 5 colors ^ 5 spatial positions = 3125 signatures) that can be exclusively allocated to single circulating biomarkers.
2) To establish imaging flow cytometer platform for visualizing QD barcodes. The imaging flow cytometer is aiming to offer a throughput of 5000 biomarkers per second, five fluorescence channels, and a spatial resolution of 1µm. In theory, with the QD barcode of 4/5 colors and 5 positions, it can offer a parallel detection up to 1024/3125 analytes.
3) To decorate the QD barcode with proper adapters for different circulating biomarkers in blood, including ctDNAs, CTCs, proteins, RNAs. We will first utilize this platform for detecting DNA mutations of lung cancer. Also, magnetic microbeads can be connected to QD barcodes for magnetic purification and reporter probes should be developed to prevent false positive result.

Intended outcomes

Corresponding to the three aims, the outcomes include a fabrication method of QD spatial barcodes, a demo system of imaging flow cytometer for QD barcode detection, a high throughput and massive parallel detection platform for DNA, RNA, and proteins. We will publish at least one paper in Optica open-access journals and share progress and results in Optica-organized symposiums. If successful, the proposed platform will show, for the first time, hundreds of circulating biomarkers (potentially to be thousands) can be detected in a single assay at the throughput up to thousands of biomarkers per second, offering high - quality and high-content data of liquid biopsy for the researchers and doctors to detect and monitor multiple cancers at all stages. <u>This platform will not only be a reliable and efficient tool for cancer research and therapy, but also pave the way for the practical application of personalized medicine</u>.

---

[1] Siegel, R. L., Miller, K. D. & Jemal, A. Cancer statistics, 2015. CA: A Cancer Journal for Clinicians vol. 65 5–29 (2015).
[2] Lennon, A. M., ... & Papadopoulos, N. (2020). Feasibility of blood testing combined with PET-CT to screen for cancer and guide intervention. Science, 369(6499), eabb9601.
[3] Alix-Panabières, C., & Pantel, K. (2021). Liquid biopsy: from discovery to clinical application. Cancer discovery, 11(4), 858-873.

Name of the proposal: Fabrication of semiconductor nanoparticles activated photocatalytic optical fiber for sustainable wastewater purification process

Category: Environment

In the 21st century, the sustainable and cost-effective wastewater treatment is a global challenging issue as the water pollution is increasing day by day due to rapid industrialization, expansion of population and unplanned urbanization. The photocatalysis is considered as most sustainable, eco-friendly and cost-effective process to purify wastewater. Thousands of research articles have been reported on preparation and photocatalytic wastewater purification performance of the photocatalyst nanoparticles, but there is no report in literature on industrial applications of these photocatalysts for wastewater treatment. The main problem with existing photocatalytic wastewater treatment process is that the powder nanophotocatalysts must be separated from water at the ned of the purification process which is difficult and need special associated technique which will increase the cost of purification process. To address these challenging issues, I am proposing an innovative technique which will open new technological aspects for hassle-free sustainable wastewater purification in large scale. This technique can be implemented to built pilot reactor in company to clean wastewater in large scale or can be used directly to clean wastewater in nature like polluted ponds or lakes.

In the proposed project, special optical fibers called photocatalytic optical fibers will be fabricated using fiber drawing tower in COPL, Laval University. The various semiconductor nanoparticles like TiO_2, ZnO etc will be incorporated in the plastic or glass optical fibers to optimize the efficiency of the photocatalysis process and to reduce the cost of purification process. The bundle of optical fibers can be put on the polluted ponds or lakes to degrade pollutants in presence of sunlight through photocatalysis process. The strong laser or LED can be used to inject light into the fibers to purify wastewater remotely. The bundle of fibers will used to built pilot reactor coupled with UV or visible light source for industrial applications. This project will bring revolution in smart sustainable wastewater purification process.

Executive Summary

Title: A Novel Method for Scaling Manufacturing of Integrated Photonic Devices with Enhanced Connectivity

Category: Information

Objectives: Developing a novel method for enhancing the coupling between the optical fiber and the photonic chip by using a mode converter design. This design improves the performance by four folds. Secondly, developing a new device which can connect optical fibers to chips using laser fusion splicing technology in less than a minute.

Outcomes:

1. Industrial prototype of mode converter design chips: This industrial prototype will act as a proof of concept that we can manufacture a low-loss mode converter on foundry process lines without any difficulty. It will act as a stage for the creation of a process development kit that can be licensed by the company and will be used in optical transceiver chips. Due to the low loss advantage of the mode converter technology, this novel technology can then be used for quantum communications and sensing equipment.
2. Prototype of fiber to chip attach laser machine: The fiber attach laser machine will be the first-ever fiber attach machine which uses a laser to connect optical fibers to photonic integrated circuits. This one-of-a-kind machine will disrupt the current glue-based attach machines and will revolutionize the integrated photonics packaging industry. The prototype will be used at small research labs, and Universities initially as they can act as beta testers for the technology. We will then use the feedback from the customers to develop bigger machines that can be integrated into a process line or can be modified into an existing machine.

Applications:

The first part of the technology will help improve the device performance which is a key parameter for integrated photonic devices. The improved performance will help in reducing the link budget in an optical transceiver, thereby improving the overall yield of manufacturing. Application spaces like quantum computing, sensing, are very sensitive to low performance devices, using the mode converters can help them in achieving enhanced outputs and bits. In telecommunications, every dB of loss translates to the length over which the optical signal can travel before repeating it, making it an application field for the technology.

For the laser fusion technology, the entire data communication industry, telecommunication industry, LIDAR, quantum communications, and biological sensors all want to avoid the use of epoxies in the packaging and are driven by reducing the cost of manufacturing. The laser fusion machine can improve the manufacturing speed of packaging by 10X and will eliminate the use of epoxies.

The combination of the above mentioned technologies, helps in making integrated photonic devices future-ready and will help in keeping up with the increasing demand for data.

Kayn Forbes: Structured light photonics for next generation chiral nano-spectroscopy

Chirality refers to an object which cannot be superimposed on to its mirror image, such as our left and right hands. The importance of studying and determining material chirality cannot be overstated. For example, the left-handed form of methamphetamine is a potent central nervous system stimulant, whereas the right-handed is a nasal decongestant found in supermarkets.

Light may also be chiral. The most well-known example of optical chirality is light with circular polarisation. Like the chiral discrimination present when you attempt to place a right-handed glove on your left hand, chiroptical spectroscopy exploits the differential interaction of chiral light with right- and left-handed types of materials. These techniques are critical to health as they provide a wealth of information about chiral materials, including the absolute configurations of chiral molecules, conformations and functionalities of biomolecules such as insulin, and molecular structure of viruses.

Until very recently, interrogating material chirality involved exclusively using circularly polarised plane waves. However, light can be chiral in more ways than its local state of polarisation. Structured light refers to optical fields which have inhomogeneous phase, polarisation, and amplitude. One very important type of structured light is the optical vortex. These beams travel in the shape of a tornado which may either twist to the left or the right. This chiral wavefront is characterised by the topological charge $\ell = \pm 1, \pm 2, ... \pm \infty$ where the sign dictates the handedness; in contrast circular polarisation is described by the helicity $\sigma = \pm 1$.

In the last five years significant breakthroughs in the field of structured light chirality have occurred and research efforts have rocketed. In particular, the pivotal role of nano-optics and plasmonic confinement has been realised: when structured laser beams and electromagnetic fields are confined into nanoscale volumes, extremely novel interactions occur. This is because chirality is a scale-dependent phenomena. We cannot place our right-handed glove on our left hand due to the chirality of both objects, however we may place both gloves of a giant on either of our hands: our hands and the giant's gloves are chiral, but the size mismatch is so large they don't interact in a discriminatory fashion. Just like the giant's gloves, unless the light is shrunk down into tiny volumes of space, their chiral structures do not interact with small chiral materials in a discriminatory fashion.

The Key Objectives of this project are to:

1) Develop the computational code to carry out the required numerical simulations to describe cutting-edge experiments in chiral nano-spectroscopies with structured light.
2) Determination of optimal chiral light structures for specific methods in chiroptical spectroscopy of biomolecules and nanostructures.
3) First experimental observation of nonlinear Rayleigh optical activity of optical vortices.

The immediate impact of this work will be the development of new ways to study chiral materials using novel types of light. These materials will range from nanostructures and metamaterials, to molecular matter including drugs and biomolecules which are key to pharmaceutical and medicinal advances. The techniques developed will also be applicable in the wider field of chiral photonics. Chiral light is central to many photonic technologies, including optical communication, computing, and information processing based on miniature integrated devices which possess the ability to sense and discriminate the chirality of the light. This work paves the way for the next generation of chiral photonic media based on structured light illumination.

EXECUTIVE SUMMARY

Alzheimer's Disease (AD) is the most common form of dementia that results in cognitive deficit including loss of planning, personality, and memory. In the United States, AD is ranked as the third leading cause of death, and approximately 5 million Americans above 65 years of age suffer from dementia caused by AD. AD is generally attributed to the maladaptive accumulation of amyloid-β protein (Aβ) extracellular plaques and intracellular neurofibrillary Tau tangles. These protein aggregates are thought to be the leading cause of neuronal cell loss and brain atrophy. An avenue of research that has attracted attention of many scientists is the role of Mitochondria in AD pathogenesis and progression. Mitochondria are pivotal metabolic and energetic machinery of cellular function crucial for energy homeostasis. Notably, **mitochondria dysfunction-mediated metabolic deficiencies are an early marker of pathogenesis of AD, however, the role of mitochondria in the disease progression is yet to be elucidated**, in particular regarding the rapid cascade of neuronal apoptosis. There is significant evidence that increased levels of Aβ proteins interact with mitochondrial proteins, and cause disruption in fission and fusion processes, boost reactive oxygen species production, and deteriorate mitochondrial function. **Optical quantitative assessment of mitochondrial function and health can be done through several image-based bioenergetic parameters,** including their size, shape and their dynamic activities such as, membrane potential activity; all of which can be estimated using fluorescence imaging.

A challenge in studying AD is the limitation of current optical microscopy technologies to image at organelle-level resolution deep inside of *in vivo* brain, which has led many scientists to be reliant on *in vitro* studies. Multiphoton microscopy modalities leverage the long mean-free-path (MFP) of near-infrared light to penetrate deeper into biological tissue. However, the long wavelength of the excitation light negatively affects the resolution and makes imaging of sub-cellular features non-trivial, if not impossible. In this proposal, **we aim to address this problem by developing a novel 3-photon superresolution microscope that utilizes fluorescence excitation modulation and Adaptive Optics to achieve superresolution imaging at a depth of more than 0.5mm in the mouse brain.** This will allow to cover cortical layers III up to IV/V. The new microscope enables quantitative assessment of mitochondrial function and health through several bioenergetic parameters, including their size, shape and their dynamic activities such as, membrane potential activity *in vivo,* which facilitates studying their role in AD pathogenesis, and allows future exploration of potential therapies and drug discovery. In this proposal, we aim to address these problems by producing a novel microscope that is capable of deep tissue superresolution across multiple regions of the brain.

Imaging deeper requires longer wavelength light. However, longer wavelength increases the width of the point spread function (PSF), hence deteriorating the resolution. To improve the resolution, we aim to develop a novel microscope that takes advantage of an established technology called Coherent Control (CC), which enables modulation of fluorescence by phase modulation of broadband ultrafast beams. Ultimately based on stimulated emission depletion (STED) microscopy, we will develop a two-beam CC modulation of a Gaussian Excitation and a Vortex modulation beam, to decipher information from a restricted area close to the center of the focus. The two beams have different dispersion regimes and modulation frequencies which produce spatiotemporally varying wave-packets. Therefore, by solving for the frequency components assigned to the center of the PSF, imaging beyond the diffraction-limit becomes possible. This technique - called Modulated EXcitation IMaging (MEXIM) requires the ideal shape of the two PSFs deep inside of the tissue. Even with near-infrared light, beyond the MFP distortions can significantly distort the PSFs. This issue can be resolved by employing Adaptive Optics technology to restore the diffraction-limited imaging at high depth and enhance the fidelity of the beams. The MEXIM microscope is expected to achieve resolution of <150nm at a depth of >0.5mm inside of the *in-vivo* brain, at an imaging rate of 1 Hz. Since mitochondria have a size range of 200-500nm, this resolution would be ideal for imaging and analysis of their morphology.

This novel microscope provides an excellent tool which enables future therapeutic research and drug discovery.

Immune Cell Tracking with Adaptive Illumination

Highly motile immune cells actively migrate in various organs and tissues in normal and disease states to initiate efficient immune response. Understanding how the immune cells migrate in various organs under various conditions is important for finding disease treatments. The major technology used for immune cell tracking in intact, living tissue is multiphoton fluorescence microscopy. As a nonlinear process, however, multiphoton excitation generates an inherently weaker signal than one-photon excitation, and high excitation power is typically required for fast tracking deep within intact tissues. Because multiphoton microscopes typically operate at the photon shot-noise limit, the maximum number of cells that can be tracked at high spatial and temporal resolution is fundamentally limited by the number of signal photons, which in turn is determined by the maximum permissible average and peak power in biological specimens. Therefore, the fundamental limit for technologies aimed at measuring real-time immune cell migration in intact tissues is the photon budget: the number of signal photons obtainable from the sample within a given period of time. Simply scanning fast, while necessary, is not sufficient for high speed and large volume imaging. This proposal will create new imaging technologies to address this fundamental challenge in dynamic immune cell imaging.

To address the fundamental limit of the photon budget, we will develop adaptive cell tracking (ACT) that will illuminate only the ROIs. A one to two orders of magnitude gain in photon budget can be achieved by ACT because the ROIs usually only occupy a small fraction of the imaging volume (1-10%). This gain in photon budget can directly translate to an increase in imaging volume or imaging speed (or a combination of the two), without increasing the excitation power on the sample or sacrificing signal-to-noise ratio (SNR). (1) To demonstrate the concept of ACT, we will image T cell migration in a live mouse by using 3D ROI localization algorithms and direct modulation of the laser output to illuminate only the ROIs. This demonstration will show how much photon budget can be saved with ACT when compared to that without ACT. However, the direct modulation of the laser output wastes a large fraction of the laser output power and is impossible to achieve the optimum performance when imaging deep. (2) Next, we will combine the ACT with the adaptive excitation source (AES) that reduces the required output power of the excitation source and ensures every photon emitted from the laser is directed towards the ROIs. To do this, we will significantly reduce the time required for the gain equalization in the AES by obtaining a good initial guess of the input pulse train with a machine-learning approach. (3) In addition, we will develop photon efficient scanning and localization algorithms to further reduce the excitation and emission photons required for cell tracking.

Through the development of imaging methods, lasers, photon efficient scanning and object localization algorithms, this work will increase the fluorescence signal by one to two orders of magnitude without increasing the excitation power in the specimen or the laser output power. While we will focus on immune cells, the technologies developed in this program are applicable for tracking any cells or molecules deep within intact tissues. The gain in photon budget will proportionally increase the tracking speed or volume (or a combination of speed, depth and volume), and ultimately enable dynamic, real-time tracking at the cellular and sub-cellular levels deep within intact tissues or organs that are completely beyond the reach of any existing techniques.

Summary: Optical techniques are valuable for diagnosing and treating disease because optical spectroscopic interactions with molecules confer specificity with regard to target biochemical information and quite favorable spatial resolution. Yet, tissues strongly scatter light, making tissue opaque within tens to hundreds of μms of propagation depth, moderating the success of optical biomedical imaging.

Some cancers are very difficult to detect with current technologies. As early detection leads to much better outcomes and lower mortality rates, new diagnostics technologies could profoundly impact our ability to detect and successfully treat disease. I am motivated by ovarian cancer, which is extremely difficult to detect and is usually detected at a late stage where treatments suffer from low efficacy.

I am focusing second harmonic generation (SHG) microscopy which is already established as a powerful tool for biological imaging. SHG has proven diagnostic and prognostic capabilities for a wide range of diseases. Of prominence is the use of SHG imaging to grade cancerous tumors by quantifying the type of organization of collagen around tumors. Moreover, cancers tend to reorganize collagen to present a spiral structure that aids in differentiating healthy tissues, benign tumors, and cancers. Despite this potential, SHG imaging is limited in imaging depth. As a result, non-invasive biological imaging (e.g., optical pathology without the need for surgery) is restricted to superficial tissues or through endoscopy and current SHG microscopy technology is extremely limited in its potential for use with *in-vivo* optical biopsies.

I propose a new approach to rendering opaque tissue effectively transparent using both advanced data science tools and wavefront control to sidestep the current limitations that restrict the SHG imaging depth. This is a radical departure from the conventional paradigm for nonlinear microscopy that relies on scanning a ballistic focus in the specimen and forming an image from the measured power from each focal point. Depth imaging is severely limited because the ballistic light intensity decays exponentially with depth.

This proposal seeks to remedy the deficiency in the limited imaging depth by posing the question: rather than throwing away multiply scattered (MS) light, can we redirect it into image formation? I will explore two methods of harnessing MS light for SHG imaging (e.g., collagen in the extracellular matrix around tumors) at unprecedented imaging depths in tissues. In Aim 1, I will unscramble the SHG light exiting the tissue to remap that information into an image deep within tissue. SHG fields exiting the tissue will be recorded with nonlinear holography. Since the SHG field propagates through tissue, the field is spatially randomized (exits as speckle). The speckle field is a distinct fingerprint of each SHG scattering source point. With a set of measurements that vary the SHG signal brightness spatially, the mapping between the SHG source points and the measured speckle will be uncovered. Armed with the random SHG speckle fingerprint for each point in the object field, the SHG image will be revealed by unscrambling the SHG light that was randomized with propagation through the tissue. Thus, I will break free from relying on image formation by scanning a ballistic focus. In Aim 2, the data will be used to estimate the transmission matrix for the fundamental field. This matrix operator describes the distortion of the input fundamental field at the image plane. This information will be used to focus the wave in the object plane through wavefront shaping to further improve the SHG image quality and enable deeper imaging depths.

This new approach to *in-situ* fundamental transmission matrix estimation opens new avenues of imaging by avoiding the need for a detector in the tissue (not possible) or relying on the accidental existence of a nonlinear guide star. Moreover, the wavefront reshaping increases the SHG signal power, and thus the image quality, and allows for increasing imaging depth. This could change the landscape for deep tissue imaging. Simulations will be employed to study the limits of imaging depth. Data from these experiments will be combined with simulation results to seek additional funding for pushing this new imaging approach to unprecedented imaging depths.

Project outcomes: A) Demonstrate unscrambling of measured SHG speckle fields to obtain an SHG image field deep in tissue. B) Demonstrate estimation of the transmission matrix of the fundamental field to the SHG image plane and use that transmission matrix to generate a brighter focus and a higher quality SHG image. C) Enable deeper imaging by pushing the depth where bright SHG imaging can be accomplished. D) Capture a set of data that will be used for papers, talks, and as preliminary data for future funding.

LOGIC: **L**ogic **O**ptical **G**ates for **I**ntegrated **C**omputing

Category: Information

This project aims to provide a stepping stone toward digital optical computing by developing integrated digital optical components such as logic gates, adders, and counters.

Applications to real-world issues Electronic data processing is ubiquitous and has a problem. The increasing difficulties in shrinking the fabrication process and increasing the clock speed led the industry to rely on parallelization with the drawback of increasing power consumption. The dream I am pursuing with my company Akhetonics is to realize the first photonic digital processor. A more grounded goal is to target the bottlenecks of electronic computing, that are easy to replace optically.

Data centers provide two basic functions that are perfect candidates. Packet routing and packet filtering. These can be performed by tens, maybe a few hundred, of logic gates and would benefit from the superior speed and latency of photonic processing at a reduced power footprint.

The emerging analog optical computing and quantum computing would benefit too. Both of these fields require some processing of the optical information before and after the core computing, and an interface with the system where they will be embedded. Let's say that they need a "janitor", and a digital photonic processor plays a crucial support role for these technologies.

Capabilities My company Akhetonics GmbH has an internal lab with an optical and electrical probing station equipped with all the required tools and instruments to characterize photonic integrated circuits (PIC). We follow a fabless approach, with a strong network of partners for fabrication. We are collaborating with the Max Planck Institute for the Science of Light, which provides a clean room with very flexible and rapid prototyping but low volumes. We have a contract with IHP that is capable of medium volume Si_3N_4 fabrication and graphene deposition. We already scheduled a run with them. For mass production, we are in contact with Ligentec and Paragraf.

I have experience in Si_3N_4 fabrication in the MPL clean room where I worked for the last two years. Also, I worked in nonlinear optics since 2013. In recent years my work focused on the realization of all-optical switches, memories, and logic gates in microresonators. However, those devices were only proof-of-principle. Here is where my co-founder, Michael Kissner, comes into play. He has a background in chip security, chip hacking, and architecture design as a researcher for the German military. Michael is an invaluable source of knowledge on device integration and interfaces. He designed an architecture for optics instead of adapting one for electronics.

Intended outcomes The most immediate outcome of this project will be patent publishing on the researched technologies, which will be immediately followed by publication in peer-reviewed journals and presentation at international conferences, such as CLEO, ECOC, and graphene week.

This dissemination will promote the research of 2D materials for optics. Currently, most of the research is in electronics despite the intriguing optical properties of graphene and friends.

As a company, we will release the first products such as PIC logic gates, adders, and counters that will function all optically at unprecedented speed. Finally, the technology will be available and easy to integrate for researchers and industry for real, not only as a proof-of-principle.

As a result of the above, I expect to establish myself and my company as one of the reference points in digital optical computing. Also, the success of this project would allow us to attract more funding, public and private, to continue on the road to optical digital processors.

Dielectric nonlinear metAmaterials for generation of Radiation at THz frequencies DART

Executive summary

The THz spectral band, between the far-infrared and microwave bands, has been for many years unexplored due to technological challenges. New applications in several areas such as medicine, astronomy, material science, communications, and security have galvanized interest in THz systems. The high bandwidth availability makes the use of THz signals with ad-hoc orbital angular momentum (OAM) a promising approach to accommodate the demand for ever-increasing wireless capacity with ultra-secure links. However, the lack of efficient, compact, and controllable THz sources has held back progress in this sector.

I propose to lead a potential breakthrough in this field by developing a new family of THz-photonics transceivers with unmatched functionalities based on a disruptive platform founded on novel artificial nonlinear optical materials. The approach is based on difference frequency generation (DFG) in dielectric metasurfaces (DM) – large-area two-dimensional metamaterials – for optical-to-THz conversion with an efficiency that is comparable to the best nonlinear materials in nature. This will mark a paradigm shift reducing the device dimensions by a factor of 1000 and enabling the generation of light in the THz-gap where existing sources cannot provide an exploitable signal.

We will design novel dielectric metasurfaces that efficiently emit THz beams with a generation efficiency that is enhanced by more than three orders of magnitude compared to the state-of-the-art and build the foundations for the development of ultracompact THz-photonics transceivers for seamless data conversion with unmatched functionalities compared to existing technologies.

The research approach is based, first, on the development of analytical and numerical models of NIR-to-THz DFG in isolated dielectric nanoresonators. Since the dimensions of the nanoresonators (1 micrometer) are comparable to the NIR signals (1.55 micrometer) but much smaller than the wavelength of the THz radiation (30-300 micrometers) this multi-physical modeling is challenging. I will consider AlGaAs and $LiNbO_3$ as constituent materials due to their high nonlinear response in the THz band. The crystal orientation and modal engineering (e.g. bound states in the continuum) will be used to enhance conversion efficiency and control the emission properties. These models will be validated in DFG experiments. Once the modeling is established, I will move to metasurface and arrayed structures. Exploiting the huge dimensional difference between NIR and THz physics, I will study nanoparticle arrangements that are individually optically resonant in the NIR and collectively form a cavity (e.g. dipole antenna) in the THz band.

I expect that the outcome of this research will be the development of a unique THz generation technology that will lead to the, long sought, leap in the THz gap and will seed new THz short-range wireless communications standards for Tbps wireless interconnects in data centers, broadcasting of HDTV channels for real-time conversations, kiosk downloading, wireless cognition, and intersystem (card-to-card, device-to-device) communication. The results will also benefit other applications requiring on-demand coherent THz light as sensing, imaging, and holography.

Integrated optical phased array-enabled ultrafast multiphoton lightsheet lensless microscopy + AI-based compressed sensing (Opa-fast-sheet)

Application for the Optica Foundation 20th Anniversary Challenge: Health category

Executive summary

Optical imaging is an important tool for biologists and doctors to understand fundamental biology and diagnose diseases. One emerging approach to this end is multiphoton lightsheet fluorescence microscopy (LSFM), which can capture images with subcellular resolution in real-time in a minimally invasive manner and generate images comparable to histopathology circumventing the need for tissue excision, enabling optical biopsy. Recently, lensless microscopy has been proposed to adapt LSFM to an optical fiber platform as an important step towards clinical translation. Lensless microscopy employs wavefront shaping to replace lenses at the distal end of the fiber leading to improved miniaturization. In order to correctly shape and steer the beam at the distal end of the fiber, the wavefront shaping must compensate for the so-called transmission matrix, which describes how the wavefront changes as it propagates through the fiber. The transmission matrix is highly variable as the fiber conformation changes, so the transmission through the fiber must be actively monitored and compensated for imaging in real world applications. Ultimately, wavefront shaping for lensless and lightsheet microscopy is inherently limited by the slow refresh rate of SLMs and camera-based wavefront sensors.

The Opa-fast-sheet project aims to revolutionize multiphoton lightsheet lensless microscopy with radically improved speed and wavefront correction by using an integrated silicon nitride optical phase array. We propose a new approach of beam shaping for lensless imaging and LSFM based on a novel integrated silicon-nitride optical phased array. Replacing current wavefront shaping techniques with an optical phased array has the potential to improve the imaging speed of light sheet microscopy by more than two orders of magnitude. In combination with compressive sensing-based wavefront monitoring, all speed bottlenecks for multiphoton lightsheet lensless microscopy will be removed. Once the Opa-fast-sheet hypothesis is confirmed, the final implementation of the technology will enable a new suite of biological studies and diagnostic methods based on minimally invasive fast volumetric image acquisitions.

NANOEYE | A novel non-destructive quantitative multimodal plasmonic nanoscopy approach to stop Myopia progression

Myopia is growing around the world. On average, 30% of the world is currently myopic and by 2050, it will be 50%, 5 billion people. Almost 1 billion of high myopes predicted by 2050 makes Myopia the leading cause of permanent blindness worldwide with significant implications for planning comprehensive eye care services globally, and vision loss among people with high myopia. But also with great global economic consequences, where the global cost of myopia from lost productivity due to vision impairment from uncorrected myopia and myopic macular degeneration was estimated to be USD 244 billion in 2015, and significant impact on learning and education. However, refractive correction remains the only option, and the causes of the increasing risk, and furthermore even the underlying structural and physiological mechanisms of Myopia are not fully understood, which is frustrating the efforts of developing treatments and lowering the Myopia-induced risks in potentially sight-threatening eye diseases.

Myopia research is a very active area due to the lack of consensus on its etiology and moderate success of interventions to stop its progression: the topic has raised interest in the scientific, clinical and industrial communities for many years. Since 1980, >10k papers address Myopia etiology/treatment. However, a general weakness is technology-oriented groups have not tackled Myopia as a research question, therefore there is a lack of state-of-the art 3D biometry tools, high resolution imaging techniques and visual simulators, which would allow a more accurate assessment and understanding.

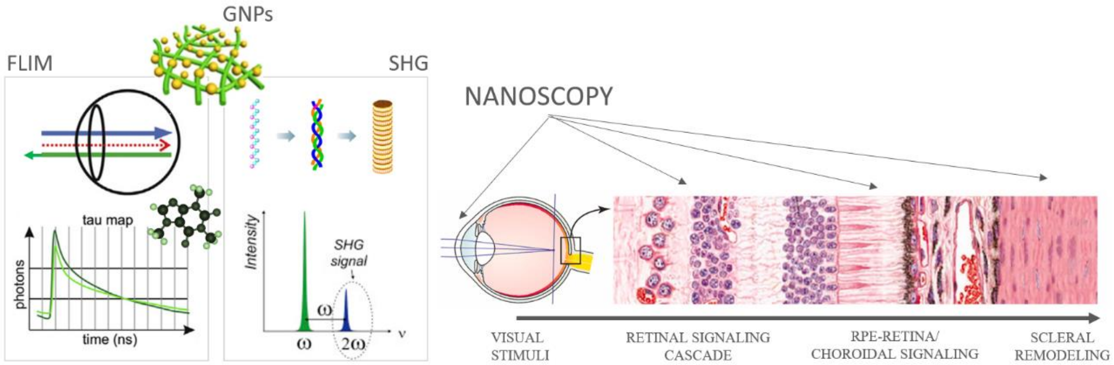


Figure. Overview of the scope of the novel non-destructive quantitative multimodal plasmonic nanoscopy approach to investigate the multilayered signaling cascade disruptions leading to Myopia development.

The goal of this project is to advance our understanding of Myopia, and help to develop new treatments. As an important step, I propose to develop new innovative optical techniques to characterize myopic eyes in unprecedented details to gain novel insights, and to enhance treatment effects. The experimental approach is highly interdisciplinary as it brings together fundamental nanophotonics and clinical human eye research, to develop new imaging technologies in ophthalmology, following a multidisciplinary approach (3 researchers and 2 institutions), involving optics, physics, bioengineering, visual sciences, ocular biology and clinical ophhalmology. The development of a SHG-FLIM microscope in combination with plasmonic methods (multimodal plasmonic nanoscopy) will have a significant impact in the way we study molecular/structural changes in ocular tissues, and consequently Myopia development, are studied. Also, gold nanoparticles are the first FDA-approved nanomaterials so our techniques could be readily translated from bench to bedside to impact clinical eye study. The expected results from the project have great innovation potential. Moreover, the development of safe *in vivo* imaging and crosslinking techniques for procedures *in vivo* will significantly impact the clinical treatment of Myopia, therefore helping 30% of the world's current population. Using light to see light.

Research on emerging solutions for Myopia prevention will help to assess their potential and propose improved interventions, potentially reaching millions. In particular,

1. A novel innovative imaging method, quantitative multimodal plasmonic nanoscopy, combining a 2P-SHG-FLIM microscope and nanophotonics methods for ocular applications.
2. Greater understanding of the molecular/structural changes during emmetropization leading to Myopia development, using novel strategies for multimodal microscopy ex vivo to quantify collagen crosslinks and endogenous fluorophores distortions in ocular tissues of special interest for emmetropization.
3. Strategies for multimodal plasmonic nanoscopy *in vivo* in human eyes
4. Nanoscopy enhanced treatments in corneal and scleral crosslinking therapeutical approaches.

Executive Summary, "Integrated Photonic Polarimeter Circuit for portable Fiber-optic Stress Sensor"

Optica Foundation 20th Anniversary Challenge

Principal Investigator: Mark C. Harrison, Ph.D.

Studies have shown that the stiffness of biological tissue can be correlated with the onset of various diseases, including cancer. In fact, the stiffness of cancerous tissue has been linked to the likelihood of metastasis. Although pathologists tend to be self-consistent in grading the likelihood of metastasis in biopsied tissue, there is still variation between individuals and the entire process is error-prone. Therefore, monitoring the stiffness of tissues in organs such as the heart and lungs can help evaluate the severity of cancer and can aid in the early detection of other diseases as well. However, methods for characterizing the mechanical behavior of living tissue samples often suffer from poor spatial resolution, are destructive to the sample being tested, or are too large to be practical in most settings. This makes tissue stiffness monitoring a method of untapped diagnostic potential. Recently, we developed a polarimetric optical fiber stress sensor based on the photo-elastic effect which addresses these issues. A portable and easy-to-use technology like the fiber stress sensor could have large benefits in a variety of settings, including in developing nations where resources for medical diagnostic equipment may be more limited. Although the sensor has demonstrated high sensitivity and resolution, it comprises several large and complex pieces of optical equipment which reduce the device portability and make it difficult to use in settings where it would be most useful.

In the past few decades, large strides have been made in the world of silicon photonics, and there are now several commercial foundries that will manufacture reliable photonic integrated circuit (PIC) designs for hire. These foundries often require use of a process design kit (PDK) which standardizes commonly-used photonic components. By standardizing processes, these foundries serve as a key link between small-scale research and large-scale commercial fabrication of integrated photonic devices. Recently, several groups have demonstrated integrated polarimetry. A polarimeter is one of the largest and most complex components of the fiber stress sensor, and is a prime candidate for miniaturization into a PIC. By leveraging the PDKs and reliability of foundries, we can design a polarimeter PIC that meets the precise needs of the stress sensor. Doing so will also make the fiber stress sensor much easier to operate.

The research funded by this grant will focus on developing integrated photonic circuits that can replace the large, expensive benchtop polarimeter used in the fiber stress sensor. Replacing it with a PIC will also allow us to make other improvements to the fiber stress sensor to reduce its overall size and the complexity of its operation. Once these improvements have been made, we will enhance the performance of the sensor by developing the capability to take parallel measurements on a single sample simultaneously. These system improvements will result in a device that is truly portable and can be used to characterize a variety of tissue samples in a variety of locations. The resulting enhanced device will be a flexible, quantitative diagnostic tool useful in a variety of healthcare settings worldwide.

With the age of zetta-scale computing rapidly approaching, humanity's thirst for high-speed digital communication shows no sign of slowing. Increased bandwidth is needed on all scales, whether to cope with exponential growth in internet traffic flowing through data centers, to increase global equity by providing broadband internet access to remote or under-developed regions or provide higher cloud connectivity to ever smaller consumer electronic devices. Free-space optical telecommunication offers a unique opportunity to address these challenges, as highlighted by forecasts suggesting that this market will be worth $2 billion by 2027. Not only is the density of free-space information channels much greater than in optical fibers, but the topology of a free-space optical information network need not be fixed. A network that can adapt to changing patterns of data traffic can reduce congestion without needing to boost the capacity of any single channel. In data centers, for example, where resources utilized at any moment can drop as low as 15%, power consumption could be drastically reduced simply by spreading out that load. Even when data traffic patterns are stable, reconfiguration is vital in environments with fast moving agents, such as fleets of autonomous vehicles or surveillance drones and crowds of people sporting wearable devices. Of course, as bandwidth is always tied to the transmitted signal to noise ratio, the benefit of any reconfiguration strategy is constrained by the cost incurred in term of power consumption***. Targeting the Optica 20th Anniversary Challenge in <u>information</u>, here, we propose to solve a key bottle neck towards realizing dynamic free-space optical systems by building extremely energy-efficient infrared wave shaping technology that can update on microsecond timescales and with spatial resolution approaching the diffraction limit***.

Two established solutions exist for reconfiguring free-space optical networks: liquid crystal spatial light modulators and micro-electro-mechanical mirror arrays. While both have been deployed in specialized applications, material constraints limit their widespread use. Liquid crystal only allows switching on millisecond timescales and micromechanical devices require large drive voltages which hinders efficient tuning. Emerging platforms based on carrier injection or phase change materials look promising for producing high speed modulation with modest electrical biases. However, to be suitable for communication, the vanishingly weak signal strengths, often <1% of the input, must be drastically improved.

This proposal will focus on the design, fabrication, and testing of nanoscale silicon antennas that by virtue of being highly resonant exhibit a strong response to very small changes to their refractive indices. Based on high quality factor-dipolar-guided-mode-resonances (DGMRs) - the nanoantennas will not only be highly responsive but will also couple efficiently to free-space with point dipole radiation patterns, leading to very low insertion loss. To capitalize on the extreme sensitivity, the subtle temperature dependance of silicon's refractive index will be used to dynamically and precisely tune the resonant frequencies and therefore scattered phases of each element. Temperature control will be delivered by nanoscale resistive heating elements which can be very efficient due to their small size. By developing nanofabrication procedures that optimize both the optical and electrical properties of the nanoantennas, we seek to demonstrate dynamic light wave shaping with speeds at the limit of thermal tuning, ~100kHz, and with low power operation <1mW/pixel. Importantly, sub-λ pixel pitch will unlock an unprecedented number of modes.

While ~100kHz wave shaping will open many exciting doors for free-space optical communication, the proposed project is the first step towards operation at much higher speeds. The key enabling concept is subwavelength pixels that are nevertheless highly sensitive. Mechanisms such as carrier injection in 2D materials and the Pockels effect produce index modulation 1-2 orders of magnitude smaller than for thermo-optic tuning in silicon. With further refinements to our nanofabrication procedure which will unlock even higher Q factors, steering rates at 10s to 100s of GHz should be possible. Such performance would allow for network reconfiguration at the scale of a single data packet.

Title: Airborne Gas Detection Metalens (AGDM) Camera
Category: Environment (Improving or creating tools to measure, monitor and mitigate climate change.)

Introduction

Global warming is one of the central challenges that humanity is facing, and it is signified by the increase in the average temperature on Earth. It leads to heat waves, hurricanes, droughts, raised sea levels, and altering ecosystems. The primary reason for these effects is connected to human activities, which include deforestation and burning fossil fuels that release greenhouse gases. Carbon dioxide accounts for 79% of all greenhouse gasses emitted due to human activity in the USA in 2020 (following worldwide trends). Therefore, its monitoring is essential for predicting Earth's average temperature growth rate.

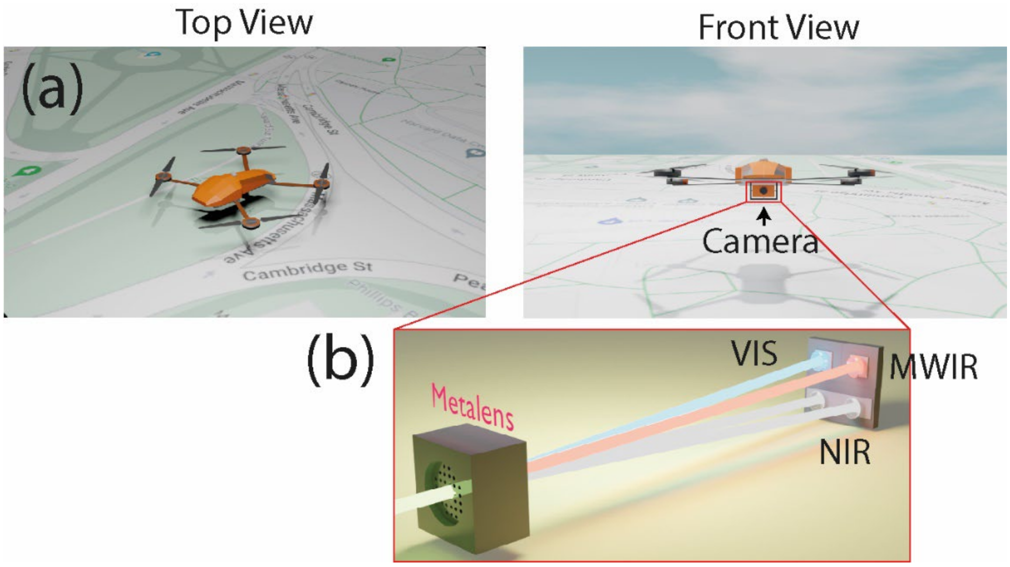


Figure 1. (*a) Concept art of a drone equipped with a gas detection metalens camera monitoring the area. (b) Schematic of a gas detection metalens camera.*

Objective

Artificial satellites provide an excellent platform for remote CO_2 monitoring, but this technology is very expensive and provides limited abilities to modify the mission objectives after the launch. In addition, a substantial volume and mass of the satellite are required to accommodate optical components of the monitoring instrument that further increase the mission's price. This project aims to minimize and simplify CO_2 detection optical instruments. Microsatellites, weather balloons, or drones could be used to deploy proposed gas detection optical instruments, expanding accessibility of the CO_2 monitoring projects to the broad scientific community. Moreover, drones can monitor CO_2 at any time of the day, unlike satellite-based optical instruments, leading to the generation of new scientific data.

Outcome

The proposed gas detection metalens camera will operate similarly to optical CO_2 monitoring instruments currently used in space. The operation principle comprises image acquisition at three different wavelengths, including 0.75 μm (O_2 band), 1.61 μm (week CO_2 band), and 2.01 μm (strong CO_2 band). Additionally, images at 4.8 μm (MWIR CO_2 absorption band) will be acquired (see Fig. 1(b)). Adding this wavelength will allow for the detection of point sources of CO_2 emission, like, biomass burning events, lava flow events, or industrial emissions. Furthermore, a proposed expansion of functionality will not require any extra optical elements.

The form factor of the CO_2 detection instrument will be minimized by employing metalens technology. Single metalens will replace multiple optical components of a traditional detection camera. Recently developed unique holey metalens technology will be used to achieve guiding of light at a visible (VIS), near-infrared (NIR), and mid-infrared (MWIR) parts of the spectrum covering three octaves.

To demonstrate the performance of the proposed camera, it will be mounted on the drone, and CO_2 detection will be performed over the streets of Cambridge in Massachusetts, USA.

The Optica Foundation 20th Anniversary Challenge Proposal (Category: "Information")
Efficient and broadband THz spin wave photodetectors (TeraSpin)
Executive Summary

Terahertz (THz) bands contain rich physics (nonlinear optics, phonon modes, fingerprints of chemical bonds) and offers many opportunities for applications such as sensing, imaging, and 6G telecommunication. Many phonon modes lie in THz, thus, highly molecule-specific signatures in the THz bands may be detected for many organic molecules. Consequently, THz time-domain spectroscopy (THz-TDS) arose as one of the most promising THz probing techniques for analytical chemistry and nondestructive testing.

Previous studies investigated GaAs/AlGaAs quantum wells with low doping and subband transitions for detecting excitations with energies below 20 meV (J. Phys. D: Appl. Phys. 55 (2022) 193001), double or single-walled carbon nanotubes (Optics Express 23, 13349 (2015)), graphene (Nat. Mater. 11, 865–871 (2012)), reduced graphene oxide-silicon nanowire array heterojunctions (Small 10, 2345–2351 (2014)) and antenna-coupled transistors (Optics Express 22, 19252 (2014)). Multiple THz detection mechanisms have been explored with these materials, including (photo)thermoelectricity of nanotubes, subband transitions within quantum wells, photoconductivity, and photovoltaic effects. While quantum confinement and doping allowed energy level tuning for higher sensitivity to THz frequencies, the signal-to-noise ratio (SNR) of the device needs to be improved by limiting the thermally excited electrons.

Despite the development of THz-TDS and the new functional materials mentioned above, THz bands are not fully utilized for applications due to the lack of low noise and high SNR THz detectors. Although hot carrier assisted transport in graphene (Science 334, 648-652 (2011)) or graphene/WS_2 heterostructure (Sci. Adv. 2019; 5:eaax9958) has been proposed to be used for broadband and tunable THz detection, simultaneous enhancements in efficiency, broadband and tunable responsivity, noise reduction and simplified device structures are necessary for practical THz applications.

Here, we propose to experimentally demonstrate our previous theoretical prediction (Sci. Rep. 11, 15976 (2021)) that THz spin waves can be triggered by fs laser pulses on ultrathin magnetic metallic detectors with near unity photon-to-spin wave power conversion efficiency. In the extreme quantum confinement limit (thickness < 5 nm), magnetic metallic layers such as nickel have significantly lower density of phonon states than for bulk. When a femtosecond laser pulse impinges on a magnetic metallic nanofilm, the absorbed pulse energy is predicted to scatter from far fewer phonons, leading to much more efficient conversion to spin polarized charge currents (provided that the magnetic nanolayer is embedded within a cavity). Thus, broadband THz spin waves might be triggered efficiently for on chip probes or spin Hall voltage readout.

To further improve upon the ultrathin metallic THz detection, we have the second aim to grow heterostructures of magnetic topological insulators (TI) (heterostructures of FeTe or GeTe on Bi_2Te_3, i.e. $[FeTe/Bi_2Te_3]_n$ on a magnetic insulator $Tm_3Fe_5O_{12}$) where (1) quarter wave and absorptive cavity effects due to the thickness of the heterostructure can absorb all of the fs laser pulse, (2) convert all the energy into unidirectional spin waves due to the time-reversal symmetry breaking coming from the magnetic insulating underlayer (Sci. Adv. 3, e1700307 (2017)) and (3) only the top/bottom surface of the TI layers conduct with spin selective Dirac electrons while the bulk of the TI does not. Hence, phonon scattering rates are expected to be reduced further. These advantages might minimize THz detection noise and improve the SNR to help achieve room temperature, broadband, voltage-gated and near-unity quantum efficiency THz detection.

Using our molecular beam epitaxy, pulsed laser deposition, sputtering systems and clean room facilities, these functional nickel nanolayers and magnetic TI heterostructures are going to be grown and fabricated into devices. Using the Ti:sapphire laser in our lab, we aim to investigate the time domain THz response of the devices using THz-TDS, responsivity and the noise spectra using fs optical parametric oscillator setup. We expect the project to yield 4 papers, a patent, 2 PhD trainings and a THz-TDS setup as its outcomes.

Integrated high-speed mid-infrared electro-optic modulator for free space optical communication

PI: Mengjie Yu, University of Southern California, 3737 Watt Way, PHE 612, Los Angeles, CA 90089, USA, 917-847-0825; mengjiey@usc.edu

Mid-infrared (Mid-IR) spectral regime from 3-5 μm is well-known as robust optical carriers for free space optical communications due to the low absorption atmosphere window and the higher tolerance to scattering than the near-infrared. However to produce high data rate optical link, direct current modulation of a quantum cascade laser is often deployed either at cryogenic temperatures up to 20 GHz modulation speed or at room temperature up to a few GHz speed. It is because that the high-speed low-loss electro-optic modulator is lacking in the mid-IR due to the material absorption and lack of individual control of both microwave and optical properties. We propose to overcome this limitation by using the integrated photonic technology where the tightly confined nanophotonic waveguide can be used to tailor the optical property via dispersion engineering and the microwave field can be tuned via electrode design.

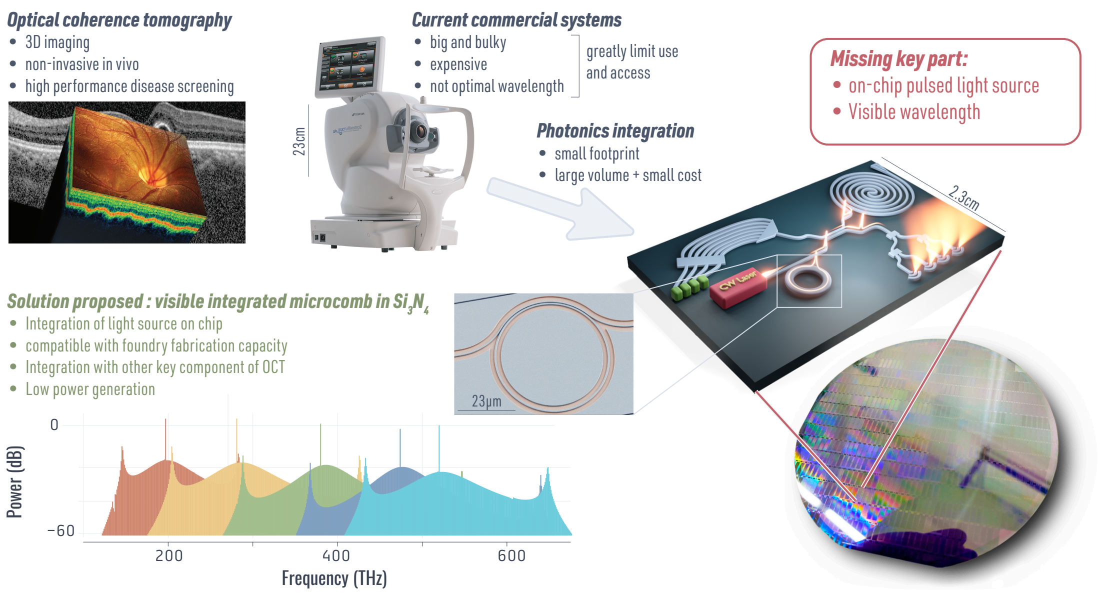
Thin film lithium niobate (LN) technology has recently attracted significant interest in data center applications due to its excellent electro-optic performance in terms of low insertion loss (< 0.5 dB), high EO bandwidth (> 100 GHz) as well as low $V_{pi}L$ (2 V*cm) demonstrated at telecommunication wavelengths near 1.5 μm. In addition, LN is a long-sought-after integrated photonic material due to its wide transparency window from 400 nm to 5 μm, large second order and third order nonlinearities as well as large piezo-electric response. It has superior advantages for reconfigurable mid-IR photonics, as compared to silicon-based photonics which intrinsically lacks EO response and different frequency generation. We propose to design and develop a low-loss integrated EO modulator on thin film LN in the mid-IR from 3-4.5 μm with > 50 GHz EO bandwidth and 10 V·cm $V_{pi}L$. The operating bandwidth and power consumption for switching is an order of magnitude beyond the state-of art mid IR modulators (of a few GHz, 20-50 V·cm). We will explore two potential geometries including suspended LN and LN on sapphire platforms to overcome the absorption-induced loss of silicon dioxide. Furthermore, we propose to develop a flat-top optical frequency comb (OFC) driven by cascaded EO modulators for wavelength division multiplexing (WDM). The device consists of an amplitude modulator and a phase modulator, where the amplitude modulator carves a flat-top temporal pulse and phase modulator imposes a quadratic temporal phase. The system transfers the flat-top profile from time to frequency. This approach would enable a high and uniform signal to noise ratio across the optical bandwidth, featuring a high pump-to-comb conversion efficiency of up to 50%. Such approach overcomes the low conversion efficiency and the exponentially decaying intensity profile of the integrated microcombs technology, and could be a highly desired WDM source for mid-IR optical communication. Together with the compatibility of high speed EO modulators, we envision a fully integrated EO-comb-driven optical data link with the potential for aggregate transmission rates of tens of Tb/s. The mid-IR nanophotonic technology will also have profound impact in areas including precision spectroscopy and imaging.

DA VINCI: DISRUPTION & ADVANCEMENT OF VISIBLE IMAGING USING NANOPHOTONICS AND FREQUENCY COMB INTEGRATION

DR. GREGORY MOILLE - UNIV. OF MARYLAND/NIST

Imaging techniques for medical purposes are at the core of non-invasive diagnosis, helping countless patients get screened to provide life-saving treatments. Optical Coherence Tomography (OCT) is a unique imaging technique based on interference, allowing for 3D reconstruction of tissues without taking a biopsy. It is desirable from both the doctor's and patient's viewpoint as this limits pain and provides instantaneous results. Although OCT techniques have swiftly transitioned from laboratory to commercial use, their presence in medical offices remains sporadic. The steep price and the system bulkiness prevent a mainstream use (*1*). In parallel, research has demonstrated that shortening the OCT wavelength presents many advantages, from resolution to penetration depth (*2*). Yet the price of such a light source is even larger, doubling down on the commercial challenge.

Photonics integration has drastically reduced countless optical systems' footprints, resulting in a considerable cost drop through mass-producing fabrication. Silicon nitride (Si_3N_4), which has recently been incorporated in foundry industries (*3*) allows for integrating most key photonics components and is a material of choice for its large transparency window and its nonlinear properties. The latter allows power-efficient parametric generation of new colors, including frequency combs (*4*). However, frequency combs fundamentally rely on the system's dispersion property, accounting for both material and geometrical dispersion of the Si_3N_4 microresonator – which must be anomalous for bright soliton pulses (inverse Fourier transform of the frequency comb) to exist. However, Si_3N_4 presents a more significant normal dispersion regime the shorter the wavelength is (larger the frequency is), which has to this day made impossible the realization of short wavelength frequency combs in this platform.



In this *Optica 20th Anniversary Challenge*, I propose to create an on-chip pulsed light source harnessing the progress made over the past five years in our group. Leveraging our unique experience in dispersion engineering of microring resonators (*5*), I aim to create a frequency comb in the visible domain. Preliminary results demonstrate the possibility through different novel dispersion engineering techniques to reach blue wavelengths with a Si_3N_4-based frequency comb. Beyond the demonstration of an on-chip, visible OCT light source, I aim to demonstrate monolithic integration of the different components to create a fully on-chip OCT system. Such a demonstration would reduce the cost by several orders of magnitude while making its use much more accessible to the many medical applications through which OCT could help patients. Visible OCT has been reported to help early screening of brain stroke and better diagnose gastrointestinal diseases such as Crohn's and ulcerative colitis. The success of this project could potentially revolutionize everyday patient care in many medical offices.

1. V. C. Coffey, *Optics and Photonics News*, September 2016.
2. X. Shu, L. J. Beckmann, H. F. Zhang, *Journal of Biomedical Optics* **22**, 121707 (2017).
3. J. Liu *et al.*, *Nature Communications* **12**, 2236 (2021).
4. G. Moille *et al.*, *Nature Communications* **12**, 7275 (14, 2021).
5. G. Moille *et al.*, presented at the CLEO 2022, SW4H.6.

Probing and perturbing the oligomerization of membrane protein utilizing nanoparticle plasmon coupling and Deep learning

Dr. Abu S. M. Mohsin, Associate Professor
BracU,EEE, 66 Mohakhali,Dhaka-1212,Bangladesh

Challenges: Membrane proteins are the first line of communication between the extracellular environment and the cell interior. This communication in cellular systems is largely under the control of complex spatial and temporal networks of macromolecular interactions called signaling pathways [1]. Traditional biochemical tools such as yeast-two-hybrid [2], co-immunoprecipitation [3] together with gene [4] and protein arrays [5] provides critical information on the constituents of interaction networks. Recently it has been known that the activation of epidermal growth factor receptor (EGFR) occurs via dimerization [6,7,8] or higher order oligomerization however the precise geometry, stoichiometry, and relevance to signaling pathways is not known at this time [9].

More recently several state-of-the-art fluorescence based non-destructive, non-invasive super resolution imaging techniques has been used in lateral micrometer and sub-wavelength range to track and analyse the biological molecules, interaction and oligomerization. However, due to the photo blinking and photo bleaching property of fluorophore and destructive nature of imaging these techniques cannot be utilized in live-cell imaging or to examine dynamic information about the uptake or aggregation. In order to investigate the oligomerization of membrane protein and subsequent activation pathway we proposed to use plasmonic nanoparticle and deep learning-based image segmentation technique in human cervical carcinoma (HeLa) cells. Plasmonic nanoparticle will be used as multifunctional probes and nano-spacers in a model cell system to investigate the organization of membrane proteins and to determine how receptor spatial arrangement influences cell behavior. The findings of this study will be helpful in spatial structuring, receptor organization and cellular function and drug delivery. Most importantly, the novelty of our work lies in the presentation of a pioneering technique that allows in-vitro cellular studies of membrane protein interaction in a non-destructive setting under the diffraction limit.

Proposed Project: The aim of the project is to determine the role of spatial organization on the function of membrane proteins. The objective of the project is as follows: **(a)** Investigate the light matter interaction of nanoparticle& structure using analytical models (Mathmatica/Matlab) & numerical methods (Lumerical-FDTD).**(b)**Probe the spatial organization of membrane proteins (EGFR). (c)Control the spatial organization of membrane proteins**. (d)** Determine how receptor spatial arrangement influences cell behaviour.

Expected Outcome: Expected outcome from aim 1: Investigate the light matter interaction of single particle and cluster on the 10-100 nm scale. We will provide evidence how the shape, size and geometry of the particle influence the plasmonic property. **Likely Impact from aim 1:** The results will be useful for understanding the fundamental properties of plasmonic nanoparticles and structures and employ them in several applications. This will help to investigate monomer-dimer transitions at the molecular scale. We expect to have one peer reviewed paper from these findings.

Expected outcome from aim 2: We will probe the spatial organization of membrane proteins (EGFR) using nanoparticle as a probe or nanospacer. We will demonstrate perturbation of spatial organization through the creation of clusters of different size, spatial extent and geometry. **Likely impact from aims 2:** The impact from this study will be high because it will address the issues of creating clusters with defined size and geometry directly. We expect to have one peer reviewed paper from these findings.

Expected outcome from aim 3: We will determine how cellular function is linked to spatial organization of membrane proteins._**Likely impact from aims 3:** The concept of spatial organization appears to be important for polyvalent ligand-receptor interactions where ligand-mediated receptor cross-linking brings components into molecular contact. However being able to ascertain the role of different sizes and geometries has been challenging because of the numerous species on the cell surface. Our novel approach will provide the link between spatial structuring, receptor organization and cellular function. We expect to have one peer reviewed paper from these findings.

The proposed project will help to address SDG 3-Good Health and Wellbeing, SDG4 Quality education and SDG 9 Industry, Innovation, and Infrastructure and help to create skilled workforce for Industry 4.0.

THUNDER - THermal UNpolarized radiation Design for Energy Recycling

Executive Summary – Environment Challenge

The world's consumption and production of energy are ever-growing and predicted to continue doing so. It has become of vital importance to find efficient and carbon-free solutions that will allow us to harvest and store energy produced from industrial processes, in order to reduce our emissions and impact on the planet. Among heat-harvesting energy technologies, thermophotovoltaics promises excellent performance. Indeed, theory predicts that thermophotovoltaics could approach the thermodynamic limit for the conversion of heat into electricity. Similarly, daytime radiative cooling promises to be a clean way to lower the internal temperature of buildings without any external energy input, other than, of course, sunlight. Recent breakthroughs in both of these topics have been made possible by developments in the field of nanophotonics, where designing subwavelength structures has resulted in unprecedented capabilities to control light over very broad wavelength ranges.

In this framework, the possibility of engineering the spectrum of thermal radiation to tailor it for specific applications is exciting, as it can dramatically boost the performance of these devices. If thermal emission possessed properties such as, directionality, a high degree of polarization and chirality, applications would benefit from it massively. Directionality, for example, is important for radiative cooling, as the light emitted by the device must not be radiated towards the object it is cooling, but needs to travel away from it. Directional emission would also benefit heat transfer and, consequently, thermophotovoltaics, providing a directed flow of energy from the emitter to the cell. In addition to this, a control on polarization and chirality could have several interesting consequences. Designing the polarization profile of the emitter can allow for more channels to be excited in the absorber, increasing the capacity of the device and the heat flux. Furthermore, chirality could be exploited to design devices with nonreciprocal responses. These properties and degrees of freedom of light have been extensively studied for coherent, monochromatic light. However, interest towards the study of these quantities in the framework of thermal radiation has not been transversal yet. This is because the magnitude of the performance achievable with radiative heat-harvesting devices has only recently been fully understood. However, recent promising results have shown that the manipulation of thermal radiation can drive devices with unprecedented efficiencies and a clean footprint.

Via project **THUNDER** (**TH**ermal **UN**polarized radiation **D**esign for **E**nergy **R**ecycling), I plan to design thermal emitters to harvest the power of thermal radiation leveraging on phenomena which are robust and due to the intrinsic nature of light. For example, I plan on designing directional emitters that rely on spin-momentum locking or on a large reactive power, a task I have previously successfully achieved with coherent nanophotonic designs. Other degrees of freedom such as Poynting vector, chirality and angular momentum will also be examined. I will develop a theoretical framework that allows for the description of thermal fields and a formalism to calculate their degrees of freedom. Via this, I will be able to evaluate their magnitudes and the possibility of engineering them to attain specific values. The devices realized with this method will serve as a model to estimate the effect that the manipulation of each degree of freedom can have on thermally emitted spectra. Once the phenomena that can enhance radiative heat transfer have been identified, they can be combined to explore their joint effects.

This is a very exciting moment to work on these topics, as devices based on thermal emission are becoming the state-of-the-art for energy conversion right in front of our eyes. Recent scientific advances are showing us the possibility for the waste heat generated in industrial processes to be exploited as an abundant energy resource. It is time to give thermal radiation the same attention that has been given to coherent, directional and monochromatic light, as the potential for discoveries in this field is vast. Discoveries in this field could be the solutions that will empower us to face climate change and pull the break on the disastrous damages we have done to the planet.

Executive summary for “Ultrafast dynamic contrast optical coherence microscopy enabled by a microcomb photonic flywheel”

Imaging the dynamics of cells by the non-invasive optical coherence microscopy (OCM) is an effective way to test their response to drugs or pathogens and monitor health. Here we propose a method to overcome the bottleneck of data acquisition in dynamic OCM imaging and improve both the imaging speed and dynamic range.

Problem statement

(1) Commercial electronic analog-to-digital converters (ADCs) limit the performance of ultrafast dynamic contrast OCM due to the compromise between the high sampling rate and large effective number of bits (ENOB).
(2) Although photonic ADCs (PADCs) can help to improve the performance of electrical ADCs by overcoming the bottleneck of electrical jitter, there is no demonstration of improving dynamic medical imaging such as OCM based on PADCs.
(3) Laser sources for PADCs with ultralow jitter and high repetition rate > 1 GHz is challenging for conventional mode-locked lasers.

Objectives

(1) PADC with sampling rate of 8 GSa/s and ENOB of >10 based on Brillouin-Kerr microcombs at 1 GHz.
(2) Demonstrate the first ultrafast dynamic contrast OCM imaging with the improved PADC.

Intended outcomes

(1) A PADC prototype with 8 GSa/s sampling rate and >10 ENOB, which can be used in universal applications not limited in ultrafast dynamic contrast OCM.
(2) Demonstration of ultrafast dynamic contrast 3D OCM imaging.
(3) Publish one or two articles in high-impact journals such as Optica.

Impact

The PADCs enabled by microcomb photonic flywheel can overcome the bottleneck of electrical jitter for electrical ADCs and improve the performance of more than 1 bit at 8 GSa/s. They can be applied to the critical applications such as radar systems, software radio, medical imaging and next-generation communication systems. In addition, it is feasible to integrate all the components onto a chip to realize a compact, power efficient and high-performance chip-scale PADC. The application in dynamic OCM imaging can not only increase the imaging speed, but also the dynamic range, providing a better tool for scientific research and health monitoring.

Title: Smart PHOTOvoltaic module for bidirectional Visible Light Communication (PHOTOVLC)

Category: Environment

Executive summary

Mobile devices are ubiquitous and their number has been continuously and considerably increasing. However, the exponential rise in data volumes over the next decade will make it increasingly challenging to provide sufficient RF resources. A novel alternative to RF communications is the so-called Visible Light Communication (VLC). Solar cells represent a relevant alternative to PDs for detecting information from a light source. Compared to PDs, the use of solar cells as a receiver has the advantages of easy alignment between transmitter and receiver, a combination of data transmission and energy harvesting, and optimization for outdoor application. However, scholars have not adequately addressed the alternative use of solar cells as receivers because they have focused on increasing efficiency in terms of energy harvesting.

The overall objective of PHOTOVLC is to develop the **first-ever** Photovoltaic module for bidirectional Visible Light Communication. Such a PHOTOVLC module allows to receive and transmit information thanks to the joint adoption of solar cells and LEDs or LDs, combined into the same device, while still producing usable electrical power. During the project, different intermediate outcomes will be generated in order to finally realize the PHOTOVLC demonstrator. Specifically: (1) a novel methodology to study different solar cell technologies in the frequency domain using various light sources as transmitters will be developed and the related testbench realized; (2) custom solar cells, including perovskite devices, will be fabricated and characterized to identify the physical parameters that play a major role on their dynamic performance. From this study, guidelines for the realization of PV cells that are optimized for VLC application, i.e. with improved frequency response (for larger data bandwidth) will represent another important outcome of the project; (3) in-depth solar cell models that take into account the dynamic behavior of the PV devices and can be used to study and design PV-based receivers for VLC applications will be developed; (4) both commercially available and custom-designed solar cells will be characterized in terms of bandwidth (to quantify performance as information receivers) and efficiency (to quantify performance as generators); (5) a new parameters' estimation method for both conventional and advanced solar cell's model will be developed; (6) novel electronic circuits able to divide the DC and AC signal for transceiver and power generator, to realize a self-powered device that can be combined with a DC-DC converter with MPPT, will be designed; and (7) different options for the integration of on-module transmitters – to enable bidirectional communication – will be studied, characterized and designed.

The research will be carried out at the Photovoltaic Materials and Devices (PVMD) group of Delft University of Technology (TU Delft). The realization of the testbench and the characterization of the different components of a PHOTOVLC module will be carried out in the Photovoltatronics Laboratory of TU Delft, whereas the characterization of the large-area demonstrator will be performed partly in the Photovoltaic Laboratory of TU Delft (indoor), and partly at the PVMD monitoring station (outdoor). Furthermore, custom c-Si and perovskite PV cells will be fabricated in collaboration with different specialists in the PVMD group and using the Else Kooi Laboratory (EKL) facilities of TU Delft.

The outcome of the project will impact important United Nations (UN) initiatives focusing on the transition towards a secure, clean, and efficient energy policy. "Sustainable Cities and Communities", "Grow Affordable and Clean Energy" and "Industry, Innovation and Infrastructure" are the three focus areas of the *17 Sustainable Development Goals* of the UN mostly affected by PHOTOVLC. Innovative PV module technologies, such as the PHOTOVLC module in this proposal, are needed in order to reach the UN's goal to significantly increase access to information and communication technologies. The use of the PHOTOVLC module represents a significant advancement in the field of optical transmission and for new 5G technologies. Integrating VLC into 5G enables the achievement of challenging targets such as lower power consumption, reduced latency, and increased number of connected devices.

Bridging the peri-urban digital divide with “fibre,” before the fibre

Mitchell A. Cox*[1] **and Abderrahmen Trichili**[2]

[1]School of Electrical and Information Engineering, University of the Witwatersrand, Johannesburg, South Africa; [2]King Abdullah University of Science and Technology, Saudi Arabia; *PI / Applicant: mitchell.cox@wits.ac.za

Executive Summary

Eventually, most of the world’s population is expected to live in an urban environment. Rapid urbanisation occurs across many developing nations, where informal settlements have little or no infrastructure for electricity, water, or communications. South Africa is one such nation. While there is a constitutional mandate to provide infrastructure in these rapidly evolving areas and informal settlements, the inevitable timescales for conventional infrastructure roll-out leaves an unmet need in the interim. These settlements are often within a few kilometres (and sometimes just across the road) of areas with excellent infrastructure.

Can we bridge this peri-urban digital divide using free-space (wireless) optical communications while balancing the need for resilience and performance with the cost? Typical, lower-cost optical wireless communication systems often use fibre Ethernet-like technologies that provide no resilience to the adverse effects of atmospheric propagation and thus have a limited range of several hundred meters.

The primary objective of this project is to leverage and combine robust, high data-rate WiFi hardware with radio over optical techniques to develop and test a low-cost, high-speed, and potentially very long-range (i.e., more than one kilometre) free-space optical communication system. We will then field test the system in a real-life application in collaboration with a local startup company that typically deploys wireless links in nearby informal settlements. At the end of the project, we plan to open-source the designs for this device for maximum social benefit. We hope to enable people to solve their own unique issues using our system but also hope that others will contribute improvements with time, creating a sustainable and evolving solution.

Our proposed low-cost, high-speed, long-range internet connectivity solution presents a unique opportunity. We can extract and use the internal WiFi channel state information (CSI) to perform environmental sensing. However, this is through the “proxy” laser beam that carries the WiFi signal. While conventional WiFi CSI-based sensing targets would no longer be applicable, as we do not use radio, we believe that we will be able to sense new and otherwise “un-sensable” (with this particular technique) environmental parameters based on perturbations of the carrier laser beams’ intensity, phase, and polarisation. Our approach will likely be more affordable than conventional optical sensing techniques because we do not require optical amplification, special optical fibre components, or expensive digitisation equipment. Instead, we “simply” make use of the very high-performance hardware that exists in consumer-grade WiFi hardware, and couple it with sophisticated deep learning that we will research and develop.

Thus, for the second objective of this project, we will focus on demonstrating this new sensing approach and then applying it to the unique and interesting application of lighting detection and positioning. Global lightning detection networks are heavily relied upon to monitor climate change, determine where lightning strikes happened (usually for insurance claims), and for early-warning systems. Unfortunately, in South Africa lightning kills about 250 people annually – many of whom live in informal settlements. Perhaps this could be alleviated with better detection networks, or indirectly through the educational opportunities afforded by a good internet connection?

We believe that the ability to provide low-cost, fast, reliable, and long-range internet connectivity with an open-source platform will help to connect the unconnected. Additionally, our system may also be used to optically sense environmental parameters, with lightning as a specific goal. Will this open up novel avenues to fund the deployment and operation of the system and help bridge the digital divide? We hope to take the first step toward this future with the generous support of the Optica Foundation’s 20$^{\text{th}}$ Anniversary Challenge.

Project Title: Compact and Scalable Platforms for Optical Analog Computing
Category: Information
PI: Nasim Mohammadi Estakhri, Assistant Professor, Chapman University

EXECUTIVE SUMMARY

Overview: In this project we propose a fully integrated platform to realize all-optical analog computation using *compact* and *scalable* mode converters. The scalable operation of the proposed structures distinguishes this design from previous devices presented in the literature, where increasing the input size would linearly increase the physical footprint of the device, thus hindering their practically when large amount of data needs to be parallel processed. The outcome of this project are low-power and integrable devices that can impart linear mathematical operations on the input signal and solve the associated integral equations. In the proposed design, the output signals can be easily accessed through a single multimode coupler placed in the signal path. The compact nature of these inverse-designed optical structures leads toward realistically scalable optical analog computers, enabling futuristic high-resolution parallel computations.

Detailed Objective, Outcomes, and Impact: The overall objective of this project is to employ powerful *computational inverse-design* approaches to create **fully integrable and scalable optical analog computing platforms** through leveraging *the inherent compactness of multimode waveguides* compared to their single-mode counterparts. This allows for realistic scalability of the device (i.e., when increasing the number of input data points), without detrimental impact on the physical footprint of the structure. For this purpose, we propose to employ multimode silicon waveguides, where the *data is carried through the amplitude and phase of multiple overlapping modes, occupying the same physical space*. Indeed, the key advantages of optical analog computing can only be unlocked through realizing real scalability in such devices, so the important **outcome of this project** is to implement scalable integrated optical analog computing elements with *significantly smaller physical footprint compared to the current state-of-the-art structures*. The single multimode silicon waveguide (operating as an analog data bus) carries the information throughout the device, and the desired operator such as matrix inversion, differentiation, integration, etc. is fully implemented via a compact inverse-designed integrated structure.

Given the nature of the project which can be appealing to both engineering and computer science community, we envision several meaningful impacts, including **(i) Scientific impacts:** Designing scalable and compact integrated analog computing, paving the way toward hybrid/electronic processors exploiting the parallel processing and inherently high computation speed of the light-based analog computation. **(ii) Educational impact:** Training undergraduate students in electrical engineering and computer science. This is especially valuable for Chapman University as a PUI. Mentorship will include research planning and execution, as well as presentation and dissemination of research results, and preparation for next career stage. **(iii) Community impact:** Organizing workshops for senior high school students and local undergraduate students to broaden their perspective of applications of light in state-of-the-art information and computing applications. Chapman University is located in Orange County, a technology hub in US, which will allow us to plan a strong collaboration with the local industry.

Monitoring Dysfunctions of the Arousal Response with Biometric Ocular Photometry

N. Pégard, UNC Chapel Hill - 20th Anniversary Challenge: Health - Executive Summary

Nearly one in five U.S. adults currently live with a mental illness, yet only few people have access to adequate mental healthcare. Even with ample financial resources, diagnosis, treatment, and support for these chronic and intermittent conditions are particularly difficult to provide outside inpatient facilities. For instance, dysfunctional arousal responses are common components of many neuropsychiatric disorders, yet these signs are routinely ignored because arousal cannot be simply measured with a sensor. The ability to detect dysfunctions of the arousal response with practical, inexpensive, and minimally invasive technology would revolutionize mental healthcare. Tracking arousal in real time would enable currently infeasible personalized medicine, with tailored treatment strategies for mental illnesses, where counseling, advice, or even fast-acting drugs could be provided to patients exactly at the time and place where they would be most beneficial.

The current state of the art technology for arousal studies is pupillometry, with bulky cameras placed near the eye that monitor the changes in pupil size that correlate with arousal. Pupillometry alone is often insufficient to reliably assess arousal states and a preferred strategy also includes heart and breathing rates measurements with additional monitoring devices. This approach is impractical and limits arousal studies to laboratory settings. Round the clock tracking of arousal in humans remains currently impossible.

We propose to tackle this challenge with a new technology, Biometric Ocular Photometers (BOPs) that can simultaneously record several biometric data that encode arousal with a single device. BOPs operate with invisible infrared light to illuminate the back of the eye, and with photodetectors to measure the flow of diffused infrared photons through the pupil. Our team has already developed a BOP device for animal studies (small rodents) and demonstrated that it can simultaneously record pupil size, heart, and breathing rates.

With the support of the Optica 20th Anniversary Challenge, we will leverage our successful proof of concept for animal research, and we will develop a wearable optical technology to monitor arousal in humans. For this, we will integrate BOPs in a modified pair of glasses with infrared LEDs that will illuminate the surface of the skin in the periphery of the eye, and with several photodetectors pointed towards the eye that will quantify diffused light through the pupil from multiple perspectives. We anticipate that the technology we propose will simultaneously capture pupil size, eye motion, heart, and breathing rate at multi-kilohertz sampling speeds. A Bluetooth connection will stream all these biometric data to the user's cell phone where unsupervised deep learning algorithms will infer arousal states in real time. Our interdisciplinary team with experts in optics, electronics, and computer science, and an established collaboration with the laboratory of Prof Jose Rodriguez Romaguera (UNC Psychiatry dpt.), brings all the expertise that is needed to develop and validate the hardware and the software for this project, and to tailor their design for medical applications.

We will first validate our prototype by comparing our capabilities against the current state of the art (commercial pupillometry and eye tracking devices, heart and breathing monitors) in controlled tests. Our team will commit to publish all the results, data, and design files in open-access journals to facilitate the replication of our systems in not-for-profit applications. We will also explore potential commercial applications of the technology.

We expect that the prototype we intend to deliver within the timeline of this award to first be of interest to medical researchers for the study of neurological disorders and open new research directions through traditional funding opportunities. Our long-term goal is to provide a wireless device for patients suffering from PTSD, anxiety or depression, that will be programmed to detect early symptoms of distress in real-time and enable new personalized medicine solutions for these patients.

Design of an Optical Brain Interface: Bio-Neural Dust

CHALLENGE

The field of optogenetics has undergone significant development in recent years. One of its applications is stimulation of neurons with light. However, when coming to stimulating the actual brain, using optical fiber inserted through the skull is not practical. To achieve neural stimulation wirelessly, the concept of neural dust was introduced. Neural dust is a type of brain-computer interface, which uses devices the size of a millimeter as wireless nerve sensors to remotely monitor neural activity. However, despite of their small size, these devices are still very large compared to the size of a neuron, making it impossible to achieve stimulation and monitoring at the granularity level of a single neuron; it is also impossible to achieve very localized brain stimulation/monitoring. In addition, CMOS technology is reaching its limits in terms of miniaturization due to quantum phenomena, making the control of CMOS sensors at the nano level very challenging. The brain stimulation at a single neuron precision level is faced with two problems; size miniaturization and biocompatibility. In the optogenetics literature, we either find miniaturized systems with no biocompatibility, or biocompatible systems but very large compared to the size of neurons.

PROPOSED PROJECT

One promising solution in designing wireless nanosensors is to use bioluminescence and biological agents such as bacteria and viruses. Besides their biocompatibility inside the human body, bio-inspired systems are stable, inexpensively manageable, their tiny size allows them to be injected noninvasively inside the brain and they are easily controlled with genes and enzymes. The goal of this project is to design and implement bio-nanosensors that can monitor and stimulate neurons at nano level by using optogenetics. The proposed bio-nanosensor contains two biosystems. The first uses the piezoelectric properties of M13 virus to harvest the mechanical energy of ultrasonic waves, converting it to electricity. The second biosystem uses a photo-protein called *Aequorin*, which generates bioluminescent blue light in the presence of Ca^{2+} ions. Both biosystems will be placed inside a transparent nanosphere creating a bio-nanosensor, which detects ultrasonic waves, converts them to electricity, which triggers release of Ca^{2+} ions in the pool where *Aequorin* is located. The reaction generates blue light emission. A network of these bio-nanosensors creates the Bio-Neural Dust that will be used as an optical brain interface to stimulate neurons *in vitro* by using optogenetics.

INTENDED OUTCOMES

The project is divided into an analytical study and an experimental study. The intended outcomes of the analytical study are journals, conference publications and a patent of the designed bio-nanosensor. The intended outcomes of the experimental study are testbed, in vitro prototype and a patent of the constructed bio-optical brain interface. The project will involve 4 graduate students (2 PhD and 2 Master), who will acquire multidisciplinary expertise and research training. We have secured use the laboratories required for our research. This project will have a significant scientific and technological impact, especially in the field of medical applications and neuroscience.

Design and fabrication of a plasmonic photonic crystal fiber multiparameter sensor for refractive index, temperature, magnetic fields, and strain for lab-on-a-fiber applications

1. Introduction

Conventionally, medical, biochemical, and related analyses are conducted in centralized laboratories. This is because the centralized labs require skilled personnel and specialized equipment. However, in recent decades, because of the need to move closer to the users, points-of-care devices such as lab-on-fibers are in high demand. The lab-on-a-fiber platforms offer several benefits. Firstly, because of their very small feature sizes, extremely small sample volumes are required for analysis. Secondly, lab-on-a-fiber devices are low-cost, generate less waste, and consume less energy. Lastly, the platform can be integrated into micrototal analysis systems to automate several laboratory processes. This would allow for fast analysis and eliminate the need for skilled personnel for operation. Meanwhile, refractive index, temperature, magnetic fields, and strain are frequently measured during medical, biochemical sample analysis.

2. Challenges

Current techniques for detecting multiple parameters in plasmonic PCF sensors mostly employ multi-peak tracking on confinement loss spectrographs. However, during multiple peak monitoring, some peaks on confinement loss spectrographs are frequently not well defined, leading to confusion during the monitoring process. Additionally, this technique slows down the measurement process when the resonance peaks are separated by several wavelengths. Additionally, potential errors are likely when using large wavelength steps in tracking the phase-matching points. On the other hand, it was recently suggested that individual plasmon modes can be hybridized into cooperative plasmonic modes to allow strongly guided modes to couple to several localized plasmonic modes for multiple parameter sensing.

3. Objectives of the research

The main objective of this research is to design and fabricate a plasmonic PCF multiparameter sensor for determining refractive index, temperature, magnetic fields, and strain for lab-on-a-fiber applications. The specific objectives are:

i. To design a plasmonic PCF multiparameter sensor for measuring refractive index, temperature, magnetic fields, and strain. The modal characteristics, wavelength, and amplitude sensitivities, as well as sensor resolutions will be computed. The concept of cooperative plasmons will be explored as part of this objective.

ii. To fabricate the designed plasmonic PCF multiparameter sensor for determining refractive index, temperature, magnetic fields, and strain variations.

4. Outcome

A plasmonic photonic crystal fiber multiparameter sensor for refractive index, temperature, magnetic fields, and strain for lab-on-a-fiber applications potentially presents the following advantages: increased portability, ease of operation, low sample consumption, fast assaying time, label-free platform, high sensitivity and high resolution, remote sensing capabilities, robustness and compactness, low-cost, multi-analyte detection capability, and a means for providing real-time results. At the same time, the sensor is not susceptible to electromagnetic interference and has high biocompatibility. Ultimately, sensor has a broad application range and will be relevant to the health sector, food industry, pharmaceutical industry, research in life sciences and related industries.

EXECUTIVE SUMMARY

Reducing and Preventing Airborne Diseases Transmission in Healthcare, Educational and occupational environments.

Dr. Ing. Pablo Fredes Donoso [1]

One of the Sustainable Development Goals declared by the UN currently in force is to guarantee a healthy life and promote well-being for all at all ages. An innovative, effective and multidisciplinary project, for the reduction and prevention of airborne disease transmission, based mainly on implementation of Ultraviolet Germicidal Radiation (UV-C) air disinfection devices is presented. This project have a key focus on Hospital Acquired Infections (HAIs)[2] and will be extended to other fields such as occupational, educational and other public indoor places, where a large number of persons congregates. The outcomes are the reductions of the number of infection diseases in the people, with high potential to save lives.

Today it is clear that reducing or preventing the Hospital Acquired Infections (HAIs), specifically airborne diseases transmission including SARS-CoV-2, is a critical and unprecedented global challenge. The U.S. Centers for Disease Control and Prevention (CDC) and the World Health Organization (WHO) continuously monitor and work to prevent HAIs because they are a critical threat to patient safety and global health security[3]. While previous studies by healthcare providers have estimated an economic burden of approximately $10 billion annually for HAIs, a more contemporary examination of the impact of societal costs included the economic value of mortality risk reductions, thereby giving an estimate for the total economic burden to society in excess of $200 billion annually.

An innovative and effective preventive action is the application of UV-C to the air flowing through UV-C Devices. Considering that a great offer in the global market of many types of UV-C air disinfection devices is available today, it becomes necessary to define clear evidence and scientific information that may contribute to a generalized, effective and secure use of the proposed solution.

The objective is the development and implementation of the Big Multidisciplinary Project to obtain real and empirical evidence of the impact of the correct use of the UV-C disinfection technologies. The enormous task includes actualization of protocols, i.e. cleaning and disinfection, a rigorous tracing of epidemiological statistics and an interdisciplinary basis following the coordination of a correct execution of the required task to complete the goals.

This evidence will be obtained from different interconnected fields, as epidemiological analysis, air treatment engineering, physical and radiometric analysis, biosecurity and healthcare considerations and microbiologist analysis. This methodology will allow implementing the best option according to the physical characteristics of the space, number of persons, the ventilation situation and specific disinfection levels required.

---

[1] *CEO and founder of Hydraluvx Spa, www.HYDRALUVX.com, Staff member of the Optics and Semiconductors Laboratory, Physics Department, Universidad de Santiago de Chile.*

[2] https://www.usach.cl/news/grupo-estudiantes-osa-usach-dona-dispositivos-medicos-desinfeccion-uv-al-hospital-sotero-del

[3] Poster DL, Miller CC, Martinello RA, et al. Ultraviolet radiation technologies and healthcare-associated infections: Standards and metrology needs. J Res Natl Inst Stand Technol. 2021;126(126014):1-33. doi:10.6028/JRES.126.014

Executive summary of the proposal tilted
“Transfer to circular economy by fiber optic sensor monitoring of waste containers”
for the Optica Foundation 20th Anniversary Challenge

Rapidly increasing generation of the municipal solid waste (MSW) is an environmental problem, which can be observed for at least 50 years. The MSW is considered as waste that comes from households, but also businesses, schools and institutions. It is caused by multitude of factors, including improper waste management, urbanization and population growth, economic development and many others. Globally, the MSW amounts to over 2 billion tons per year.

Proper disposal of the MSW includes keeping it in the secure areas, preventing the leakage and spreading of waste, limiting concentration of gases. Limited space in the residential areas force the development of various techniques of waste collection and treatments. One of such solution was implementation of underground and semi-underground waste containers, which help limit the odors, make public spaces cleaner and make easier to collect and transport the waste. However, it does not solve the main issue related to the circular economy, such as reduction of waste, limitation of gas emission, waste management efficiency and possibility of spontaneous combustion.

Therefore, the aim of this project is to design the fiber-optic sensor system and embed it in the aforementioned containers to allow for real-time monitoring. The task of the sensor system will serve as:

- monitoring the level of collected waste inside the container,
- detection of the container leakage,
- detection of the emission of volatile organic compound (VOC),
- monitoring the temperature and humidity inside the containers,
- monitoring the proper closure of the container lid.

The sensors will be functionalized to increase their specificity and ensure proper operation (e.g., ZnO coating for temperature monitoring, microsphere structure as a probe).

Application of the presented fiber-optic sensor system will reduce the dangers to the environment immensely. The outcome fiber-optic sensor system will help transfer to circular economy by improving in the monitoring capabilities of the waste containers and in turn the environment and reduction of the release of dangerous byproducts resultant from waste decomposition and energy necessary for waste management, therefore improving its safety and quality.

Executive Summary - Reduction Techniques for Dissipative Systems

Dissipative systems or dissipative solitons are complex dynamics that exist in physical and biological nature. Much of the rich dynamics exists beyond traditional mathematics. This dissipative soliton research discipline has been developed by world-leading Professors Nail Akhmediev and Adrian Ankiewicz, at the Australian National University (ANU). This makes the ANU the priority research facility to develop and drive this proposed research challenge.

Contemporary mathematical & scientific studies focus on conserved system models which can also have stochastic or statistical frameworks, and where the meaning of experimental data is determined empirically. These modeling frameworks are subject to entropy constraints. Entropy constraints are brought into focus by conserved system self-preserving dynamic objects called solitons. The self-preserving soliton dynamics in light-wave fiber communications have been seen to prolong the effects of entropy.

A deeper study of entropy constraints and their 'elasticity' may be explored deterministically with Prigogine's ideas of reversibility and irreversibility on dissipative solitons and dissipative system models, which are self-organizing. *This is a crucial area of research that needs to be developed, not just across physics, but also in biophysics modeling for improved precision health medicines. This research may also assist in utilizing self-organizing quantitative economic frameworks to optimally deliver global clean climate environment initiatives*, in a symphony of support of key industry sectors, inclusive of OPTICA commercialization research projects.

INFORMATION: My dissertation on 'extreme waves in dissipative systems' is a fundamental road map focused on new laser signal developments with the master laser equation. This is an engineered technology described by a dissipative soliton equation. It borrows from the pattern dynamics of nature. In my PhD research studies, the 'spiny solitons' discovery holds applications to super-continuum generation and can be a serious attraction for commercialization. Analytical insights into the high-power ultra-short pulse characteristics of spiny solitons can advance technological laser limits and represent a fundamental challenge of importance in improving reduction technique methodologies. The significance of these techniques applied to the laser master equation is that it is based on the Ginzburg-Landau superconductivity formulations, applicable across general physics and that it can be adapted to numerous modified research and laser models. The application of new laser signal technologies is crucial across a plethora of industry commercialization sectors from laser research developments, data and storage information, industrial cutting, emerging augmented and holographic technologies, and also medical diagnostic tools and precision tools for non-evasive laser surgery.

HEALTH: Dissipative soliton system dynamics of nature can model biological processes that inherit self-organizing properties. Healthy biological processes maintain stable properties that may be ideally identified with analytical reduction techniques. Health complications can emerge when a biological process deviates from stability. Analytical dynamical insights to aid understanding of deterministic reversibility of the deviation path from order to disorder and vice versa are crucial to improving medical research. These reduction techniques may assist us to foster cross-disciplinary research discoveries, beyond current medical linear techniques and methodologies. To better guide precision medicine research. This may present to OPTICA new cross-disciplinary synergies, alongside medical laser research developments, especially to address recently-observed mortality concerns.

ENVIRONMENT: A stable climate offers health and longevity benefits. This challenge may *only* be achieved if the 'accommodation' of lasting co-operation between China and the United States is maintained. The need for this 'accommodation' is seriously expressed by professional politicians and strategists for geopolitical order. As a complex geopolitical dynamical system, the two existing superpowers, as the primary driving parameters, can maintain the most influential stabilizing geopolitical 'soliton-type' behaviors to best guarantee long-term financial investment and commercialization initiatives. My deep belief is that this ultimate challenge is of the highest importance, so that this must be secured. The international OPTICA community may play an important role by using fundamental research developments to strengthen national economies across the globe. This requires insightful initiatives of 'accommodation' for organized geopolitical financial security. In evolving financial market regimes, requires developing and extending new financial engineering models to better stabilize and secure investment strategies for global preservation of the environment and stable climate. These reduction techniques may aid in establishing new optimal financially engineered models for evolving market regimes.

Executive Summary

High-Speed and Efficient Quantum Light Generation with Semiconductor Quantum Emitters Embedded in Integrated Photonic Structures

Impact: In this project, we propose to use semiconductor artificial atoms in nanofabricated optical cavities to generate single and entangled photons efficiently and at gigahertz rates. The project will use semiconductor quantum dots (QDs), the most efficient on-demand quantum light sources to date, which emit photons with near-unity efficiency upon excitation. These QDs will be integrated with high-quality-factor optical cavities fabricated by photo- and electron-beam-lithography to efficiency couple the emitted photons into optical fiber networks. Based on quantum light traveling through these networks, our QD-cavity source offers a high-speed solution for secure quantum networking applications such as ***unbreakable encryption for data storage and transmission*** via ***certified random number generation***, ***quantum key distribution***, and ***entanglement swapping***. These applications are based on entanglement distribution and measurement with end-to-end efficiencies higher than 75%, a threshold for a ***loophole-free Bell-test***. This test will result in private or shared encryption keys with ***unprecedented low bias***, with a ***quantum privacy signature*** which alerts the user(s) if adversaries try to tamper with the keys to obtain their information. Therefore, this signature is the ultimate form of security, ensuring that the encryption keys are known only by the target users.

Objectives: The focus of this project is to design and fabricate optical cavities that can efficiently extract quantum light from QDs and into optical fiber. Our novel cavity design will extract photons more efficiently compared to other state-of-the-art solutions, surpassing the threshold for generation of unbreakable encryption keys. Our system is based on a novel dual-structure cavity: circular trenches in the shape of a bullseye, and a vertical top-down cavity consisting of planar mirrors at the bottom and a concave mirror on top (Fig. 1). We have already fabricated and characterized bullseye cavities, and during this program, will design and fabricate vertical cavities that are compatible with the bullseye cavities. During the 1-year period of this project, we will:

(1) Design and simulate the dual-structure cavity to result in record-high photon collection efficiencies ($> 75\%$).
(2) Fabricate these cavities using molecular-beam epitaxy and nanofabrication.
(3) Characterize cavity performance with classical light (quality factor $Q > 20{,}000$).

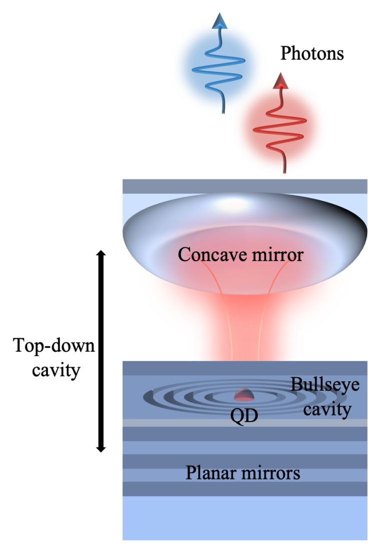


Fig. 1. A quantum dot embedded in a dual-structure optical cavity.

Team: This project will be led by Poolad Imany, who is a postdoctoral associate in Quantum Nanophotonics Group (QNG) at the National Institute of Standards and Technology (NIST) and University of Colorado Boulder, Colorado. Imany is also the Founder and CEO of Icarus Quantum Inc, the only company in the United States that works on commercializing quantum emitters for the purpose of quantum networking technologies. Imany has more than nine years of experience in quantum light generation and quantum networking, and will leverage decades of expertise from the QNG group in QD wafer growth and nanofabrication.

Facilities: For Multiphysics simulations, we will use NIST's multicore, gpu-equipped workstations. For nanofabrication, we will use NIST's world-class cleanroom facilities. Finally, we will characterize our devices at NIST and University of Colorado Boulder's laboratories equipped with tunable lasers and superconducting nanowire single-photon detectors. Although Icarus Quantum is the institution leading this effort, the NIST and University of Colorado Boulder facilities will be used through a cooperative research and development agreement (CRADA) between Icarus and these institutions.

EXECUTIVE SUMMARY

Silicon photonics and printable photonic ink LEDs for a new affordable medical sensor platform

Optica Foundation 20th Anniversary Challenge Category: Health

The Challenge: Traditional medical sensors consisting of discrete optics cannot keep pace with patient need. This limitation was highlighted during the COVID-19 pandemic, when the standard pulse oximeters used to measure blood oxygen levels yielded incorrect diagnoses for people with darker skin pigmentation, thicker skin, or lower blood flow rate. These standard oximeters used discrete optics, including LEDs (660 nm and 940 nm), filters, and photodetectors from that must be sourced from separate supply chains, assembled, and packaged into a single device. Accurate devices that can compensate for skin pigmentation require four or more LEDs of different wavelengths. However, adding additional discrete optical components increases the complexity of packaging, resulting in poor adoption due to their high cost. This illustrative example, pulse oximetry, is not alone in suffering the challenges imposed by discrete optics. Existing medical sensor products, such as carbon monoxide poison detectors, require eight or more LEDs and are niche as a result. Looking to the future, the $20 billion noninvasive medical sensor industry needs a way to achieve accuracy, complexity, and versatility while maintaining a low cost to expand global access to healthcare.

Proposed Project: *This Optica Foundation 20th Anniversary Challenge will provide critical seed funding for demonstrating the world's first affordable noninvasive medical sensors based on silicon photonic chips*. The promise of silicon photonics is that it will enable integrated optics to replace discrete optics in the same way that integrated circuits replaced discrete electronics. Our company's vision is to print LEDs of different wavelengths directly onto a silicon photonic chip to avoid the costs associated with discrete optics and their packaging. We are pioneering a new class of printed photonic inks for light sources and detectors (actives) based on nanoscale black phosphorus (BP), a material that exhibits desirable opto-electronic properties including direct-gap light emission and high conductivity. BP is a 2D semiconductor that can be tuned to emit over a broad spectrum from visible to infrared based on the number of atomic layers. **In this project, we will separate a multi-layer (polydisperse) BP solution by layer number to achieve inks that emit at specific wavelengths relevant to medical devices. We will then demonstrate printed BP LEDs fashioned from these inks on silicon chips. This project will leverage key results from our company's work on BP over the last several years.**

Intended Outcomes: The final outcome of this project will be LEDs fashioned from monolayer BP (emission at 600-900 nm) and bilayer BP (emission at 800-1200 nm) that we print on a silicon photonics chip. To achieve this result, we will use density gradient ultracentrifugation (DGU) to separate monolayer and bilayer BP from a multi-layer (polydisperse) solution. We will engineer this process specifically for BP to achieve maximum yield using a combination of surfactants and centrifugation parameters. This technique has been commercialized for graphene, giving confidence in the approach. Next, we will characterize the opto-electronic properties of inks of both BP (native p-type) and doped-BP (n-type) with optical emission bands at 660 nm and 940 nm wavelengths required to discriminate between oxygenated and deoxygenated blood. Electrical transport meeting sheet and contact resistance metrics in line with existing commercial devices will be targeted. The final prototype LED devices will be printed onto a silicon photonics chip using aerosol jet printing. **This advance will represent the first ink-printed BP LEDs on silicon chips.**

New Capabilities: The success of this project will illustrate how printed photonic inks can enable silicon photonics to reach its full potential as a transformative technology. An integrated pulse oximeter will be a major step toward sophisticated medical, non-invasive devices that will improve patient outcomes and provide more relevant health data per dollar. At scale, our new photonic chip medical sensor platform will enable access to affordable, state-of-the-art medical care for people all over the world. This advances here have the potential to be used in the broadest terms and across industries. Printable photonic inks solve one of the most important outstanding problems in silicon photonics platform. Namely, the need for an on-chip gain medium applications requiring multi-wavelength operations including environmental monitoring, communications, and quantum photonics. Finally, the photonic inks expand the reach of additive manufacturing and open the way for printed opto-electronics.

Pradeep Subedi, Ph.D. Iris Light Technologies, Inc.

Name of the proposal:

Ultra-low loss, all-fiber, acousto-optic isolators and circulators (LowLoCircl)

Category: Information

Applicant: Riccardo Pennetta, Humboldt University of Berlin

Executive summary

The introduction of low-loss optical fibers probably represents the single most important advance in the growth of our current global telecommunication system, which, in turn, fostered the rapid development of all kind of novel and more efficient fiber-based optical components. To meet our growing demand for secure communication and to interconnect future quantum computers, it is likely that our "classical network" will soon operate side by side of a so-called "quantum network", which, extremely sensitive to loss, poses new constraints and challenges to the performance of existing fiber devices. In particular, already demonstrated quantum networks prototypes explicitly pointed out a surprising flaw in our current fiber technology, namely the absence of low-loss non-reciprocal fiber components (i.e., isolators and circulators). To date, the best commercially available fiber-coupled circulators rely on free-space optics and feature high insertion-loss of approximately 1 dB at telecom wavelengths, which only increases for NIR and visible light.

Proposed project

In this project, I propose a solution to this pressing technological challenge by designing and fabricating novel all-fiber non-reciprocal devices based on acousto-optic interaction. These devices will combine ultra-low insertion loss (<0.1 dB), large extinction ratio (at least 20 dB), polarization independent operations and no frequency shift of the transmitted light. They will be built from standard single-mode fiber and therefore could be readily integrated into existing fiber networks. Furthermore, they will be electrically switchable and reconfigurable within a response-time smaller than 100 µs.

The elementary units of my proposal are so-called fiber null-couplers. In brief these are fiber couplers, whose splitting ratio can be controlled via acoustic waves traveling along the coupler waist. It is well known that the acousto-optic effect breaks Lorentz reciprocity if the acoustic frequency is large enough, i.e., of the order of 1-10 GHz for fiber-based devices. However, in practice, it is really challenging (and not yet demonstrated) to excite such high frequency waves in optical fibers via electrical actuation, an imperative requirement for any technologically relevant device. In this proposal, I show that, some unique and, so far, unexplored properties of null-couplers allow to break Lorentz non-reciprocity with acoustic waves of any frequency. As a consequence, I demonstrate how this concept can be applied to the design of novel electrically-actuated all-fiber isolators and circulators with ultra-low loss.

Intended outcomes

The most striking feature of the proposed devices is their ultra-low insertion loss, which is comparable to the one of standard fused couplers (< 0.1 dB). For this reason, these non-reciprocal devices could become a new technological standard for all optical systems in which low-loss are key, as in particular for current and future quantum networks. Indeed, after an initial phase of careful design and parameters optimization, the future of these devices could go beyond the pure research environment, due to the relatively simple and potentially low-cost fabrication procedure.

Executive summary

- **Challenge**

  Portable diagnostic or therapeutic devices based on purely microwave or optical analysis have proved their importance in health monitoring and remote health care services. But these devices lack versatility of applications and their range of operation is restricted by the inherent limitations of each technology. None of these devices are useful to monitor the condition of inner organs like kidney, liver, lung, bone, muscle, brain etc. Integration of the microwave and optical technologies can bridge this gap and can expand the scope of remote health care for a plethora of medical issues. This integration requires measuring the frequency of the microwave signal with high precision. Photonic measurement of microwave signal is a well-known research field and progressed a lot in recent years. But none of the reported techniques meet the three main criteria such as low fabrication cost, high precision and possibility to realize on an integrated photonic circuit platform simultaneously to translate this technique for our vision in healthcare applications. The challenge is to optimize the photonic technology, satisfying all these prerequisites such that the technology can be utilized to provide a personal diagnostic or therapeutic healthcare device which is presently unavailable.

- **Proposed project**

  Our proposal is to integrate microwave and photonic technology to design a low cost portable diagnostic or therapeutic device to monitor different health conditions which is otherwise impossible with conventional personal healthcare machines. We shall use a microwave wearable antenna to probe the target. Any change happening in the target will be manifested by a change in dielectric property of the target. Hence the received microwave signal will be frequency shifted. Our previous simulations predict this shift may range from tens to hundreds of KHz. Such small frequency shifts cannot be tracked by any available RF measurement technology. On the other hand, an optical signal modulated by RF signal can be utilized to track the frequency change of the modulating RF signal. We shall utilize this property to design a photonic arrangement to measure the RF signal frequency with required precision. First we shall produce a proof of concept photonic arrangement. Next the proof of concept design will be tested with known microwave signal inputs. After this the design will be tested with real time data available from the microwave wearable device placed on human phantoms with specific conditions. Finally, the design will be fabricated on an integrated circuit platform and will be tested for validation.

- **Outcome**

The outcomes of the project can be divided in short term and long term outputs.

Short term outcome:

1. An integrated cost effective photonic device for measuring instantaneous RF signal frequency in a limited bandwidth with very high precision.

Long term outcome:

2. A portable, cost effective photonic-microwave device for self-assessment of health disorder to facilitate self-monitoring and remote diagnosis.
3. A low cost device for frequency measurement of RF signal which may be utilized in various other applications like communication engineering, military applications etc.

Executive Summary

Nanophotonic scintillators for low-dosage X-ray imaging of sensitive materials and particularly its medical application in PET-CT scanners

The purpose of our research is to develop a new kind of scintillators that are based on novel concepts in nanophotonics. Such scintillators will be orders of magnitude more efficient than those available today in medical imaging, particularly for CT and PET-CT scanners. Such a breakthrough will lower the dose rate of X-ray radiation inflicted on patients, which is especially critical for leukemia patients during diagnostics. Scintillators convert X-rays to easier detectable light, usually in the visible domain. The efficiency of this conversion is a bottleneck limiting most of the technology in this field. Our approach can increase brightness, sharpness, and conversion time, which is very important for the medical application of PET-CT scanners. The Optica award will enable us to participate in the 10-ps international challenge, aiming to shorten the scintillators conversion time to a regime that will revolutionize PET scans and all applications of time-of-flight detectors. We propose to achieve this goal by introducing the phenomenon of superfluorescence to the field of scintillators. This concept has been proposed in theory by our group, but has not been shown experimentally so far. Being based on fundamental science, our project is high-risk–high-gain, hard to finance by conventional means, yet having the potential for a major advance in medical imaging.

To achieve this ambitious goal, we will use the award as a stepping stone that will help us establish a new collaboration between international academic groups and health care industrial partners such as the PET-CT scanner division of the GE corporation. A very broad range of testing instrumentation and material production methods are available at Technion's inhouse facilities. The X-ray testing environment has been conceptualised and built by the applicant of this proposal in our own laboratory. The central tool of the project is a proprietary X-ray imaging microscope that is specially designed to characterise the performance of scintillation materials, which will be tested in real PET-CT scanners. With this instrumentation, we have recently achieved the first demonstration of the enhancement of the conversion efficiency by means of the Purcell effect in nanophotonics – showing the feasibility of the high-risk ideas of this proposal. The grant support will enable us to purchase a sensitive EM-CCD and an X-ray tube equipped with a polycapillary half-lens for parallel X-ray beam collimation. This equipment will enable us to achieve **superfluorescence-based scintillation**.

Executive Summary

As an all-solid laser device, fiber lasers play a pivotal role in advanced manufacturing industry especially in the fields of space science, earth and environment science, medical and life science, due to the intrinsic advantages such as good beam quality, high lasing efficiency, compact structure and low energy consumption. The modernization of advanced fiber laser would become a powerful technical tool for mankind to further understand and transform the world. On the other hand, for free space science technology, such as space laser communication and remote sensing, light passing through a long-distance transmission would inevitably encounter the atmospheric turbulence, the cloud and the smoke which would cause strongly loss for the beam power and the interference for the information carried by the light wavefront due to the scattering effect induced by the inhomogeneous media. Therefore, it is of great importance for the free space science technology to further study the long-distance free space transmission based on the novel fiber laser light source which could mitigate the above limitations to some extent.

In the past decade, random fiber lasers (RFLs), featuring as an open-cavity structure, have attracted considerable attention due to the unique properties. In typical RFL configuration, random distributed Rayleigh scattering provides the optical feedback, while the stimulated Raman scattering (SRS) or active gain mechanism in rear-earth doped optical fiber provides the gain amplification. Therefore, no resonant cavity is needed in RFL, since the fiber itself bears with the three crucial components (i.e., the gain medium, the feedback mechanism and the optical confinement) for the lasing process. Thanks to the release of constraints from the conventional resonant cavity, various applications based on the concept of RFL have been innovated such as the generation of special lasing wavelength, high power/efficiency output, low noise lasing and remote distrusted amplification. It is worth noting that by combining the high power/high spectral density and the low coherence features RFLs have been revitalized recently in the fields of high-power low coherence light source, speckle-free imaging, temporal ghost imaging and speckle correlated imaging.

In view of the above background, here in this proposal we focus on the research of digital fiber laser propagating through long distance free space transmission. The RFL based seed light source and possible modulation techniques could be integrated deeply by optimizing the wavelength, linewidth, power and polarization features of the lasing output, along with introducing the wavefront shaping and spatial coherence modulation techniques in order to realize high power low spatial coherence lasing light source that is preferable for long distance space transmission. Meanwhile, the retention characteristics of both the average beam power and the carried wavefront information passing through inhomogeneous medium would be considered comprehensively. We aim to provide alternative option of digital fiber laser light source that enables long distance transmission in the atmosphere for the development of space science such as free space laser communication and remote sensing.

Executive Summary

Stress is a unique individualized experience that can both cause a disease and exacerbate existing neuropsychiatric diseases such as mood-, substance use-, and eating disorders. The global COVID-19 pandemic has caused affective disorder prevalence to balloon, and it is expected that numbers will continue to rise at alarming rates in the coming years. Despite this clear urgency, neuroscience research has shown painstakingly little progress when it comes to diagnoses, prevention, and prognosis of stress-related disorders. Sophisticated optical approaches must be adopted to understand how- and which- dysfunctional brain circuits drive affective disorders. Light sheet microscopy has emerged as a powerful tool to image large intact samples with high resolution. Used in conjunction with optogenetic and genetic manipulation strategies, light sheet micrscopy provides a unique opportunity to perform large scale functional and structural circuit mapping with single cell resolution.

Why are certain individuals susceptible to stress disorders, while others appear to be resilient? Early detection of stress effects on the brain can help predict affective disorder vulnerability and improve precision of interventional strategies. Using targeted functional brain imaging to characterize an individual as being 'high risk' for developing an affective disorder or stress-induced relapse in a patient with a substance use disorder can dramatically impact individualized treatment strategies, reducing the cost burden of treating affective disorders *after* they manifest. Achieving this goal begins with robust preclinical models that are conducive for innovative optical imaging approaches with novel viral labelling and biosensor technologies. These studies are optimally designed for using holistic, environmentally controlled approaches to unbiasedly characterize brain networks regulating the larger stress response. To this end, our goals are to 1) elucidate unique brain circuit biomarkers impacted by stress, 2) characterize distinct stress-specific neuronal ensembles within these circuits, 3) identifying potential key sex differences in stress response brain circuitry, and 4) isolate circuit- and ensemble-specific biomarkers that can predict- and be targeted to prevent or mitigate- stress disorders.

This project will use whole brain light sheet microscopy and neuronal ensemble-specific optogenetics to identify and manipulate stress ensembles in the mouse brain. We will gain unparalleled insight into the mechanism underlying stress disorders, paving the way for improved prevention, diagnosis, and treatments.

Aim 1: Identify whole brain stress-activated ensemble circuitry using light sheet microscopy with automated high-resolution single-cell brain atlas registration. We will use a genetic mouse line, FosTRAP2, that facilitates permeant access to transiently active neurons to isolate and fluorescently-tag stress-activated neurons in the mouse brain. Once tagged, these brains will undergo delipidation (i.e., "clearing"), whole brain imaging with light sheet microscopy, and automated machine learning-based single cell detection, quantification, and atlas registration. Accordingly, we will develop and provide a comprehensive database containing the location of all stress activated neurons in the male and female mouse brain.

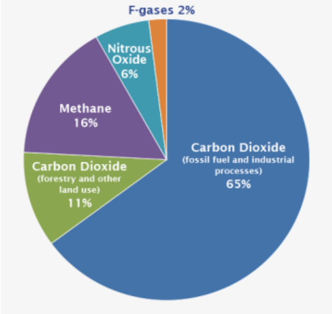
Aim 2: Use optogenetic inhibition of the insula to assess the effects of "removing" this network hub on anxiety-like behavior. We and others have identified the insular cortex (insula), a cortical area intimately involved in emotional regulation, sensory processing, valence, decision making, and many other behaviors, as an affective network hub that regulates amygdalar circuitry. Aim 2 will zero in on insula stress ensembles to determine if optogenetically inhibiting this population of cells can prevent the emergence of negative affect in mice.

This highly translational and reverse-translational approach has the potential to shift how affective disorders are diagnosed and treated by defining biomarkers early in disease progression. Understanding how stress impacts the brain at a molecular and circuit level *before* affective disorders manifest can vastly improve strategies to mitigate the long-term impacts of stress and identify those at risk for developing affective disorders.

Low-cost and miniaturized mid-infrared photonic chemical sensing platform for continuous ecosystem monitoring

Samuel Serna (Bridgewater State University)

Figure 1: Global greenhouse gas emissions [1]



- Climate challenge problem: Based on Environmental Protection Agency (EPA) studies (*Fig. 1*), **G**reen **H**ouse **G**ases (GHGs) like carbon dioxide (CO_2 at 76%) and methane (CH_4 at 16%) are the highest polluters of the environment today [1], contributing significantly to our current climate crisis. Since "*we need to measure to define policies for effective change*", this project emphasizes sensing technology and readout analytics to "monitor" as well as "predict" when GHG emissions exceed threshold values. Real time detection of "above-threshold" GHG emissions is more actionable than historical, slowly varying data. In addition, the determination of GHG type, its concentration and geographical site will enable efficient mitigation strategies. However, such a comprehensive distributed and networked GHG monitoring and predictive detection system does not exist today.

- Solution: We propose to build low cost mega-distributed and networked monitoring and predictive sensor arrays for real time detection of GHGs, providing information on chemical specificity, concentration, and geographical site, with data accessible on cellphones via integrated photonic circuits fully integrated with the source, detector and read-out electronic system, designed to work in the mid-infrared region, where GHG have their characteristic fingerprints.

- Impact: With real time and site-specific detection of "above-threshold" GHG emissions, leaks can be fixed in a timely fashion. Farmers can modify their cattle fodder in real-time to reduce methane gas emissions. Massive deployment at low-cost is possible due to foundry manufacturing of sensor arrays and will enable continuous monitoring of the soundness of our environmental ecosystem. For example, for methane, this project can lead to redesign of human intervention in the carbon cycle ecosystem by providing real time on-site emissions data for both fossil methane (20%) and methanogens (80%) based on chemical flow data, industrial practice as well as governmental policy and regulation.

- Vision: We envision a system of mega-distributed and networked planar sensor arrays based on miniaturized **P**hotonic **I**ntegrated **C**ircuit - **Ch**emical **E**nvironment **M**apping (**PIC-ChEM**) technology to detect site-specific GHG emission concentrations in real time, for both monitoring and prediction. The use of PICs and integrated detectors will allow the implementation on mobile devices.

- Technology: Photonic integrated circuit sensors (PIC sensors) monitor changes in the optical properties (refractive index, phase, polarization, intensity, wavelength) of photons transmitted through on-chip waveguides [2]. With each sensor we can measure changes in intensity at specific wavelengths (also called on-chip absorption spectroscopy), providing information on a specific GHG and its concentration. With large, low cost, manufacturable planar arrays of such miniaturized sensors, we can perform simultaneous multi-species detection. Distributed and networked sensor arrays can allow us to gather data from multiple locations simultaneously. Prototypes will be fabricated with dies from a commercial foundry, showing the potential for massive distribution. Machine Learning (ML) algorithms can be leveraged to recognize patterns for different gases and provide real time site-specific concentration data on each GHG [3]. Our envisioned sensing system can be placed on an Unmanned Aerial Vehicle or a drone, both desirable due to their low Size, Weight, Power and Cost (SWAP-C).

- Prior established art: Integrated photonic gas sensor that can detect 200 ppm of methane gas at room temperature using on-chip absorption spectroscopy has been demonstrated with the proposed technology [4]. Near-infrared (NIR) on-chip digital Fourier transform spectrometry (dFT) [5] and large scale foundry manufacturability have also been demonstrated. The principal obstacles that will need to be overcome to accomplish our method at scale include the development of on-chip integrated light sources, Read Out Integrated Circuits (ROICs) [6], ML/Neural network algorithms, implementation of mega-distribution, and creation of networked sensors with data accessible by cellphones.

References:

[1] https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data
[2] Marris-Morini, et al (2018). Nanophotonics, 7(11), 1781-1793.
[3] Tânia F. G. G. Cova and Alberto A. C. C. Pais, Front. Chem., 26 November 2019
[4] Su, Peter. MIT PhD Thesis, DMSE, May 2020
[5] Kita, Derek et al (2018). Nature Communications 9:4405.
[6] Guglielmi, E.,et al (2021) Journal of Lightwave Tech, 39(22), 7326-7333.

Summary. With the OPTICA 20th anniversary challenge, we will demonstrate ***the world-smallest laser particle operating in human physiological conditions***. Such virus-sized nanolaser will be delivered into the cytoplasm of the living cells and emit ultranarrow laser emission for a unique spectral nametag. This new optical probe resolves the color limitation of fluorescent probes and opens new avenues in multiplexed biomedical studies for drug development, disease diagnostics, and high-resolution tissue imaging.

Fluorescent probes are ubiquitous for bio-labeling and spectrum-based assays. Despite the easy usage, their broadband emission due to the intrinsic quantum nature (spectral linewidth 50~100 nm) limits the multiplexing ability to only a handful of resolvable colors. This small color palette often restricts the number of unambiguous color tagging and comprehensive understanding of the single-cell state characterized by various biomarkers. To address this issue, my lab colleagues and I have worked on intracellular microlasers, which are tiny enough to go inside the cells and generate ultranarrow laser emissions with a linewidth of 100 to 1000 times narrower than fluorescence following optical excitation. Thick silica surface coating made color tags insensitive to surroundings. Therefore, we could track the movement of thousands of living single cells tagged with microdisk lasers within the breast cancer organoid using hyperspectral microscopy.

Reducing the size of laser particles to the nanoscale is highly desirable because it will minimize the perturbation of homeostasis and allow more probes to be tagged to a single cell. The nanosized particle will prevent any obstructions in microvessels while it is traveling in the bloodstream. Delivering multiple nanolasers in a single cell will dramatically increase the number of spectral nametags. This strong motivation in biomedical application shares same goal of laser miniaturization with fundamental nanophotonic research and industrial application in on-chip integration, display, and photonic computing.

My early postdoctoral work in plasmonic-assisted laser miniaturization laid the foundation for this unique idea. Plasmonics is considered one of the promising ways for subdiffraction-limit laser. The evanescent light on the metal surface can be amplified to generate an ultrasharp laser emission. Nevertheless, almost all the plasmonic lasers demonstrated to date have needed the gain medium to be >1 μm because of the large cavity loss. Recently, we demonstrated the smallest plasmonic laser in volume by placing a perovskite semiconductor nanocube on the gold substrate. The size was equivalent to the emitted wavelength of light. We also found so-called beneficial plasmonic effect, in which strong light and matter interaction in plasmonic nanocavity boots up the brightness of the gain material to continue the miniaturization.

Here, we propose the 1-2 year period project to make exciting innovations on nanolasers for biomedical study. The experimental approach is highly interdisciplinary as it brings together the knowledge and the tool from both plasmonic physics, nanochemistry, and cell biology. Our project has one specific aim below.

Aim 1: Demonstrate biocompatible plasmonic nanolaser particle. The plasmonic laser devices have been prevented from stand-alone usage because of the necessity of the metal substrate and metal sputtering on the semiconductor structure on the substrate. In addition, the perovskite material we used in the previous demonstration is limited for the biological environment due to water solubility and toxic lead ions. In this aim, we will develop a three-dimensional (3D) plasmonic nanolaser particle by coating optically thin gold on the surface of the water-insoluble III-V semiconductor nanodisk. This new material combination between near-infrared gain and plasmonic metal is expected to maximize the beneficial plasmonic effect. Pico-second optical pumping will help accumulate as many as Purcell-accelerated carriers in population inversion states to lower the threshold. Therefore, we will break our previous record to achieve a sub-400 nm scaled stand-alone laser whose volume is reduced by ~ 30 folds from the state-of-the-art substrate-supported plasmonic laser. We will evaluate the biocompatibility of the plasmonic nanolaser and conduct proof-of-concept experiments for tagging developed tiny lasers into sub-micron-sized immune Jurkat T cells and functionalizing the nanolaser surface with biological molecules.

Executive Summary

Human Breath Analysis: Frequency Comb-based Non-Invasive Biomedical Diagnostics

The exhaled human breath contains a remarkably complex mixture of gases and is an unparalleled window into the health of the individual. If harnessed, medical breath analysis promises to be a powerful and inherently non-invasive diagnostic tool. A portable device capable of quantitatively detecting molecular species characteristic to certain disease states (biomarkers) within the exhaled breath would have the potential to transform medical care: allowing the early detection of disease, easier screening, and faster medical intervention in a variety of contexts - ultimately improving the health and prognosis of patients worldwide. However, there is currently no compact, low-cost, deployable breath analysis device with the molecular sensitivity and selectivity to provide medically relevant information across multiple disease states for point-of-care use by clinicians in real time. This project aims take a critical step towards this ideal, creating a prototype optical sensor with the required molecular sensitivity and selectivity for medical breath analysis, while remaining compatible with future compactification efforts.

There is currently a great push to develop and apply photonic technologies to medical breath analysis measurements. However, it is a challenging task to achieve the required selectivity, sensitivity, and broad use cases while maintaining a small device size. This project will explore the use of a near-ideal optical interrogation source for molecular spectroscopy dual near-infrared electro-optic frequency combs. Previous experience in the design, construction, and utilisation of near-infrared optical frequency combs for molecular spectroscopy - and their application to medical breath analysis – has demonstrated that the near-infrared absorption features of important biomarkers are too weak without optical enhancement. Instead, these electro optic combs in the near-infrared will be converted to the 1000x more spectroscopically sensitive mid-infrared spectral region with a nonlinear crystal, removing the need for an optical enhancement cell that traditionally hampers the compactification efforts of optical breath analysis devices. In addition, the use of two combs allows for the performance of dual-comb spectroscopy, replacing another traditionally bulky (and difficult in the mid-IR) component – the spectrometer responsible for unravelling the absorption of the interrogating light at each frequency – with a simple photodiode and radio-frequency components. This project will allow us to demonstrate the first proof-of-principle of a device that can deliver on the long-term dream to create a photonic non-invasive, affordable, portable quantitative diagnostic tool.

This technology has the promise to provide a future low-cost, compact, deployable device with sufficient molecular sensitivity, accuracy, and selectivity to provide medically relevant information to the clinician in a variety of contexts.

At the completion of the project, we will have advanced the frontier in precision spectral analysis and created a compact prototype breath analysis system in the mid-IR that is 1000x more sensitive than its near-infrared counterparts. Additionally, the proposed methodology is compatible with future photonic chip integration, opening the doorway for the development of a robust, compact, low-cost and lightweight breath analysis device suitable for rapid breath analysis for clinical use. This has the potential to have a transformative impact on applications ranging from pre-symptomatic disease detection and diagnosis, critical patient monitoring, measurement of human fitness, performance and compliance testing, breath fingerprinting, and other gaseous measurement applications beyond breath analysis.

Executive Summary

The focus area of NECTO is *information*, with a specific challenge of development of a new integrated photonic device to protect the digital-infrastructure from the anticipated data-traffic congestion crisis of the Internet-of-Things (IoT) era. There will be more than 29 billion IoT devices in 2030, more than double the 2021 figure. These devices will drive an exponential increase of data-traffic. Ericsson predicts a 4-fold increase of global data traffic from 2021 to 2027 with a significant portion of such traffic for the purpose of performing Artificial Intelligence (AI) tasks, like pattern recognition, in the cloud. To date, there is no compact digital-computing platform which can perform AI tasks on a high-throughput massively parallel data stream in real time – this is the main reason why data must be transferred to the cloud.

To overcome such a Challenge, NECTO will develop a new truly compact photonic chip to perform AI tasks on a high-throughput massively parallel data stream at the 'edge' of the data infrastructure landscape – *edge*, here, means at the point of data collection. Thus, by performing AI directly at the point of collection, demand for cloud computing services will be reduced. The proposed photonic computing chip is inspired by how humans process and infer information, i.e., neuromorphic. It will be developed on all-passive components exploiting chaotic light dynamics, whereas other reported chips are based on heat-generating active nonlinear components. Thus, the new chip will be a truly compact system. The new chip is envisaged to impact other technological areas, for example, micro-satellite computing – it will be immune to space radiation, not heat-generating, low-size, low-weight, low-power and low-error rate.

To realize such a chip, a high-quality factor cavity exhibiting chaotic wave dynamics is central. Therefore, minimizing loss is key, and it has shaped the workplan of this project. The chip will be developed on a silicon-on-insulator platform, capitalizing on the well-established integrated photonic fabrication processes. To suppress radiation loss and maintain light confinement, a symmetric (z-direction) cavity will be developed on a photonic crystal platform. Insertion loss will be minimized by developing a new impedance matched mode-converter between the photonic crystal and silicon strip waveguides using the recently reported inverse design technique. High-quality fabrication of the chip will be performed in world-class partner iMEC, Belgium. It will be packaged and fixed with a high-coupling input/output interface in the world-class packaging facility, National Tyndall Institute, Ireland. The prototype will be demonstrated for two key AI applications, namely nonlinear wireless communication signal equalization and pattern-recognition of sensors' signals. In my previous research, pattern-recognition of sensors' signals has been performed using a 'bulky' version of neuromorphic computing system in the lab; the compact neuromorphic chip will underpin the realization of an *offline* wearable sensor.

The 20th Anniversary Challenge from Optica will enable Dr Phang, an early career researcher, to embark on a novel and adventurous journey marrying chaos wave optics with photonic neuromorphic computing. Dr Phang has developed his career on cross-disciplinary research encompassing computational photonics, information photonics, chaotic electrodynamics, wireless communication, machine learning and photonic neuromorphic computing. Optica Challenge funding will enable Dr Phang to conduct frontier research in collaboration with world-class international partners, iMEC and the Tyndall Institute. Dr Phang will capitalize on his involvement in complementary research projects like the flagship H2020-Rise6G wireless communication and a British Council project on photonic sensing for environmental monitoring to demonstrate the photonic neuromorphic technology as a key-enabler in the areas of information-and-communication and environmental monitoring. He will be supported by an advisory group to help him engage with academia and industry, bring photonic neuromorphic computing through the technological development process, and extend the impact of the neuromorphic photonics in other areas, like light-matter interaction and hyperspectral imaging.

Nanoscale nonreciprocal photonic components

CATEGORY: Information

The project aims to develop new ways to control light in *nonreciprocal* [1] ways, similar to ways we control electricity with modern semiconductor technology. Nonreciprocal behaviour of light is difficult to achieve, and it is currently limited to relatively large systems, representing a roadblock for making light-based information technologies and devices smaller, cheaper and more energy efficient. Expected outcomes of this project include first demonstrations of nonreciprocal control of light by tiny devices made with nanotechnology. The outcomes should progress the development of vital next-gen information and communication technologies (ICT).

Nonreciprocal components, including isolators and circulators are indispensable components for communication systems. Although, free-space nonreciprocal components are currently available commercially, their miniaturisation and on-chip integration has proven to be a challenge. 21st century information and communication technologies might depend on nonreciprocal optical isolators and circulators as much as 20th century ICT developments depended on nonreciprocal semiconductor diodes and transistors.

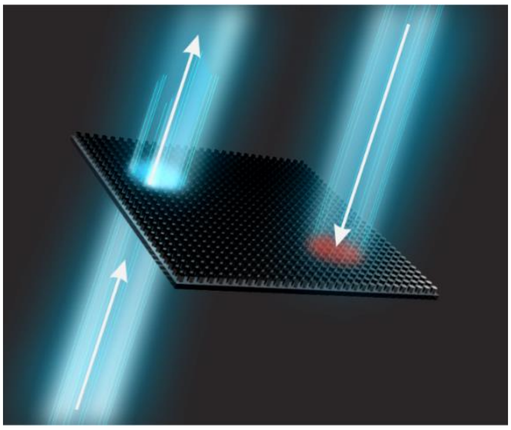


Fig. 1. Concept image of nonreciprocal transmission of light through a metasurface.

The project proposes to miniaturise nonreciprocal optics with metasurfaces made of novel emerging material platforms for nonlinear optics. Recently, metasurfaces, often 100 times thinner than a human hair, made a tremendous progress from fundamental concepts [2] to mass-fabricated consumer products [3]. Today, new frontiers in metasurfaces research are being actively explored is nonlinear optics which changes the basic principles of interaction between light and matter, including reciprocity breaking. I recently demonstrated nonlinear metasurfaces with asymmetric generation of optical harmonics [4]. With this project, I aim to build upon this progress to achieve nonreciprocal self-action. For this I will incorporate into the design novel photonic material platforms of two categories: epsilon-near-zero materials and phase-change materials – both of which offer giant nonlinear self-action effects compared to more standard Kerr-type nonlinearities of dielectrics. I will deliver laboratory demonstrations of first nanoscale nonreciprocal metasurfaces and will perform their characterization.

INTENDED OUTCOMES: The project aims to fill knowledge gaps enabling manufacturing of sub-micrometre small nonreciprocal optics, such as optical isolators and circulators. The project will deliver isolators operating at low intensities (mW) of continuous-wave (CW) light sources. The isolator designs will be compatible with standard nanofabrication technologies. The research outputs will be disseminated via peer-reviewed publications in premier journals and presentations at reputable conferences and congresses.

APPLICATIONS TO REAL-WORLD ISSUES: The developed nonreciprocal components based on nonlinearity will be fully passive and self-biased, which makes them ideal in applications for pulsed or periodic operations, such as in optically controlled transmission switches, directional filters and power limiters, as well as chip-scale LiDARs.

[1] C. Caloz et al., "Electromagnetic Nonreciprocity" Phys. Rev. Applied 10, 047001 (2018).
[2] S. Kruk and Y. S. Kivshar, "Functional meta-optics and nanophotonics governed by Mie resonances," ACS Photon., 4, 2638 (2017).
[3] Products - Metalenz https://www.metalenz.com/products/
[4] S. Kruk et al., "Asymmetric parametric generation of images with nonlinear dielectric metasurfaces" Nature Photon. 16, 561–565 (2022).

EXECUTIVE SUMMARY

Project Title: **X-ray Quantum Nano-Tomography for Medical Imaging**

Sergio Carbajo, Assistant Professor
UCLA, Electrical & Computer Engineering
UCLA, Physics & Astronomy
Stanford University, SLAC Photon Science

The science of X-rays is over 125 years old, starting with Wilhelm Röntgen's discovery of X-rays in 1895 rendering the first Nobel Prize in Physics. X-rays have fundamentally impacted humankind in many scientific and technological areas and have so far been responsible for over 25 Nobel Prizes in Physics, Chemistry, and Medicine-Physiology.

The ubiquitous use of X-ray technology in commercial applications, airports, and hospitals may seem to declare that there's little left to discover regarding the fundamentals of X-ray science and its applications in medical imaging and therapies. But recent work in quantum electrodynamical (QED) theory has revived interest in studying new, non-intuitive regimes to record X-ray images as a means to revolutionize coherent tomographic (CT) imaging, one of the most powerful imaging techniques today known as CT scans recognized with saving hundreds of thousands lives from cancer screening in the US alone. Through the Optica Foundation 20th Anniversary Challenge, we aim to demonstrate a novel nanoscale quantum tomographic X-ray technique to disrupt the current X-ray medical imaging paradigm and expand to emerging applications in life sciences and beneficial cost-accessibility tradeoffs relative to comparable commercial and medical instrumentation.

This project presents two specific near-term objectives for future nanoscale, high-brightness X-ray imaging techniques based on tomographic QED:

- First, we will experimentally demonstrate that X-ray emission through quantum interference of electrons is possible from a quantum electrodynamical standpoint for the first time. This foundational physical demonstration will confirm that it is possible to tune the X-ray emission wavelength up to 10s of keV as well as the emission monochromaticity and directionality by shaping electron wavepackets interacting with nanoscale materials.
- Second, we will extend this demonstration to the interference of two coherent near-field X-ray tomographic images by arising from an electron wave packet shaped to produce multiple distinct, coherent X-ray pulses. Exploiting the quantum interference produced by the wavepackets, we will obtain and reconstruct tomographic images with nm-scale resolution and element specificity with a far lower dosage compared to state-of-the-art CT scans.

Our approach constitutes a novel electron-photon quantum interference method that will become an important tool not only for nanoscale X-ray imaging devices but also for operando diagnostics and endoscopic radiation therapies. Technologically, we anticipate a novel, ultrabright X-ray source that dramatically reduces the cost and size, is fully integrable and portable, and offers a power and energy scalable architecture to enable on-chip and integrable hyperspectral X-ray frequency combs. Our aims may also open the door to the engineering of quantum-level controlled X-ray sources and their real-world applications including ultrafast microscopy, quantum simulation, compact XFELs, quantum-level semiconductor lithography, atom-by-atom matter assembly, and a plethora of new and old theorized nanoscale radiation sources.

Asymmetric Pharmaceutical Synthesis with Molecular Hall Effect

Shoufeng Lan, Texas A&M Engineering Experiment Station, Texas A&M University

Overview: More than 80% of U.S. Food and Drug Administration or FDA-approved commonplace pharmaceuticals such as ibuprofen carry an inherent flaw, pairing the active and beneficial ingredient with an ineffective or toxic counterpart. The underline mechanism is chirality, which discerns the dissimilarities between objects and mirror images. One prominent example is human hands because the left hand is the mirror image of the right hand, but they are not superimposable. Each handedness or so-called enantiomer of chiral objects should have the same probability of occurring, like the left hand and right hand always appearing in a pair. Unfortunately, the pairing of left- and right-handed chiral materials might not be favorable or often detrimental in the pharmaceutical industry, for example, the thalidomide tragedy that led to more than 10,000 birth deformities in the 1960s. Therefore, asymmetric synthesis, or selecting/sorting one enantiomeric handedness over the other, is a pressing need yet a grand challenge for human health and the pharmaceutical industry. According to the symmetry principle, the asymmetric synthesis should have a fundamental force (i.e., electromagnetic, gravitational, strong, and weak) to break the symmetry. The only one that breaks the parity-inversion symmetry is weak interaction. That is why all atoms are slightly left-handed, and indeed it results in enantiomeric excess, however, on the level of thermal fluctuation. Emulating the weak interaction using light and magnetism, we found a new magneto-chiral effect (MChE) that is several orders of magnitude stronger. Although the MChE could lead to enantiomeric excess in principle, implementing it for practical applications in asymmetric synthesis is a daunting task, which is also the challenge we will address. To that end, we have three specific objectives based on our recently published works on the MChE. (**1**) Electromagnetically induce enantiomeric excess by developing a plasmonic magneto-chiral system. (**2**) Dramatically enhance the plasmonic MChE with nanostructures to achieve an unprecedented spatial separation of chiral pharmaceuticals, which we named the molecular Hall effect. (**3**) Obtain enantiopure pharmaceutical molecules with on-demand handedness fully controlled by light and magnetism. Like the electronic Hall effect that lays the foundation of modern electronics, the molecular Hall effect could contribute to asymmetric synthesis, hence the pharmaceutical industry and human health.

Outcomes and Unique Aspects: Our proposed research will produce a universal physical means to separate chiral objects for asymmetric synthesis – in stark contrast to current techniques that use existing chiral objects (e.g., catalysis for the 2001 and 2021 Nobel prizes in Chemistry) to biologically and chemically transfer handedness. These chemical and biological methods are expensive, may only apply to specific molecules near the asymmetric center (proximity effect), or may damage more complex molecules with multiple chiral centers. Due to its physical rather than chemical or biological nature, our proposed method can enable all chiral species to be selectively sorted by their inherent handedness, potentially achieving absolute enantioselectivity. Also, the research will generate a molecular Hall effect from our proposed plasmonic magneto-chiral technique, providing the elusive spatial separation of chiral molecules favorable for asymmetric synthesis in pharmaceutical manufacturing.

Potential Impact: To the scientific community, the proposed research will introduce a relatively unknown phenomenon called plasmonic MChE, enhanced by momentum matching and directionally controlled by the polarization of light. With broader impacts, it can also lead to the cost-effective production of a wide range of enantiopure drugs. As 80% of FDA-approved drugs are chiral, our technique can play a role in the pharmaceutical industry and human health in general. Also, since the predicted global market for asymmetric synthesis is ~133 billion dollars by 2030, our research can contribute to the U.S. and the world economy.

Executive summary

Title: Mid-infrared laser correction of photonic chips fabrication errors to improve manufacturing yield and reduce energy consumption.

Challenge category: Information

Project summary:
Data consumption is increasing at an exponential pace (2X every 3 years). Standard electronic chips are reaching their fundamental bandwidth limits and the energy consumption of these devices is too important to keep up with the data growth. Over the past years, photonic chips have proven to be a scalable technology that promises higher bandwidth and lower power consumption. Photonic chips are now widely used for transceiver applications in datacenters. However, due to the inherent sensitivity of light, process variations affect the phase of photonic components inside the chip. This problem reduces the manufacturing yield and achievable performances of these devices, slowing down the adoption of the technology. Active thermal tuning techniques must be added to the chip, increasing the power consumption and diminishing the potential energy saving.

Simon Duval, co-founder and VP R&D at Femtum, wants to tackle this challenge with his R&D team by proposing a new mid-infrared fiber laser solution that permanently corrects photonic chips after their fabrication. By exploiting nonlinear refractive index change in silicon waveguides with the proprietary short pulsed mid-infrared lasers developed at Femtum, Simon aims at demonstrating the first resonance tuning of a microring resonator across its whole free-spectral range.

This first demonstration will serve as a building block for correcting various phase sensitive components in photonic chips to reduce power consumption, increase manufacturing yield and enable new, simplified designs. The current project will convince Femtum, its investors and its clients in photonic chips manufacturing to invest more into the development of an automated solution that could be commercialized at scale and that could accelerate the deployment of photonic chip technologies in datacom as well as in quantum computing, lidar and biosensor applications.

About Simon Duval and Femtum:
Before creating Femtum with its partner Louis-Rafaël Robichaud, Simon demonstrated the first mid-infrared femtosecond fiber laser at 2800 nm during its PhD studies at Laval University. While being an industrial post-doctoral fellow at Femtum and Laval University, Simon built an R&D team of 6 people and acquired managing skills. He and his team also developed and matured an industrial nanosecond fiber laser and an application lab that will be used in the framework of this project.

Femtum inc. is a deeptech Canadian startup now incubated at the National Institute of optics (INO). Now 4 years old, the company is the world's first manufacturer of short pulse 3 μm fiber lasers. Femtum technology platform comes out of several decades of research at the Center for Optics, Photonics and Lasers and is currently used for scientific and industrial applications. The company is proud to offer its support to this bold project by allocating human resources and user time in its application lab and for its lasers.

Early detection and monitoring of neurodegeneration via advanced ophthalmic imaging

Neurodegenerative diseases constitute a severe health problem worldwide. Parkinson's and Alzheimer's, alone affect the lives of hundreds of millions of people globally. They impose significant stress on healthcare system costs and limit the level of activity of patients and their family members in the work market, which in turn has long-term financial consequences. Neurodegenerative diseases are progressive and currently not curable, efforts towards their early detection, management and progression prediction are thus crucial.

Recently, our research group has managed to design and build a new fast and precise scanning laser ophthalmoscope capable of recording the fast, delicate motions of the human eyeball with and unprecedented level of accuracy. Our goal is to push the limits of our current understanding of the connection between eye motion (also known as saccadic motion) and the early detection of neurodegenerative diseases and their gradual progression.

Our main objective is to create a clinical-use device based on our laboratory prototype along with protocols that will ultimately result in the pathway towards the popular clinical use of eye motion as diagnostics for early-stage detection of neurodegeneration. We have the proven technical and clinical expertise as evidenced by our group’s current and past work on biomedical ophthalmic devices design, construction and clinical use. Goals include the design and deployment of data acquisition protocols, visual tasks, data analysis and synthesis methods for extraction of features characteristic for various neurodegenerative diseases. We plan to undertake exploratory studies with normal controls and patients in currently collaborating medical clinics. Our clinical efforts will initially focus on data analysis with the goal of extracting collections of candidates for biomarkers of neurodegeneration.

Title: Fiber tip-based surface-enhanced Raman simultaneous pathogen detection in cerebrospinal fluid samples

Category: Health

In-vivo rapid detection and identification of pathogens, such as bacteria, viruses, fungi, and parasites, in patients' cerebrospinal fluid (CSF) samples continue to be a challenge for clinical diagnostics. Bacterial infections can cause death in a couple of hours. According to the latest reports from the World Health Organization, antimicrobial resistance is of major growing public health concern. Resistant bacterial infections alone are associated with nearly 4.95 million deaths per year, with 1.27 million deaths directly attributed to AMR. The latter occurs when bacteria, viruses, fungi, and parasites change over time and no longer respond to medicines. Hence, it is crucial to directly identify and distinguish pathogens' origin and to monitor the treatment response to their resistance. Current detection methods typically require in-vitro sample monitoring. The most commonly used technique that gives a fully reliable result is polymerase chain reaction (PCR). However, the test is ready within up to four hours and is an expensive bacterial monitoring procedure. On the other hand, bacterial resistance tests and identification are performed through CSF culture examination, which can last up to four days whereas bacterial infections can cause irreversible health damage if the right treatment is not applied. To the best of our knowledge, there is a lack of a rapid, cheap, in-vivo detection method that can immediately distinguish between bacteria and viruses, between types of bacterial infections and meanwhile serve as a tool to monitor a real-time response to treatment. Hence, we propose a label-free and highly specific optical sensor based on Raman spectroscopy. It has recently been tested in our laboratory the possibility to distinguish E-coli and Staphylococcus aureus in the same sample by implementing machine-learning algorithms on the obtained Raman spectra. Nevertheless, to further enhance the signal and precisely detect more variants of pathogens within the same sample, surface-enhanced Raman Spectroscopy (SERS) can be applied. The use of SERS substrates in the identification between N. meningitides, S. pneumonia, and H. influenza bacteria has already been demonstrated. Yet, the mentioned study has been performed in in-vitro conditions. To overcome this problem, we go a step further in this proposal and suggest fiber tip-based SERS substrates that can be placed inside the lower spine through the lumbar puncture and give real-time information on different pathogens present in the CSF as well as show the dynamics of the treatment. The possibility to fabricate SERS substrates on the glass fiber tip using two-photon polymerization (2PP) has already been reported. Therefore, to further bring this technology closer to clinical implementation, in this project we will fabricate SERS substrates on a biocompatible polymer fiber, which can stay in a body without causing additional discomfort. The fiber-based SERS system will be connected to the illumination and collection parts, which will be fully integrated on a polymer platform. A commercially available 785nm laser diode will be used as an illumination light source with up to 50mW output power. The light from the laser to the fiber will be coupled through 2PP printed microlens. On the detection side, the collected signal from the SERS substrate through the fiber will be coupled to the commercial spectrum analyzer. Obtained spectral data will be proceeded with ML algorithms to precisely identify a present pathogen.

This research is possible to realize since Brussels Photonics at Vrije Universiteit Brussel, where I am a postdoctoral researcher, has longstanding experience in fiber and plasmonic sensing, micro- and nanofabrication and biophotonics. The Photonics Innovation Center at VUB has facilities for in-house two-photon polymerization fabrication, micro- and nanostructure metrology and Raman measurements. Moreover, we collaborate with the UZ-Brussel hospital, which provides us with clinical samples from patients. This project will result in a proof-of-concept demonstration that can play a revolutionary role in pathogens detection in CSF saving lives. Finally, through outreach events, the knowledge on bacterial infections and damage to our health will be spread helping to prevent the overlooked pandemic of antimicrobial resistance.

EXECUTIVE SUMMARY

Name of Proposal: SpheroScan: WGM-Enabled Microbial Sensor

Category Addressed: 20th Anniversary Challenge (Optica Foundation)

The physical effect of Whispering Gallery Modes (WGM) changes the way how pathogens can be detected in agriculture and food production. It allows inline monitoring of production processes at any stage of the supply chain, thus establishing an unprecedented level of efficiency, quality, and safety.

SpheroScan, an WGM-enabled sensor system, features capabilities that none of the existing analytical technologies can match, namely:

- very short time to result (< 3 min.)
- on-site process integration
- automated operation independet from a laboratory

The sensor data is immediately actionable to control the production process. Continuous monitoring provides mass data which is a valuable source for process improvements.

This is made possible by an innovative optical technology in combination with microbiological methods. Micro beads from polystyrene are brought to produce the WGM effect when excited with laser light. Such beads with a biologically functionalized surface are added to the liquid analyte and work as highly specific probes. Once the target organism or molecule binds to a bead, its WGM light signature (Fluorescent Resonance Signature – FRS) changes thus giving an immediate indication of the target's presence.

Current quality control methods for pathogens are slow, laborious and give only spotlight data depending on the intervals of probing and the availability of laboratory capacity. It can take up to four days to detect Salmonella in animal products using standard lab-based methods. This means that quality control results typically are only available after production or even after shipping. In case of a contamination, entire lots must be disposed of and the loss absorbed by the manufacturer. If shipped already, consumers can be harmed with more negative consequences for the manufacturer. At this stage, it also becomes a matter of public health. Salmonella infestations alone cause medical costs of about $4.1 billion each year in the USA with over one million cases and close to 400 deaths (USDA: "Cost Estimates for Foodborne Illnesses", 2018).

SpheroScan allows the producer to take action while a process is running (Advanced Process Control). Thus, major savings in raw materials, time and energy can be achieved. It will also make visible the sources and drivers of contaminations (e.g. in the supply chain) and help to reduce . This will raise the awareness for quality and provide the basis for proactive quality management in agriculture and food processing. Hence, we envision food production on a new level of efficiency and quality that will bring food on the consumers' table that is fresh, unadulterated and save at the same time.

Currently, a lab version of the sensor is available to refine the FRS-technology and test it with varying target organisms. Within the Project, a first field demonstrator of an inline measuring FRS system will be built and tested in a first field application, namely Legionella contaminations in fresh water supply. The results of the study will be published in a scientific journal and presented at an international scientific conference.

LIGHTING RESEARCH SOLUTIONS LLC
Research • Education • Design • Development • Verification
www.LightingResearchSolutions.com | Philadelphia, PA 19122 USA

The Earth and its inhabitants deserve darkness

September 12, 2022

Executive Summary
Humans use electric light at night to illuminate our homes, our streets, sidewalks, outdoor sporting events, buildings, facades, landmarks, bridges, parks, parking lots, and commercial and industrial properties. Nearly everything we interact with at night is illuminated. Light at night has become essential to our feeling of security and to our ability to extend our activities into the evening.

But this is not without cost. Outdoor electric light sources placed by humans to illuminate the night—often called *artificial* or *anthropogenic* (i.e., "human generated") light at night (ALAN)—is seriously eroding natural light-dark cycles across the planet, having marked impacts on the biological functions and rhythms of humans, plants, and animals. This includes impacts on mortality (through light attraction or aversion), disruption of migratory and diurnal patterns, increasing or decreasing population size, altering natural competition, disturbing inter-species communication, and negative impacts on human health and well-being.

A significant portion of the Earth's population—especially in Europe and the Americas—now experiences light-polluted nights, which creates a sky glow that limits or eliminates our view of the night sky, poses significant problems for amateur and professional astronomical observations, negatively impacts animals that use the night sky for navigation, and wastes a significant amount of energy at great financial cost. The estimated cost of this wasted energy exceeds USD $7 Billion.

Without serious intervention, the problem is projected to get worse.

The objective of this project is to advance the science in architectural lighting with the goal of developing strategies to reduce the negative impacts of ALAN, to disseminate research findings to spread awareness of these negative impacts, and to develop a lighting standard to minimize the negative impacts of ALAN (especially sky glow).

Corresponding to these objectives, the project will constitute three tasks.

Task 1 | advance research: the goal of this task is to advance research in the field of architectural engineering to provide actionable guidance for the lighting professionals that design and install lighting systems. The outcome of task 1 is a journal-quality research paper that will be submitted to an Optica journal, likely Optics Express. The impact of the work is two-fold: 1. It addresses the problem closer to the source (i.e., the lighting professionals installing lighting systems), and 2. It sends a message to the non-lighting researchers of the world that lighting researchers are interested in protecting darkness for the Earth and its creatures.

Task 2 | disseminate and advocate: to goal of task 2 is to spread awareness of the negative impacts of light at night by participating in up to 5 industry and industry-adjacent events. This will be done by presenting current and future research findings and recommendations. The outcome of this task is a series of educational presentations and scientific reports. The impact of this work is an increased awareness and sensitivity to the impacts of the lighting systems that our industry installs.

Task 3 | reduce sky glow: the goal of this task is to develop a joint standard of the American National Standard Institute (ANSI) and the Illuminating Engineering Society (IES) through my role as Co-Chair of the Color Committee of the IES. The outcome of this task is a lighting standard that provides recommendations for reducing the negative impacts of ALAN, especially sky glow. The potential impact of this work is large. IES standards are influential, and this will be the first standard of its kind for an industry that is dealing with the problem directly.

Thank you for your time and consideration. I am grateful for this potential opportunity. Thank you.

Name: Enabling wide accessibility of Optical Coherence Tomography (OCT) through the development of cost competitive systems based on low-cost, low-intensity noise supercontinuum (SC) sources. **Category:** Health.

Intended Outcomes: 1) Development of high-power, low-intensity noise SC sources based on cascaded Raman fiber lasers. 2) Development of compact OCT system using the novel SC source.
3) Experiments with animal models using the developed OCT system

Optical Coherence Tomography (OCT) is a life transformation technology that revolutionized health care industry. At the heart of OCT system contains a broadband optical source which enables low-coherence interferometry in the spectral domain (SD) and hence it is also called as SD OCT. Latest developments in optical sources having more than octave spanning bandwidth, and in high-speed optical scanning elements, enabled OCT in obtaining ultra-high resolution (few µm) 2D and 3D images at high speeds and sensitivities that provide powerful monitoring and diagnostics capabilities of many diseases like Glaucoma, Skin cancer, Diabetic retinopathy, Coronary artery stenosis etc. Further, due to non-invasive nature, OCT provides highly comfortable and hygienic (without having to add any biomarkers) method of imaging biological systems and therefore, it was heralded as the most important technological development in ophthalmology. However, OCT technology is still very expensive and as per the latest (2021) Nature journal's review article, OCT systems cost around £30,000 to £100,000 and the systems are limited to typical clinical settings. This has significantly limited the access of OCT to only high-income developed countries. However, there are billions of people with the same healthcare needs from low-income and developing countries. For example, being from a remote village in developing country such as India I have seen many elderly people losing eyesight due to non-accessibility of OCT. As per 2021 statistics, there are about 80 million Indians having severe visual impairment out of which 8 million are blind. Given that current pace at which the OCT is advancing, these numbers are worrying, and millions of people would have been saved from blindness if only this technology is easily accessible and affordable. Motivated by this, the goal of this project is to enable accessibility of OCT technology to billions of underserved populations across the world through the development of cost competitive systems. The major contributor to the cost of the latest OCT systems is the broad-bandwidth optical source itself. This is because, the need for obtaining ultra-high axial resolution OCT images with higher speeds and sensitivities requires advanced broadband (multiple octaves spanning bandwidth) optical sources. Supercontinuum (SC) sources perfectly satisfy these requirements. SC is defined as broad bandwidth optical spectrum generation through nonlinear frequency conversion of an input pump laser which is focused to high intensities in a dielectric medium. The most useful form of SC is generated in optical fibers and has greater than octave spanning bandwidth ranging from visible to far infrared (2.5µm), with average power spectral densities (PSDs) of >50mW/nm. In optical fibers, the entire bandwidth of SC is generated within the single waveguide mode and hence preserves the spatial coherence properties of the input laser. Such SC possesses brightness and focusing properties like a laser while having broad bandwidth like an incandescent white-light bulb. These characteristics make SC sources unique, and they have revolutionized many applications including OCT. High-peak power pulsed lasers are typically used as pumps for SC generation. However, costly nature of sophisticated pulsed lasers, low-average PSDs and significant amplified intensity noise in SC generated due to high peak powers used for SC generation makes them not only costly, but unsuitable for latest OCT requirements such as high SNR and high contrast images. Continuous wave (CW) SC, providing higher PSDs, are best suited and cost competent sources for OCT. However, their higher intensity noise levels (in demonstrated SCs so far) and the use of expensive specialty Photonic Crystal fibers (PCFs) make them not suitable for satisfying the latest requirements of OCT images and expensive. This is where I want to leverage my research expertise on wavelength agile, cascaded Raman fiber lasers (CRFLs) and low-intensity noise, high-coherence fiber lasers. Our latest work demonstrated, the best method to achieve CW low-intensity noise CRFLs over a wide wavelength tuning range (1µm to 1.5µm). It won the best student paper award at SPIE photonics west Fiber Lasers conference and was accepted for post-deadline presentation at Advanced Solid State Lasers conference. Such CRFLs can naturally be used as pump sources for low-noise SC generation using low-cost commercially available standard Telcom fibers (instead of PCFs). Inspired by this, the current proposal achieves the goal of much needed low-cost OCT technology, without compromising on the performance requirements, through the development of low-cost, low-intensity noise SC sources.

Name of the project: MOdular system for the MEasurement of the electric field by E-FISH technique (MOMEFISH)

Category: ENVIRONMENT

Highlights:

- **Construction of a modular system for the effective measurement of the electric field. It has the advantage of adapting to different types of experiments, thus facilitating the diagnosis of this type of devices**.
- **It is of particular interest for the characterization of devices applied to fusion, such as plasma reactors, the new source of clean energy that is currently being developed.**

Plasma physics has become a field in its own right in recent decades. The many applications that have been developed in fields as diverse as medicine, industry, etc., clearly show the strategic importance of this field, which involves multiple lines of current and future development.

A project is presented for the design and construction of a modular system to measure the electric field in plasmas, using the Electric Field Induced Second Harmonic (E-FISH) technique. This technique allows the generation of a radiation with a wavelength equal to half of the original one (second harmonic). This project arises from the importance of measuring the electric field, and the difficulty of carrying out non-intrusive measurements in the discharge itself. Laser spectroscopy has been a widely used tool, but it is usually designed for a single experiment. The possibility of designing a diagnostic that fits multiple plasma physics devices represents an important advance in the field.

In this project we plan and design such a diagnostic, which will be tested in an air plasma generated with different geometrical conditions and different spatial resolutions. The laser system to be used for spectroscopy is a nanosecond NIR laser, which is a more economical option than other lasers of shorter time duration. Finally, this system will be tested in real plasma experiments located in different laboratories to check its reliability.

These preliminary measures will be used to study their application to devices such as fusion reactors, which are key to the energy and ecological transition that the world is currently undergoing.

Project summary

Title: Volumetric light modulation and measurement using virtual array imaging

Challenge category: Health

Our challenge is to enable volumetric imaging at high spatiotemporal resolution, using simple commercially available components. This is, lower complexity and higher spatiotemporal resolution than the many existing volumetric microscopy methods.

This problem is motivated by the study of neuroscience, where such volumetric imaging is needed to measure fast neuronal activity reporters with the goal to study, for example, information storage in the form of persistent neuronal activity.

To address limitations in spatiotemporal resolution of current volumetric microscopy, we propose to develop a new class of volumetric imaging method to enable fast, localized optical neurophysiology of live behaving zebrafish. We aim to enable record neuronal activity at 50 Hz bandwidth from a 700x500x110 μm^3 volume with cellular resolution. Unlike existing cell-resolved volumetric microscopes that only resolve up to ~10 Hz, or existing fast volumetric microscopes that compromise cell resolution, <u>our original approach to volumetric recording is multi-focal virtual image formation with a single camera</u>. Each frame captures an array of virtual images focused at different depths of the sample, generated by reflections inside an optical cavity made with off-the-shelf components. The virtual array imposes different path lengths onto sections of the imaging aperture, thereby allowing simultaneous focusing at multiple depths on a volumetric sample while maintaining a diffraction-limited resolution.

Our hypothesis is that virtual array microscopy would enable high-speed volumetric activity recordings with cellular resolution, and that its implementation would allow probing fast dynamics of excitatory synaptic release during persistent activation in the whole zebrafish brain. The long-term goal of this project is to understand neuronal circuit function during animal behaviors by enabling high-resolution, high-speed volumetric optical neurophysiology for larval zebrafish.

Specific Aim 1. Investigate volumetric image formation using a virtual array. This Aim will test whether multifocal imaging generated by a reflective light cavity can be used to capture three-dimensional data with high resolution and will characterize performance of custom image reconstruction algorithms.

1.1 <u>Implement prototype volumetric microscope.</u> A mirror arrangement will be designed to simultaneously focus an array of virtual images onto the camera of a standard epifluorescence microscope.

These advances have the potential to enable fast, localized, wide volumetric microscopy for study of neurophysiology and thus to expand knowledge about neural mechanisms of behaviors and of psychiatric disorders.

Moreover, our proposed solution using virtual arrays of multifocal images is widely applicable to any volumetric or multiplane optical measurements. For example, virtual array imaging could be combined with off-axis holography to record 3D light fields for transmission matrix characterization of complex scattering systems. Virtual array imaging would be also applicable to measure multiple images of an object in an ultrafast sequence, due to the differential delay in path length incurred by each virtual image. The same design principles of could even also enable 3D light projection by creating multiplane patterns in a sample at multiple depths from different areas of a projection device.

Executive Summary

"Retinal Imaging for Retinopathies"

New Diagnostics to Explore the Links between
Infectious & Non-Communicable Diseases in Low Resource Settings

There is a growing recognition that understanding disease co-morbidities and multi-morbidities is of significance in improving healthcare outcomes, particularly in low-resource settings, where health data is often siloed and held in constrained data bases. For example, there is now a growing recognition that the relationship between communicable and non-communicable diseases (NCDs) in both low- and middle-income countries (LMICs) and high-income countries (HICs) is increasingly important. Evidence shows that endemic infectious diseases (including those caused by parasites such as malaria) interact strongly with non-communicable diseases such as vascular disease and diabetes mellitus. Such multi-morbidities are becoming increasingly important in part due to changes in demographics and lifestyles (including dietary changes).

Despite investments in LMIC healthcare, systems remain vertically integrated by disease group, such that it is challenging for different clinicians, running separate malaria and diabetes clinics in a rural hospital for example, to establish linkages, as records are still primarily held for single disease groups.

My aim is to develop a new tool that will enable scientists to have "a window into the eye" of these two very different and but related diseases – both of which are of increasing in prevalence in LMICs – namely type 2 diabetes and malaria. This will involve creating a low cost instrument that can provide clinically-relevant information in the diagnosis of both diseases using retinal imaging. We propose to interface the instrument with a smart-phone camera and use it to detect the characteristic discoloration, visual features, and oxygenation of the retinal vessels, associated with both diseases. Establishing the linkage between malaria and diabetic retinopathy has the potential to make screening campaigns easier, thus leading to significant increases in early detection, associated with better outcomes. Although there have been research efforts to create easy-to-use instruments, they have suffered from low quality images, making their use challenging, especially with limited training. In order to improve the accessibility and reach of diagnostics, as well as improving performance, we will implement a new three coloured LED illumination, allowing us to obtain high quality images with ultralow cost designs. We will also use a deep-learning tool (running on the phone's GPU, not requiring wireless access, often unavailable in rural settings) providing diagnostic decision support for healthcare workers. Data will be downloaded later (once networking is available) into digital health records, using privacy-enabled cloud-communication.

We have already developed proof-of-concept instruments and working with clinical partners at the University of Edinburgh, we have started to validate the AI decision support tool using a training database of 300 reference retinal scans, associated with both diabetes and malaria and including controls. In this project, we will complete the technical developments, in close collaboration with our clinical partners in Tanzania and Edinburgh to ensure that the design and implementation are fit-for-deployment. The prototypes will be validated in a field-based study in Tanzania. The project has a number of technical and collaborative risks, that will be mitigated by collaboration with a strong team in Glasgow, with experience of having worked with clinicians at Kilimangaro Christian Medical Centre.

A key goal of this project is to develop a capability in retinal health screening for LMICs that is closer to that provided in high-income countries. We will ensure that our technologies perform across multiple ethnicities, particularly those involving darker skin pigmentations where retinal imaging quality can be different and often with lower signal-to-noise due to the strong absorption of light by melanin. Following this initial study we intend to develop translational pathways through the further engagement of clinicans with the long-term aim of promoting inclusivity in research and technology development for retinal imaging.

Electrochemical Zero-mode Waveguides Based Digital Sensing of Biomarkers

Challenge:

Biomarkers are biological molecules present in bodily fluids and tissues which provide critical knowledge on human health. Detecting and quantifying biomarkers are useful in disease diagnostics, prognosis, evaluating the efficacy of therapy and treatment, and drug discovery and development. Current detection methodologies including enzyme-linked immunosorbent assay (ELISA), polymerase chain reaction, western blotting, and electrochemical sensors lack either a low limit of detection (*i.e.*, quantifying attomolar concentrations) or a low detection time or a combination of both. This limits their use for detecting biomarkers that are found in low concentrations which provides valuable information on human health. Thus, to quantify these biomarkers, it is necessary to develop a new sensing methodology with a low limit of detection and faster sensing time, that is also cost-effective and user-friendly.

Proposed project:

The overarching goal of this project is to develop a digital, ultra-sensitive, cost-effective, and user-friendly sensor system for quantifying biomarkers. We aim to achieve this by employing **an advanced nanophotonic platform called zero-mode waveguides (ZMWs) in combination with optical dark-field microscopy**. In this project, we will develop our sensor targeted to Interleukin-6 (IL-6), one of the common cytokines to understand the condition of several diseases including COVID-19, HIV, and Alzheimer's. ZMWs are cylindrical or conical nanopores in a thin metal film (typically 100 – 200 nm thickness) with a bottom pore diameter smaller than the wavelength of visible light, capable of confining excitation radiation within the nanopore with the intensity decaying exponentially along the axial direction. We will exploit this feature of the ZMW to quantify biomarkers using scattering of plasmonic nanoparticles (NPs) as a readout mechanism. Imaging the ZMW substrate under dark-field mode blocks the trans-illumination but effectively captures the low-angle light scattered by the individual nanopores. The inherent light scattering by the nanopore increases with the insertion of plasmonic NPs such as silver inside the nanopore due to their localized surface plasmon resonance (LSPR). Using this principle, we will quantify the biomarker concentration in two ways: 1) Construct molecular architecture to attract and hold IL-6 in the nanopores and use silver NPs to specifically bind to the nanopores containing IL-6. By monitoring and counting the number of nanopores with the NPs, we can quantify the IL-6 concentration. 2) Immobilize IL-6 on the surface of silver NPs using molecular architecture followed by releasing silver particles and microscopically counting them on the ZMW substrate and relate to IL-6 concentration. Further, we will improve the limit of detection and detection time by increasing the mass transport of silver NPs inside the nanopores using a voltage gate.

Outcomes:

We expect that the proposed nanophotonic-based platform, zero-mode waveguides will quantify IL-6 in the atto molar range (~10^{-18} M) within 30 minutes including assay formation and readout. Naturally, the platform can be extended to quantify other biomarkers by forming suitable assays. Further, the approach can be transformed into multiplex sensing by co-functionalizing nanopores with multiple recognition elements targeting different analytes and will be sensed by employing different size plasmonic NPs. Lastly, dark-field microscopy can be implemented on a smartphone-based detection setup, making it an easily accessible point-of-care platform. Overall, the proposed sensing platform with an ultra-low limit of detection will push the boundaries of sensing by quantifying new biomarkers and thus improving human health.

Executive Summary

“An innovative optical fibre device for Micro-pollutants and Greenhouse Gas Monitoring”

Over the last century, the world’s population has increased rapidly leading to an exponentially expansion of industrial manufacturing plants. A by-product of manufacturing is the emission of pollutants into the atmosphere and also river. Fine particles in atmosphere generated from power plants, motor vehicles, and residential wood burning can bypass the nose and throat and penetrate deep into the lungs and some of them can enter to the circulatory system.Studies in the past decade have found that an exposure of fine particle can cause a premature death from heart and lung disease. The report by World Health Organization (WHO) in 2016 showing that the ambient air pollutant due to exposure to fine particulate matter of 2.5 microns are responsible for an estimated 4.2 million premature deaths every year.

Thailand is one of the countries in southeast Asia (ASEAN) that air quality especially in the capital (Bangkok) has been obviously getting worse in the beginning of 2019. The pollution level (PM2.5) and greenhouse gas (CO, CO, NO_2) remains at hazardous level in many areas of Bangkok and the surrounding provinces. Experts conclude that the combustion from diesel engines, burning of biomass and industrial activities are the main causes of the situations from both inside country and neighbouring countries. According to a report by the Bangkok Metropolitan Administration (BMA) Health Department, it is showing that nearly 40,000 people in the two main districts of Bangkok have gone to hospitals to receive treatment for respiratory diseases since September 2019.

Therefore, the research on the development of air quality monitoring and take mitigating actions to reduce air pollution are of interest. Many air quality sensing methods have been developed over the past decade. While these techniques are widely used for gas sensing applications, monitoring methods based on optics have proven to be an ideal method for remote and real-time particles and gas monitoring. The proposed particles and gas monitoring system in this project include 3 optical systems.

1. Fiberized SPR sensor using the kretschmann configuration for CO_2 and CH_4 detection by depositing a selective material on metal surface of SPR system.
2. Hollow-core polymer optical fiber specific absorption characteristics of CO_2 and CH_4 occurring in the mid-IR region spanning from 2 to 12 microns. The concentration of gas can be deduced from absorption measurements by knowing the absorption strength of ethylene at specific optical frequencies. This approach eliminates functionalization procedure and necessity of regular recalibration. The absolute measurement will be achieved by 1) implementing a reference arm isolated from the environment; 2) using a reference at wavelength far from the peak, or 3) using modulation techniques commonly found in gas sensing.
3. Fiber Bragg grating will be used for fine particles trapped monitoring for PM2.5 detection.

Two simultaneous factors were established within the last decade which enabled this project in this timeline. (a) Advances in the field of photonics and nanotechnology, that enabled the wavelength selectivity proposed in this project. (b) The enormous leap in manufacturing techniques which enabled autonomous technologies and the next generation of compact air-pollutant monitoring. The novel fiber particle and gas sensor proposed in this project offers a step change in both physical size and power consumption compared to existing commercially available gas sensing technology, making it an ideal candidate for low-cost surveying and exploration missions.

Executive Summary for (Health Category)
'Non-contact cardiac cycle monitoring using microcomb-based dual-frequency terahertz lidar'

The challenge. – Cardiac cycle monitoring, that is the continuous detection of heartbeat rate and its variability, is of critical importance to medical diagnosis and public heath observation. To date, the conventional approaches such as electrocardiogram (ECG) device need to maintain contact with human body to work properly, which is not suitable for the increasingly demanding situations where efficiency, comfort, and a high level of hygiene are required. Non-contact techniques have been developed using novel image/video analysis and microwave/radiofrequency radar or laser lidar approaches. However, these new methods suffer from low resolution, high instability or the inconvenience and inefficiency caused by the need to undress, rendering them immature for practical clinical deployment or long-term in-home usage. As such, the development of robust non-contact cardiac cycle monitoring technology that is with a high resolution and a low noise floor and that is also with the capability of penetrating clothes without imposing any health hazard is urgently needed.

Proposed project. – Leveraging the cutting-edge microcomb technology and the parallel continuous-wave photomixing multifrequency terahertz (THz) generation method that are at the front line of photonics and THz research, a dual-frequency THz lidar will be developed to perform non-contact cardiac cycle monitoring. Using various microresonator platforms for microcomb generation, low-noise nonlinear optical waves with THz-range oscillation frequencies will be produced with a compact near-infrared laser. A high-speed PIN diode will be adopted to convert the optical waves into two THz signals whose frequency instabilities (or phase noises) are correlated. By applying the frequency-modulated continuous-wave (FMCW) lidar scheme to the pumping laser, the two THz signals would be frequency-swept over multi-gigahertz range with a >100 kHz sweeping rate and an ultrahigh linearity. More importantly, the frequency sweeping directions of the two THz signals are always opposite, which can cancel the microcomb frequency instabilities and the phase noise in the microwave reference during the simultaneous measurement of displacement and velocity. A collimated THz beam containing the two sweeping frequencies will be directed to the target (e.g., the chest wall of a patient) and the reflected THz power will be collected and down-mixed to the radiofrequency (RF) domain. Off-the-shelf RF components including amplifiers, couplers and mixers will be utilized to perform heterodyne operations in real time to derive the accurate distance and velocity from the two RF signals. As a result, the THz lidar can perform highly sensitive ranging and velocimetry without being impacted by the noise contained in the microwave/laser signals, thereby establishing a reliable scheme for non-contact cardiac cycle monitoring. In this project, ranging and velocimetry tests and proof-of-concept heart rate monitoring will be conducted, and the results will be analyzed and compared with ECG measurement to characterize the performance of the developed THz lidar.

Intended outcomes. – 1) Because THz waves can penetrate most fabrics without causing potential health hazard, the developed THz lidar can perform convenient and safe non-contact monitoring with a high efficiency and a superior reliability. 2) With the high carrier frequency, the high emission directivity, and the comprehensive sensing capabilities enabled by the FMCW lidar technology, the THz lidar can not only provide clinically practical non-contact heartbeat rate monitoring but also perform high-precision ranging and velocimetry simultaneously in changeling situations. 3) Owing to both the unique nonlinear dynamics of microcombs and the multiple-THz-signal generation with parallel photomixing technology, the novel dual-frequency scheme allows the THz lidar to reach a resolution of a few tens of microns in ranging (with the assistance of phase sensitive technique), and a precision of 100 μm/s in velocimetry, showing orders-of-magnitude improvement over prior THz-based measurements. 4) As the THz generation relies on low-cost and compact microcomb technology and the signal processing is executed in the RF domain with off-the-shelf electronics, the developed dual-frequency THz lidar offers remarkable cost-effectiveness and the potential to be widely deployed with low maintenance cost. 5) With several recent breakthroughs in chip-scale microcomb generation and on-chip THz transmitter and receiver integration in the photonic integrated circuit (PIC) industry, the developed dual-frequency THz lidar scheme may be transferred into an all-on-one-chip compact version for mass production. 6) The developed low-noise multifrequency THz waves can be readily used in THz-based environmental monitoring and high-speed wireless communication applications.

Executive Summary of "Developing Low-Cost, Portable, Integrated OCT Systems Using Low-Loss Silicon Nitride Platform"

Optical coherence tomography (OCT) is a non-invasive imaging modality that provides depth-resolved, high-resolution images of tissue microstructures. Every year, more than 30 million OCT scans are performed all over the world. It has become the de facto diagnostic and monitoring tool for ophthalmic diseases, and an emerging imaging technology in other areas such as dermatology, gastroenterology and breast cancer imaging. However, the cost of an OCT system is typical from tens of thousands of dollars to easily exceeding $100,000, the size of an OCT system could be on the order of meter cubic, the parts in the OCT system are separated and need to be actively aligned. The cost, the size and the misalignment of the parts are prohibitive these powerful imaging systems to all but the busiest and most sophisticated practices.

We plan to develop a prototype for a low-cost, portable, integrated OCT system based on silicon photonics, more specifically low loss Si_3N_4. The light source, interferometer and spectrometer of the OCT system will be independently developed and then integrated onto the same carrier to ensure the success of the project. The integration of light source will be developed and achieved through two approaches in parallel: i) The higher risk but higher degree of scalability and integration approach - gain chips and Si_3N_4 resonators based frequency combs. ii) The lower risk and more conventional approach - SLD diode and Si_3N_4 photonic chip co-package. The integration of the interferometer will be based on the low loss Si_3N_4 platform, the reference arm will have a length that is long enough to match the path length of the sample arm. The sample arm will be miniatured using a co-packaging process with MEMS scanners. The integration of the spectrometers will also be based on Si_3N_4 platform and achieved through two approaches in parallel i) The stationary FTS with a Si_3N_4 grating. ii) Si_3N_4 AWG with lenses integrated on the edge of the chip. All these components will be developed around a central wavelength of 1050 nm, and retinal scans will be taken with our system in collaboration with OCT experts also at Shanghai Jiao Tong University.

The outcome of our proposal is expected to be **a prototype of a low-cost, portable, integrated OCT system**. The device we envision, in final form, will be **two orders of magnitude** reduction in price and **several orders of magnitude** reduction in size and weight. It will have the size and weight less than a typical mobile phone, and will have the capability of providing retinal scans at a resolution of less than 10 μm, comparable to midrange clinical devices currently on the market. The schematic of the OCT system is shown in **Fig. 1**. All three core parts of the OCT system are miniatured and integrated on the same carrier using components and technologies developed in this project.

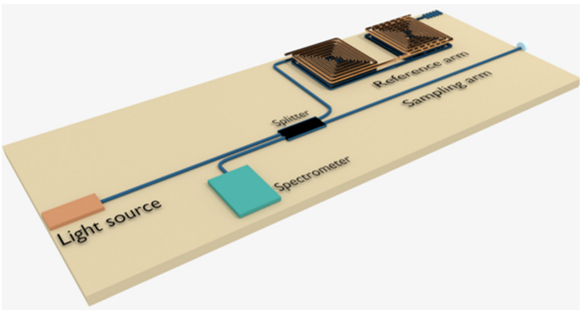


Fig. 1. Schematic of proposed OCT system. All three core parts of the OCT system (light source, interferometer, spectrometer) are miniatured and integrated on the same carrier.

We expect our systems could be further adapted for imaging and diagnosis of diseases in other specialties using different wavelengths as well, especially in dermatology, dentistry and oncology. Our results will help to reduce costs of the health system while increasing accessibility and compliance for better disease management. We hope that the components and the technologies we developed in this project will help pave the way for low-cost, portable OCT systems and incorporating integrated photonics into optical imaging technologies.

Optica 20th Anniversary Challenge | Environment Category | Executive Summary

Chip-integrated mid-infrared laser and spectroscopy towards scalable environmental monitoring

Xiyuan Lu, Assistant Research Scientist, University of Maryland Colleague Park | NIST

The challenge: In 2022, people around the globe are struggling to deal with heat, tumbling the record stood for over 100 years. Right now, the heat is challenging around the major cities, burdening the electrical grids. Down the line, the extreme weather poses higher risk of other hazards including flooding, superstorms, and diseases. Global warming is one major pressing challenge for our generation.

To solve this environmental challenge, we need to first measure the environmental gases quantitatively, and collect big data with large variety, volume, and velocity. Mid-infrared spectroscopy is the key technology to measure environmental gases, including carbon dioxide and methane, as these gases have absorption signatures at 2-5 micrometers. So far, high-quality mid-infrared spectroscopy, limited by table-top laser and detector setups, can only happen in labs rather than in the field, and is prohibitively expensive to deploy to collect the big data. Satellites can provide an overall analysis of the atmosphere, but lack the local data that is important for regulatory action and enforcement. To collect big data for environmental monitoring from automobiles to drones/air crafts, to farms and factories, we need a scalable spectroscopy technology that is cheap, portable, and manufacturable.

A key challenge for scalable mid-infrared spectroscopy is the laser source, as the mid-infrared gap (2.5-5 micrometers) is not accessible by direct band gap lasers from semiconductors in nature. In recent years, significant efforts have been put in integrating laser sources, with approaches including heterogenous integration and nonlinear photonics. Yet most efforts are focused on visible and near-infrared wavelengths, attracted by commercial interest (virtual/augmented reality, LIDAR for autopiloting etc.) and the thrusts in quantum optics (where quantum systems have emission wavelengths in visible or near-infrared). The mid-infrared spectroscopy, though crucial for environmental monitoring, is comparatively far less explored in the context of integrated photonics. The heterogeneous integration approach, while considered as the favorable path at the visible and near-infrared, does not attract the same level of interest at the mid-infrared, in part because of the lack of direct bandgap materials. Lacking this technical path, nonlinear photonics seems to be the way to go for scalable mid-infrared spectroscopy.

Proposed project: I propose to address this challenge using nonlinear optics in the silicon nitride photonics platform, which has been successful in wide-band nonlinear optics, and is supported by wafer-scale foundry fabrication. My proposal contains three parts: developing the photonic chip for efficient generation and vertical emission of the mid-infrared light, and exploring the packaging considerations with laser and detector for spectroscopy.

- The proposed key photonic device (< 0.1x0.1 mm footprint) performs two major functionalities:
  - convert telecom laser light to widely-tunable mid-infrared coherent laser light, through a nonlinear optical process called widely-separated Kerr optical parametric oscillation;
  - emit the generated mid-infrared light vertically out of the chip plane efficiently, through high-quality orbital angular momentum emission.
- Also investigated is the packaging considerations to incorporate the photonic chip with high-power telecom laser diodes by edge coupling, and the infrared detector in flip bonding/expoxy.

Intended outcomes: I intend to deliver a functional mid-infarared spectroscopy prototype in 3 steps:

- **0-8 months:** demonstrating telecom-pumped mid-infrared OPO generation on silicon photonics.
- **9-16 months:** demonstrating efficient mid-infrared out-of-plane emission in such OPO devices.
- **17-24 months:** exploring packaging considerations with laser and detector to the photonic chip.

Mobile Quantum Gravimetry for Near-Surface Geophysics

Xuejian Wu
Department of Physics, Rutgers University, Newark, NJ 07102
Email: xuejian.wu@rutgers.edu

Application Information
Application to The Optica Foundation 20th Anniversary Challenge
Category: Environment
Project Duration: 2 years
Budget: $99,880

Project Summary

Gravity mapping is important for inertial navigation, resource exploration, refining the geoid, hydrological studies, and hazard monitoring. Gravity cartography, mapping the vertical gravity (g_z), gravity gradient ($\partial g/\partial x$), and even its second spatial derivative ($\partial^2 g/\partial x^2$), can access this target directly by sensing minuscule local variations ("anomalies") in the gravitational field. The strength of these anomalies is typically 0.1-50 E, where 1 E=10^{-9}/s^2 (Eötvös unit) is a change in the gravitational acceleration by 1 nm/s^2 over a 1-meter distance.

Exploiting the nature of quantum phenomena, quantum technologies are developing rapidly toward precise sensing. Matter-wave interferometers are robust quantum sensors and are being developed for measuring inertial forces. In contrast to classical sensors, atom interferometers use recoil momentum from photon and matter-wave interactions to coherently split and recombine matter waves. Since laser wavelength defines photon momentum with high precision, atom interferometers are accurate and are thus ideal sensors for precision measurements. Recently, transportable quantum gravimeters have been demonstrated for mobile gravimetry. However, due to complexity and fragility, quantum sensors that are sensitive to the gravity gradient or the second spatial derivative have not yet been tested out of a laboratory.

We propose a scalable quantum gravimeter by dropping multiple cold atomic clouds trapped in diamond-shaped mirrors to simultaneously measure gravity and its high-order derivatives. By combining the beyond state-of-art gravimetry from the recent development of Quantum Information Science and Engineering with application in Near-Surface Geophysics, we aim to demonstrate a shared-use mobile quantum gravimeter that will open new capabilities in geophysical exploration. The quantum gravimeter will allow the application of gravity methods for mineral and water exploration and for the monitoring of subsurface processes that have not previously been available. In Year 1 of this project, we will demonstrate the feasibility of matter-wave interferometry based on diamond-shaped magneto-optical traps and develop an algorithm for modeling gravity distribution for arbitrary underground test objects. In Year 2 of this project, we will demonstrate the prototype of the quantum gravimeter and implement water table leveling measurement in the lab.

Our quantum gravimeter will enable accurate characterization of gravity, the gravity gradient, and the second-order derivative of gravity at the same time. Such measurements will support the discovery and monitoring of previously undetectable structures and processes. The ability to sensitively measure contrasting density in subsurface materials permits the detection and inspection of buried minerals, salt domes, petroleum reservoirs, varying rock types, and bedrock structures. It also permits monitoring of underground fluids, like sequestered CO_2 or the water level in aquifers and other groundwater resources. The low operation cost, high sensitivity, and broad applicability of the instrument will attract usage from a wide range of research fields in academia and industry.

High-power 2-µm frequency combs for rapid greenhouse gas sensing (comb2u)

Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) compose 98% of global greenhouse gas emissions, and remote, sensitive detection of the concentrations of these gases is critical for understanding and monitoring regional emissions. Dual frequency-comb-based remote sensing has proved to be a unique tool for kilometer open-air path remote monitoring of such gases in the 'eye-safe' wavelength range of 1.6 µm. Despite the remarkable progress in Er-fiber-based laser systems at this wavelength for this application, the 2 µm wavelength region – which is also eye-safe - has many potential advantages since strong absorption lines are present here, as shown in figure 1. For example, CO_2 shows an almost two times higher absorption coefficient in this wavelength range compared with 1.6 µm, making sensitive tracking of small variations attractive. Although frequency down conversion to this wavelength is possible, Tm, Ho, and Cr-based oscillators directly emitting in this wavelength range are still more attractive due to their simplicity. To cover the minimum broad absorption band of the above gas (about 13 THz from 2000 nm-2200 nm), reducing the repetition rate difference Δf, or increasing the fundamental repetition rate f_{rep} can be applied. Later one is more favorable since both measurement speed and bandwidth of dual-comb spectroscopy (DCS) quadratic scales as the fundamental repetition rate. However, state-of-the-art oscillators in the 2-3 µm wavelength range show limited average power within Watt-level, making remote sensing challenging.

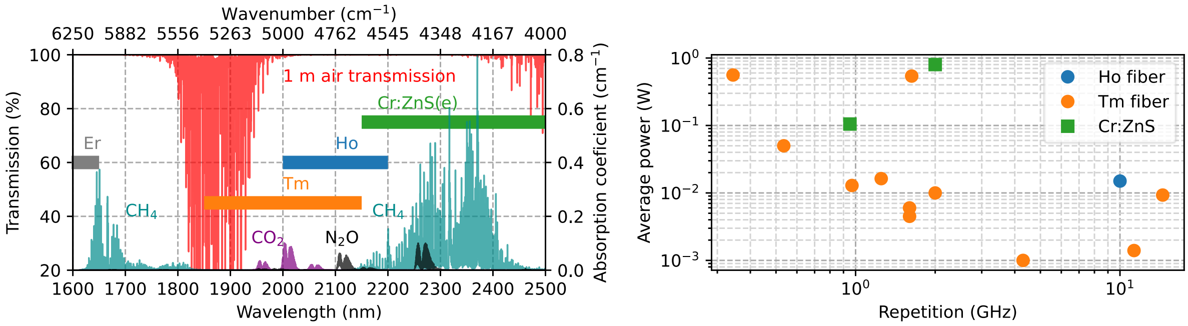


Figure 1. Left, laser emission range illustrated with 1-m air transmission and greenhouse gas absorption coefficient in the 1.6-2.5 µm wavelength range (from HITRAN database). Right, state-of-the-art of high repetition-rate mode-locked oscillators in 2-3 µm.

The current project aims to design and develop industrial-grade, robust, compact, cost-effective, diode-pumped high-power high-repetition-rate mode-locked oscillators around the 2-µm wavelength range based on Tm-doped gain media for rapid greenhouse gas sensing applications. I expect the successful completion of the current project will have the following outcomes and impacts:

- The key specifications I aimed to achieve with the high-power high-repetition-rate 2-µm oscillators are Watt-level average power, repetition rate >250 MHz, and nJ pulse energy. This unique source will further be used to improve greenhouse gas sensing in terms of faster detection speed, high sensitivity, and long-distance detection.
- Within the period of the current project, I expect 1-2 journal publications and >2 submissions for conference proceedings. In addition, one or two master's students will be involved in the current project and get proper training in ultrafast laser development and gas-sensing.
- Establish collaboration with other groups working on the frequency-comb, bridging the laser source development with spectroscopy research.
- Promoting next-generation spectroscopy based on frequency combs at around 2 µm wavelength range. Seeding non-oxide nonlinear crystal based OPO or DFG process further generates MIR radiations. Such MIR comb systems are highly interesting for spectroscopy, environmental monitoring, and medical diagnostics.

In-plane telecom lasers grown on SOI for integrated silicon photonics

As the crux of next generation communication systems and data interconnects, Si-photonics has been underpinned by the development of some key components such as low-loss Si waveguides and high-speed optical modulators. While Si has been employed to make excellent passive components, efficient light emission still relies on III-V compound semiconductors due to the indirect band structure of Si. Heterogeneous integration approaches such as wafer-bonding and micro-transfer printing have enabled the integration of high-performance III-V lasers on Si-photonics platforms via evanescent coupling strategies. However, the cost and yield of manufacturing is less than optimum compared with monolithic integration, and the large footprint of evanescent coupling limits the scalability of this approach. Monolithic integration of III-V lasers via direct hetero-epitaxy could further benefit Si-photonics in terms of cost, scalability, and integration density. In the past few years, III-V quantum dot lasers with impressive performance have been grown on Si using direct blanket hetero-epitaxy. However, the micrometers thick buffer layers necessary for defect engineering severely impedes the light coupling between the III-V active devices and the passive Si elements underneath. As an alternative, selective hetero-epitaxy of III-V alloys on Si using the aspect ratio trapping (ART) technique enables closer placement and hence more efficient light coupling between the III-V gain material and the Si-waveguides. Limited by required aspect ratio in conventional ART method, the III-V material volume is often at the nanometer scale making the realization of electrically pumped lasers challenging. To solve this dilemma, we have demonstrated an integration scheme named *lateral aspect ratio trapping (LART)* with selectively grown large-area dislocation-free InP membranes on (001) SOI wafers patterned by conventional photolithography. These III-V crystals locate right on top of the buried oxide layer and feature a unique in-plane configuration with the Si device layer, which results in strong light confinement within the epitaxial III-V and allows for compact and efficient butt coupling between III-V and Si in the same plane.

Recently, we have achieved optically pumped lasing of telecom micro-ring lasers and distributed feedback lasers using LART. In this project, we propose to develop electrically pumped telecom lasers on industry-standard SOI wafers through monolithic integration using LART. To achieve practical lasers, we will optimize the parameters to allow lateral growth of defect-free III-V crystals on SOI long enough to support electrically-pumped lasing. Also, to facilitate the lasing unique structure design is necessary for the lateral junction. In this project, we will focus on developing growth techniques and designing laser structures for the integration of practical lasers on SOI using decades of our experience in Metalorganic chemical vapor deposition (MOCVD), device fabrication and characterization. *Putting high-performance lasers exactly where they are needed in the photonic integrated circuit is the most unique and brightest point of this project.*

The proposed in-plane telecom laser on SOI will provide a practical solution for light emitting and efficient coupling with passive components on the Si-photonics platform, the final obstacle between cost-effective integration of electronics and power-efficient photonics. Furthermore, integrating III-V lasers onto SOI substrates will enable the next generation photonic integrated systems to have lower manufacturing cost, as well as be compatible with the well-established Si CMOS electronics.

Wide-Range Multispectral Imaging for Spatial Ripeness Estimation of Durian Fruits

The challenge of durian ripeness estimation is the apparent features of durians are not directly relative to their ripeness levels, i.e., color. Moreover, the durian husk is very thick that is difficult to directly investigate the inside qualities, i.e., maturity and ripeness level, without peeling it. The ripeness needs to be estimated before peeling durians for customers. The peeled durians with disappointed ripeness levels will be a waste product in markets. Thus, high accuracy and non-destructive methods are needed for durian's ripeness estimation to satisfy the customers as well as classify the oversupplied fruits for food processing in order to balance demand and supply in the global market

Here, we propose to combine a broad-band multispectral imaging module and machine learning to spatially evaluate the ripeness level of durian fruits. As the machine learning is embedded, the accuracy for ripeness level estimation can also be improved simultaneously through the data collection from our system and retraining of our analytical models. During the change of durian's temperature (ΔT_D) under a surrounding temperature, the images of a durian fruit are obtained by a broad-band multispectral imaging module upon the illumination of ultraviolet light sources (UV-A) and halogen-tungsten light sources, respectively. The captured images consist of a three-dimensional (3D) image and multispectral images covering visible to far-infrared regions that create a data set used for spatial ripeness estimation. The data set is used to train for spatial identifying the ripeness level of the durian into unripe (highlighted as green), ripe (highlighted as yellow), or overripe (highlighted as red) stages by means of a machine learning method. More spectral images can be obtained by placing band-pass filters and/or polarization filters in front of the multispectral imaging module.

The intended outcome of this project is to achieve a field prototype with an accuracy of more than 95% of ripeness estimation for onsite markets to satisfy the demand of customers (waste is expected to be reduced by half or around USD1,500M). The balancing between demand and supply can maintain the economic value (>USD500M) of durian products in the global market. Furthermore, the new platform can be extended to monitor the maturity of durian fruits on trees before harvesting in order to obtain durian fruits with high quality (immature fruits cause the low quality of durian products).

Application category: HEALTH

Deep learning-empowered compressive optical coherence tomography for tele-ophthalmology

What is the challenge?

The ongoing pandemic of coronavirus disease 2019 (COVID-19) has witnessed an accelerating pivot in the healthcare industry from face-to-face encounters to telehealth: the telehealth's share in US has surged by 2,250% since January 2020. Unfortunately, ophthalmological clinics found themselves in a challenging situation to adapt to this new normal due to the heavy reliance on the diagnostic equipment. In fact, the adoption of telehealth in ophthalmology is among the lagging specialties which is almost tied with physical therapies. Take optical coherence tomography (OCT), the most widely used tools in ophthalmology, as an example, it not only requires on-site operations by trained specialists but also generates immense amount of data, both of which are incompatible with the current telehealth paradigm. Recently, remotely controlled OCT machine that does not require human operation was reported by Izatt Group. However, the second gap remains unfilled: a commercial 200 kHz swept-source OCT (SS-OCT) system could easily produce a raw data bandwidth of ~400 MB/s, which is 20~30-fold larger than the speed of 5G wireless or broadband connection.

How are we going to address it?

The objective of this project is to develop a compressive SS-OCT system that could support real-time streaming of OCT raw data via current network with satisfactory reconstruction quality. Specifically, we will physically reduce the system's data bandwidth by a factor of 20 (use only 5% of the raw data) and achieve a peak-signal-to-noise ratio (PSNR) of 20 dB during the reconstruction. We plan to achieve this by jointly optimizing the data compression and image reconstruction schemes with the aid of artificial intelligence (AI).

In our proposal, the data bandwidth will be first compressed by reducing the quantization and by performing two-dimensional sub-sampling, and the images will later be recovered by using neural networks. We will use an end-to-end deep learning-based training framework to discover the optimal sub-sampling pattern along with the best performing reconstruction networks. Moreover, the learned sub-sampling pattern will be implemented on an existing retinal SS-OCT system and the trained reconstruction networks will be deployed on a remote host computer. For the system demonstration, human eyes will be imaged and the compressed data will be streamed over the network to a remote host computer. The OCT images will then be reconstructed in real-time to showcase its utility.

What about the outcome and the impact?

The major outcome of this proposal is a prototype compressive retinal SS-OCT system which would mark the new state-of-the-art performance in terms of using the least data bandwidth to deliver the best reconstruction image quality. This would lead to the real-time streaming of OCT data via common broadband connections for the first time. It should also be noted that the proposed method only requires minimal modifications on the hardware (i.e. re-programming the data acquisition board) and is compatible with most existing SS-OCT systems.

The success of the proposed project would bring us closer towards the realization of the first-generation tele-OCT system: in conjunction with the recently advanced robotic OCT technology, the proposed prototype could be immediately compatible with the current telehealth paradigm. We believe such a progress could be promising remedy to the problems faced by the ophthalmological clinics during this on-going pandemic: millions of patients with eye conditions will no longer need to visit the clinics to receive face-to-face treatments. They can instead visit an unmanned booth with the tele-ophthalmology system installed, while the OCT images of the patient would be streamed real-time on the screens of the tablets or laptops in the ophthalmologists' offices hundreds of miles away.

Ultra-Compact and Efficient Electro-Optic Modulation Using Nanophotonics

(Category: Information)

Challenge:

Exponential growth of data traffic, information and communication devices, and power-hungry data centers have led to a rapid increase in global electricity consumption. To minimize their energy usage and environmental impact, there is an urgent need to develop miniaturized electro-optic modulators (EOMs) that are more energy-efficient and cost-effective. Over the years, a wide variety of electro-optic materials and photonic designs have been integrated with EOMs on a chip platform to extend the performance boundaries, but their device compactness, modulation efficiency, energy consumption, and optical bandwidth are still limited.

Proposed Project:

Here we propose to create a hybrid plasmonic-photonic (HPP) EOM incorporating a two-dimensional (2D) polar semiconductor to overcome the limitations. The HPP waveguide structure enables deep-subwavelength transmission with an extreme optical mode confinement down to a nanometer thin dielectric region. A large spatial field overlap with an embedded 2D polar semiconductor is thus possible, and the accompanied plasmonic enhancement will significantly increase the light-matter interaction over a broad range of wavelengths. 2D polar semiconductors have unconventional out-of-plane dipoles that can align with the transverse magnetic (TM) mode of the HPP waveguide, which leads to a gigantic electro-refractive effect. *Our goal is therefore to experimentally realize this new EOM device architecture and demonstrate superior performance in terms of device size, modulation efficiency, energy consumption, and optical bandwidth*. New 2D polar semiconductors with a strong out-of-plane polarization and negligible absorption loss over a broad telecommunication wavelength band will also be identified and tested.

Our research contains two main tasks: *(i) Design of EOMs integrating HPP waveguides and 2D polar semiconductors.* We will explore different HPP waveguide geometries to maximize the mode overlap and model the electrical and optical effects of incorporating 2D out-of-plane dipoles. We will also carry out a system-level design of EOMs and investigate design tradeoffs to optimize the mode overlap, interaction length, modulation efficiency and speed, as well as energy consumption. *(ii) Experimental demonstration of 2D polar semiconductors and high-performance EOMs.* We will exfoliate and transfer 2D polar semiconductors onto substrates to study their crystal structures, surface morphology, and intrinsic optoelectronic properties, besides verifying their out-of-place dipole characteristics. We will utilize standard cleanroom nanofabrication techniques to realize EOMs and thoroughly characterize their modulator behaviors and performances. These tasks encompass theoretical design and electrical-optical-circuit multiphysics simulations, nanofabrication process development and device integration, as well as rigorous measurement for conceptual validation and performance characterization. The project will have a 1-year duration.

Research Outcomes and Impacts:

Our research is expected to deliver the following outcomes: (i) Verification of the nanophotonic approach and the demonstration of high-performance EOM devices; (ii) The filing of one patent and the publication of two high-impact journal papers prioritizing Optica open-access journals; (iii) Dissemination of research results in leading conference, invited seminars, and Optica-organized symposiums, Optics & Photonics news magazine, Optica's websites and facebook pages; (iv) Integration of knowledge generated into educational courses and training of students to help their career growth in photonics.

Our nanophotonic approach will overcome EOMs' bottleneck of weak light-matter interaction and enable truly compact EOMs for densely-integrated information processing on chip with superior performance. Ultralow energy consumption can be envisioned, thus reducing the electricity usage in data centers and allowing optical interconnects to compete with electrical interconnect technologies. Low driving voltage and capacitance achievable in our device permits CMOS-compatible operation and higher modulation speed. Wavelength-division multiplexing for high-throughput communication links will be possible owing to our device's broadband operation. Our research will drive the field of energy-saving information processing and accelerate on-chip information networking and computing.