PHOTONICS RESEARCH GROUP

SILICON-PHOTONICS-BASED SPECTROSCOPIC SENSING FOR ENVIRONMENTAL MONITORING AND HEALTH CARE

Roel Baets
Ghent University and imec

Optica Webinar May 9 2022

GHENT UNIVERSITY

imec
embracing a better life

ePIXfab
The European Silicon Photonics Alliance

OPTICA
Formerly OSA

ePIXfab: European Silicon Photonics Alliance

ePIXfab is an *open alliance* of international organizations that promotes silicon photonics science, technology and applications

Advocate

Latest advancements in the field

Represent

European silicon photonics community as a whole

Train

With respect to silicon photonics tech. & app.

Consult

To determine the feasibility for innovation

Roadmap

About the technological trends and evolution

7th ePIXfab Silicon Photonics Summer School

C2N, University Paris – Saclay (France)

20-24 June 2022

SCOPE

- comprehensive coverage of basic and emerging topics
- deep dive into the latest trends and hot topics
- to bring mastery to the beginners & raise excellence of the experts

FEATURES

- 20+ top-notch lectures by experts from across the globe
- Poster sessions for enhanced interaction and engagement
- Social events to share, learn and discuss with peers and experts

SPEAKERS

Roel Baets (UGent-imec)
Andrea Melloni (Poli. di Milano)
Frederic Boeuf (STMicro.)
Bert Offrein (IBM)
Delphine Marris-Morini (Uni. Paris-Saclay)
Antonella Bogoni (Sant'Anna)
Jonathan Doylend (Intel)

Laurent Vivien (CNRS, Uni. Paris-Saclay)
Wim Bogaerts (UGent-imec)
Robert Halir (Malaga University)
Gunther Roelkens (UGent-imec)
Yannick Paillard (Scintil Photonics)
Kristinn Gylfason (KTH)
Michael Zervas (LIGENTEC)

Bertrand Szelag (CEA-LETI)
Bart Juyken (UGent-imec)
Augustinas Vizbaras (BROLIS)
Peter Ossieur (UGent-imec)
Eric Mounier (Yole)
Daniele Melati (Uni. Paris Saclay)
Abdul Rahim (ePIXfab - UGent)

MORE INFO:

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ABSTRACT

Spectroscopic sensing is a powerful modality for numerous applications in medicine, biotechnology and structural health monitoring. Often the implementation is bulky or costly, which is a barrier for high volume markets. Integrated photonics - in particular silicon and silicon nitride photonics - is changing this and will boost spectroscopic sensing to such markets, for example in personalized medicine. This webinar will discuss underlying principles, technologies and application cases.

Acknowledgements:
Photonics Research Group, Ghent University – imec
imec: SOI and SiN PIC manufacturing platforms
ePIXfab, European Silicon Photonics Alliance
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SPECTROSCOPIC SENSING: VAST APPLICATION SPACE

Low cost solutions
in the market

CO_2, CO, CH_4 sensing

Blood oxygenation

Low cost solutions
under development

Structural health monitoring
(bridges, windmills,
gear boxes…)

Glucose sensing
(+ lactate, ureum, ketones)

Biosensors
(immuno-assays, diagnostics…)

Ultra-compact low-cost
gas sensing

Food spoilage monitoring

Water pollution monitoring

Trace gas sensing

Therapeutic monitoring (eg drugs)

Low cost solutions
To be developed

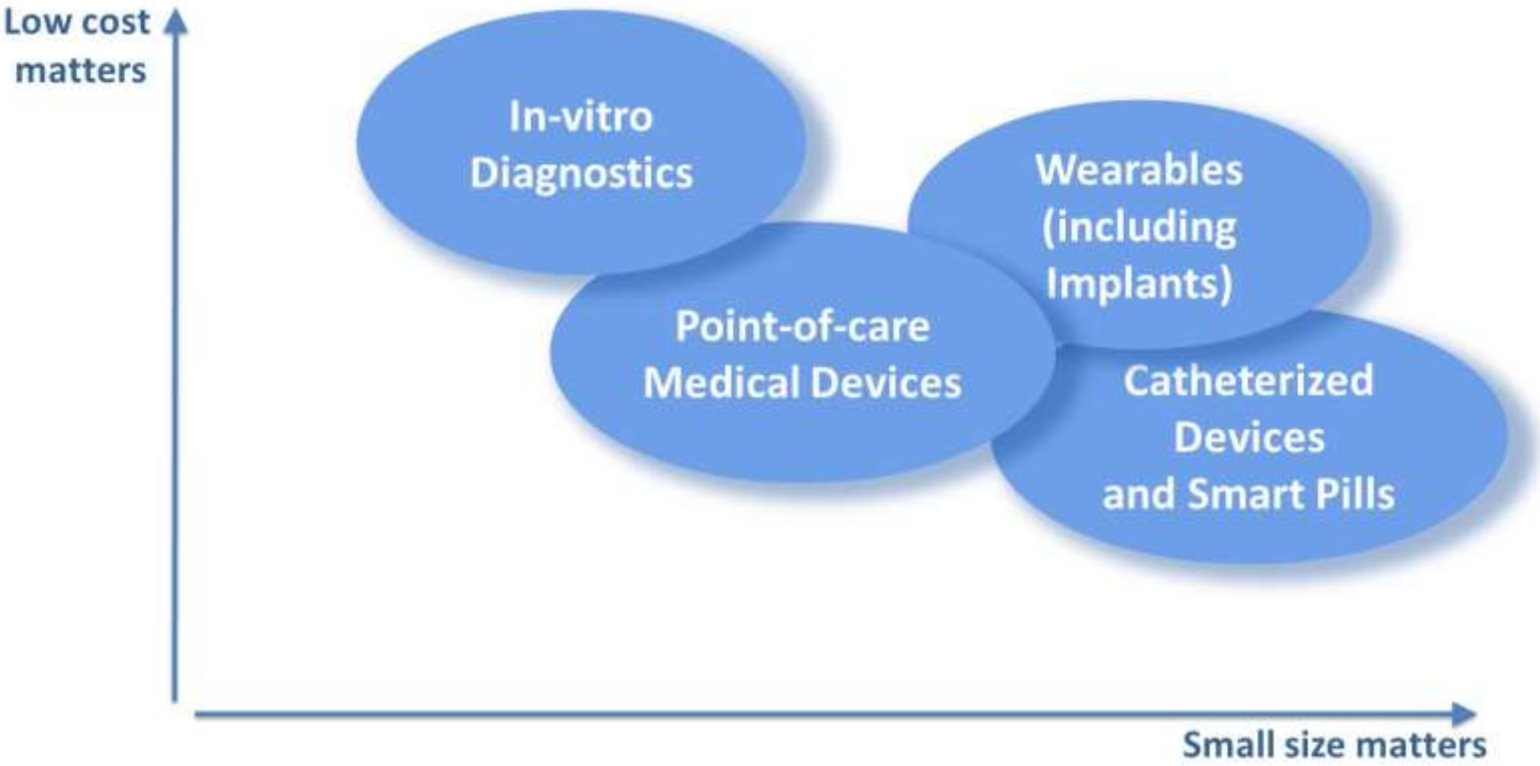
WHY MOVE TO MORE INTEGRATED SOLUTIONS USING SILICON PHOTONICS?

Low cost in volume

Mature technology and supply chain

Extreme miniaturization

Medical applications



GHENT UNIVERSITY imec

OUTLINE

➡ Brief introduction to silicon and silicon nitride PICs

Spectroscopic sensing modalities

On-chip spectrometers

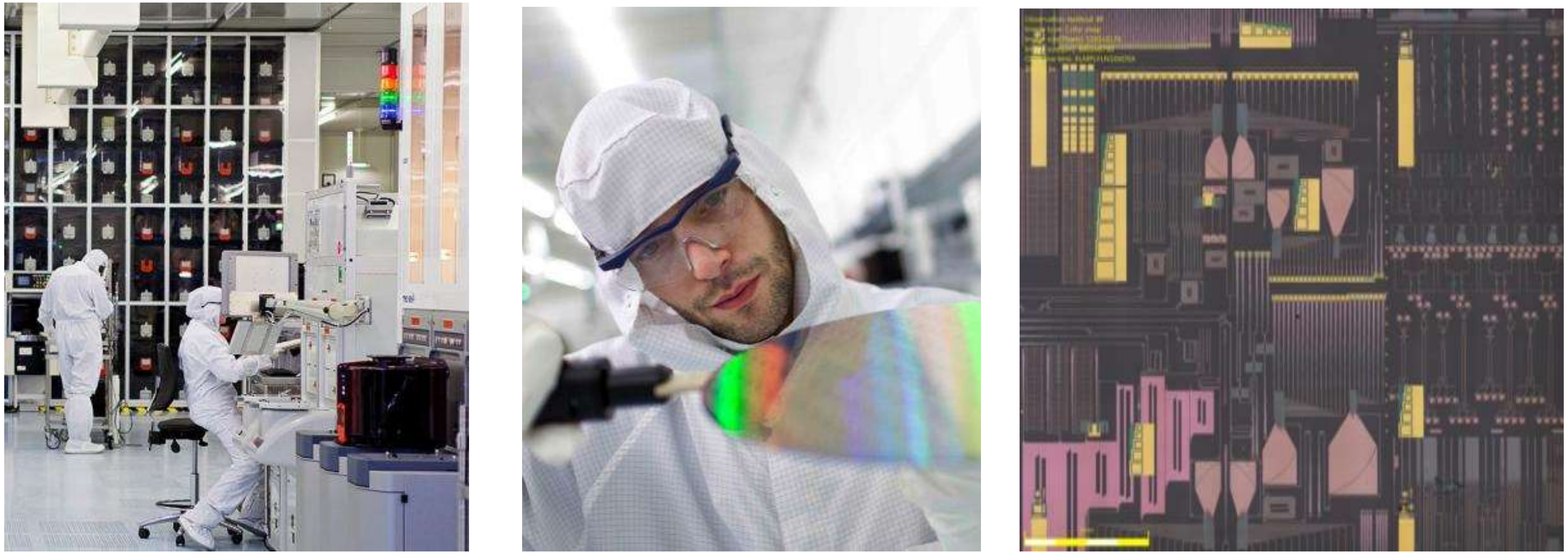
On-chip tunable lasers

On-chip Raman spectroscopy

Application cases

WHAT IS SILICON PHOTONICS?

The implementation of high density photonic integrated circuits by means of CMOS process technology in a CMOS fab

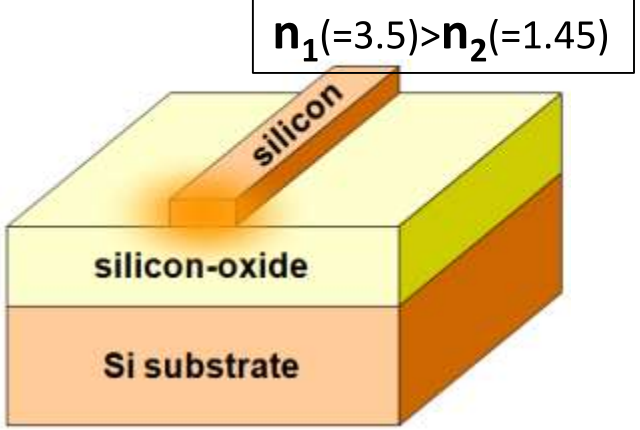


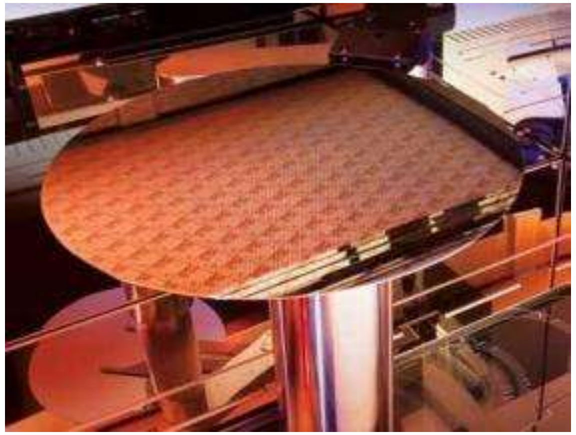
Pictures, courtesy of imec

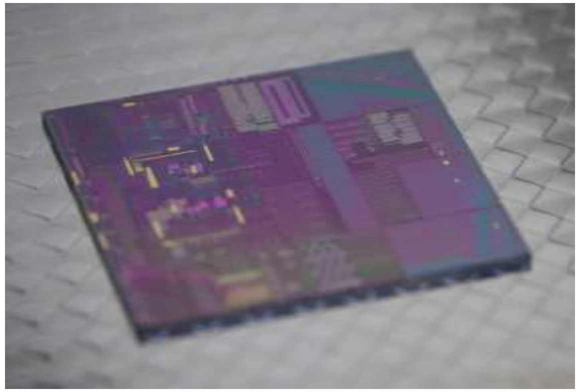
Enabling complex optical functionality on a compact chip at low cost

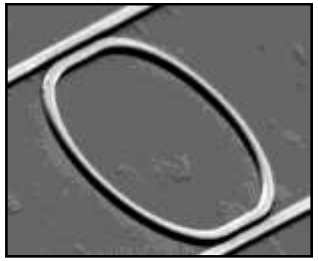
WHY SILICON PHOTONICS

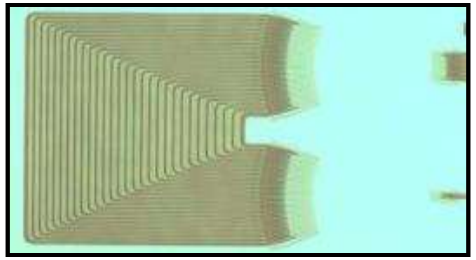
- High index contrast ⇒ **very compact PICs**
- CMOS technology ⇒ **nm-precision, high yield, existing fabs, low cost in volume**
- High performance passive devices
- High bitrate Ge photodetectors
- High bitrate modulators
- Wafer-level automated testing
- Hierarchical set of design tools
- Light source integration (hybrid/monolithic?)
- Integration with electronics (hybrid/monolithic?)

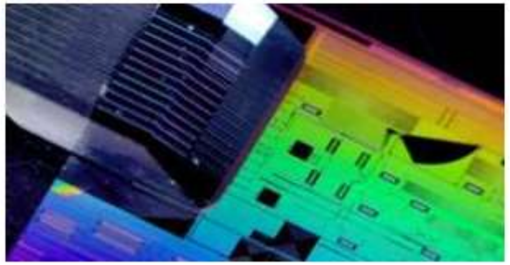












CHIP COST IN A CMOS FAB (ORDER OF MAGNITUDE)

	Simple/small chip	Complex/large chip
Very low volume (**MPW**) (~ 100-1000 chips per year)	100€	1000€
Low volume (<10K chips per year)	10€	100€
Moderate volume (10K – 1M chips per year)	3€	30€
High volume (>1M chips per year)	1€	10€

In high volume, the chip is "for free"

Even in moderate volume the cost per chip is low

Even in low volume the chip has a high value for money

TRANSCEIVERS FOR DATA CENTERS AND FOR TELECOM

Under development:

Data rate: 800 Gb/s

Symbol rate: 100 Gbaud

Typical data rate: 100-400 Gb/s

Typical symbol rate: 25-50 GBaud

- PSM4 (4 parallel fibers)
- WDM (4 wavelengths)
- PAM4
- Coherent (2 polarisations + QPSK)
- Coherent (16-QAM)

Ayar Labs

Finisar

ACACIA COMMUNICATIONS, INC.

CISCO

Inphi Think fast.

JUNIPER NETWORKS

aurrion

CISCO LIGHTWIRE

ELENION TECHNOLOGIES

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TeraXion

molex

ciena

IBM

Mellanox TECHNOLOGIES

KOTURA

LUXTERA NANOPHOTONIC INTEGRATED CIRCUITS

CISCO

Caliopa

HUAWEI

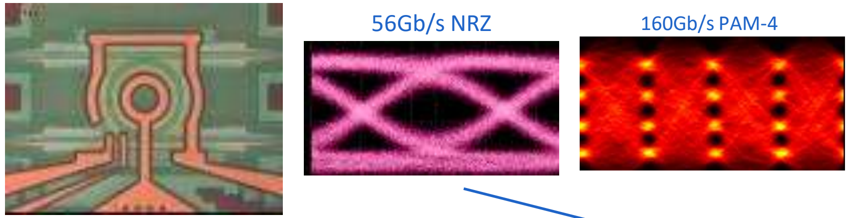
GHENT UNIVERSITY

imec

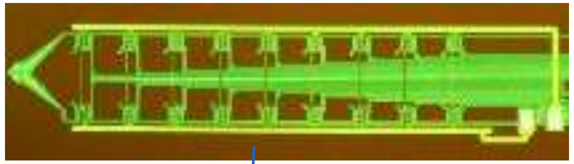
Typical Silicon Photonics Platform

Enabling 56Gb/s+ Transceivers

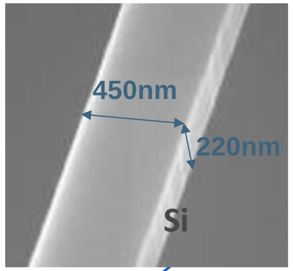
56+Gb/s Silicon Ring Modulator



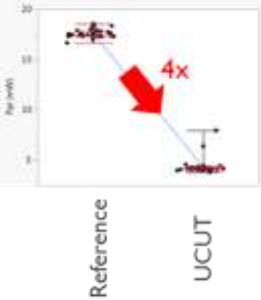
Silicon WDM filters



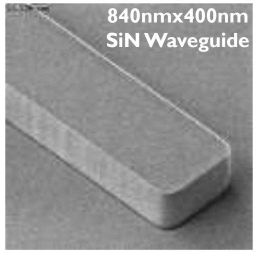
Low-loss high-density passive waveguide circuits

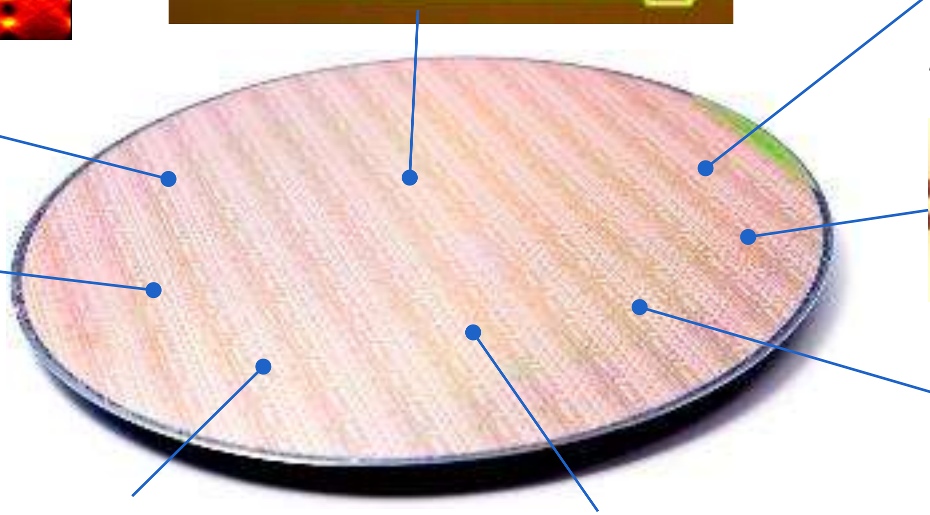


Low Thermo-Optic Power Consumption

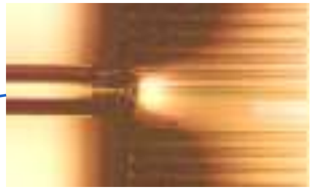


Integrated SiN waveguides (0.2-2.5dB/cm)

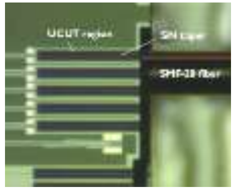




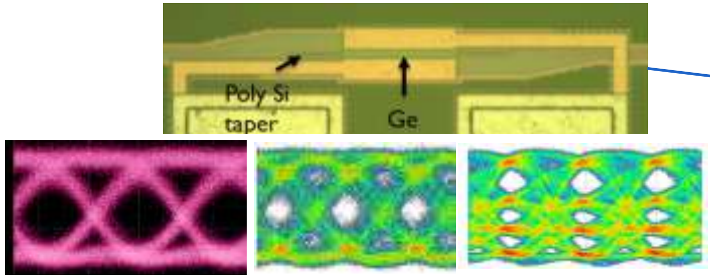
Edge Coupler 3um MFD (<2dB)



SiN Edge Coupler 9um MFD (<3dB)

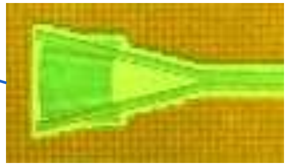


56-128Gb/s GeSi Electro-Absorption Modulator

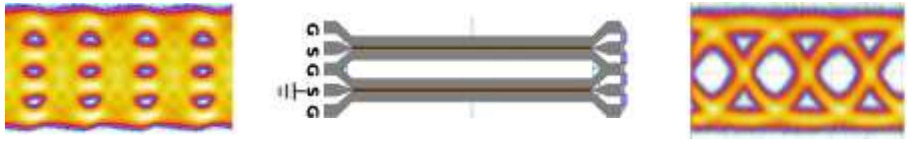


56Gb/s NRZ 100Gb/s NRZ 128Gb/s PAM-4

SMF Grating Coupler (2dB/5dB)

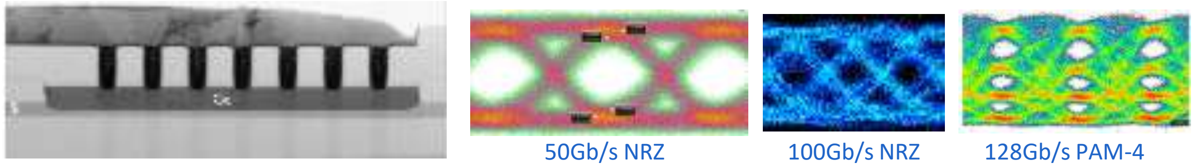


56Gb/s Silicon Mach-Zehnder Modulator



106Gb/s PAM-4 56Gb/s NRZ

56-128Gb/s Ge Photodetector

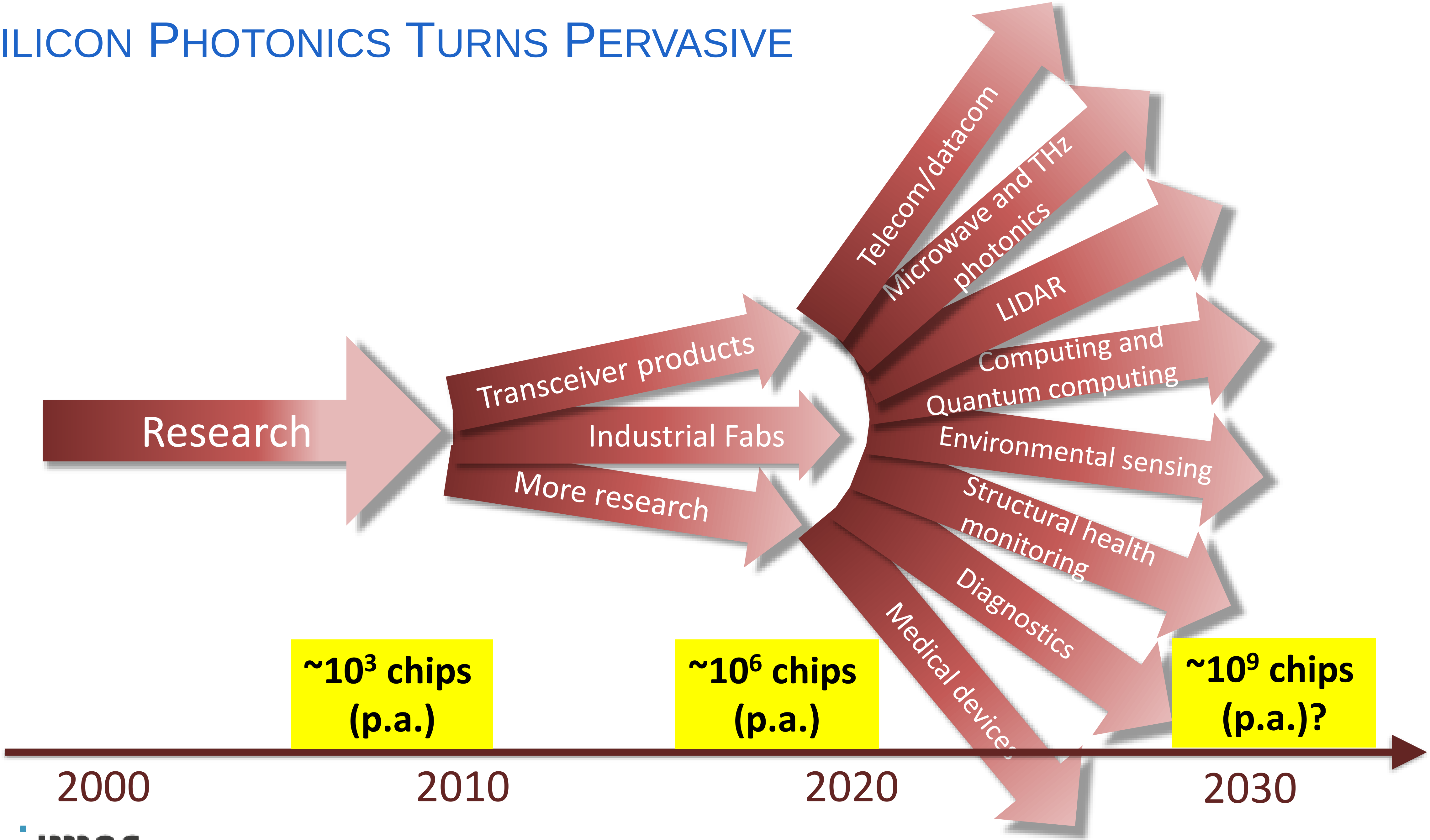


50Gb/s NRZ 100Gb/s NRZ 128Gb/s PAM-4

Pictures, courtesy of imec

Other platforms (Thick SOI, electronic-photonic co-integration, SiN) have complementary assets.

SILICON PHOTONICS TURNS PERVASIVE



Research

Transceiver products

Industrial Fabs

More research

Telecom/datacom

Microwave and THz photonics

LIDAR

Computing and Quantum computing

Environmental sensing

Structural health monitoring

Diagnostics

Medical devices

~10^3 chips (p.a.)

~10^6 chips (p.a.)

~10^9 chips (p.a.)?

2000

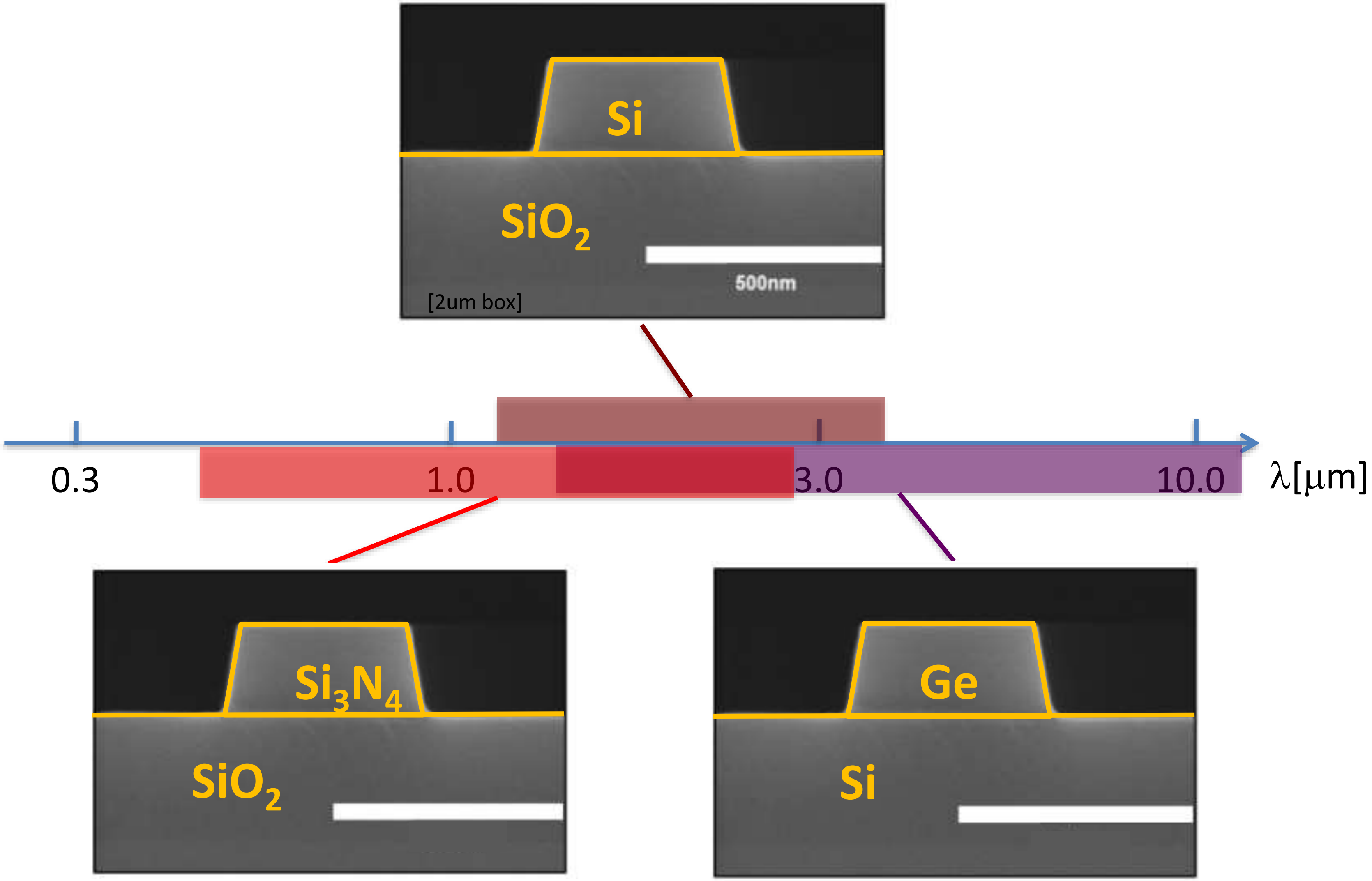
2010

2020

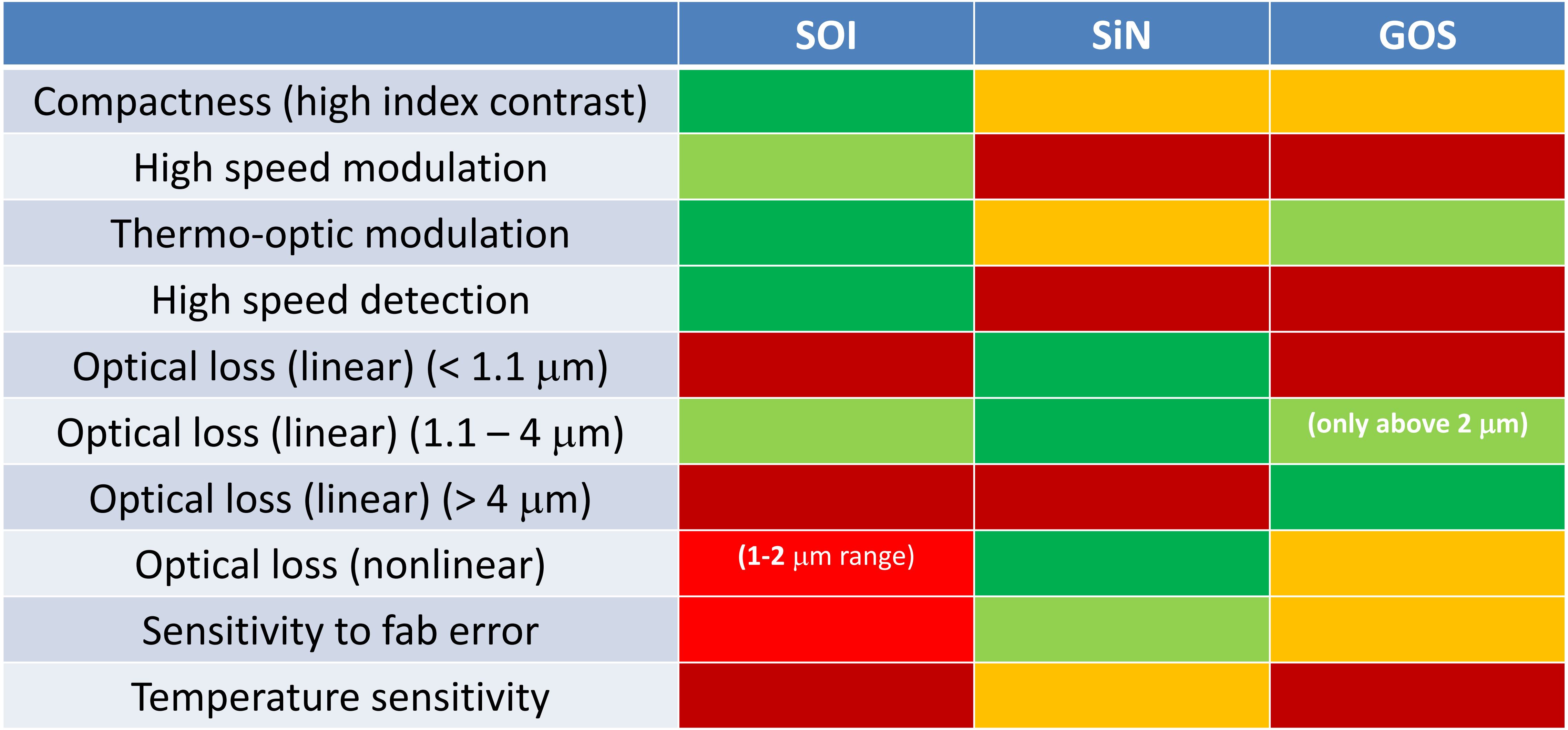
2030

Silicon photonics: extending the wavelength range

Without leaving the CMOS fab



Complementarity of SOI and SiN and Ge-on-Si (GOS)



	SOI	SiN	GOS
Compactness (high index contrast)	🟩	🟧	🟧
High speed modulation	🟢	🟥	🟥
Thermo-optic modulation	🟩	🟧	🟢
High speed detection	🟩	🟥	🟥
Optical loss (linear) (< 1.1 µm)	🟥	🟩	🟥
Optical loss (linear) (1.1 – 4 µm)	🟢	🟩	🟢 (only above 2 µm)
Optical loss (linear) (> 4 µm)	🟥	🟥	🟩
Optical loss (nonlinear)	🔴 (1-2 µm range)	🟩	🟧
Sensitivity to fab error	🔴	🟢	🟧
Temperature sensitivity	🟥	🟧	🟥

OUTLINE

Brief introduction to silicon and silicon nitride PICs

➡ Spectroscopic sensing modalities

On-chip spectrometers

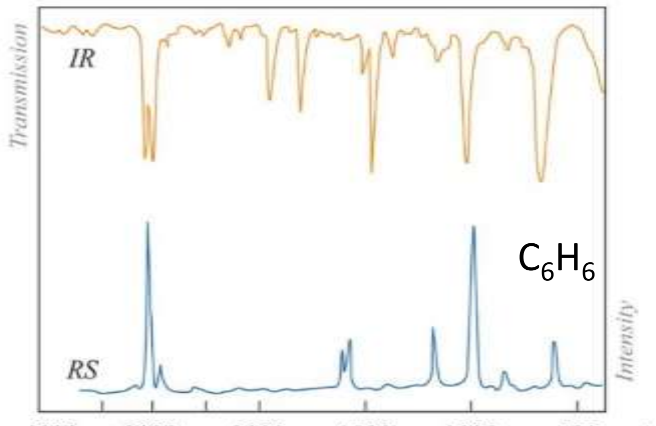
On-chip tunable lasers

On-chip Raman spectroscopy

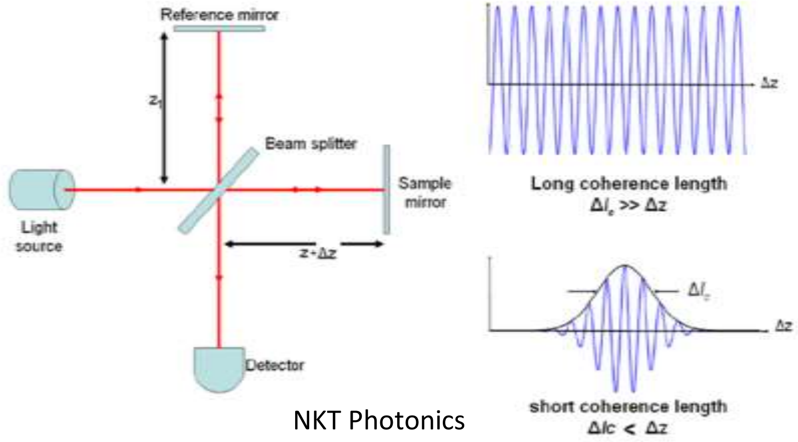
Application cases

OPTICAL SENSING MODALITIES (WHERE SILICON PHOTONICS CAN HELP)

Vibrational spectroscopy (absorption, Raman)

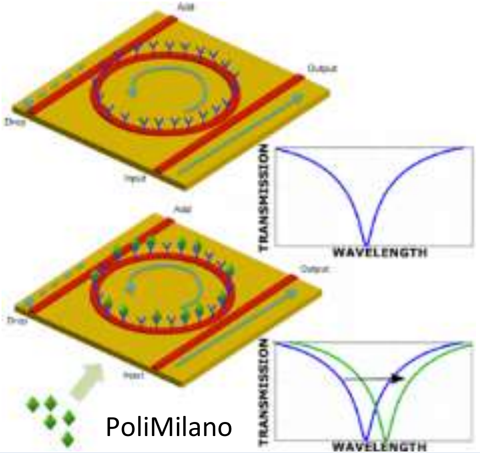


3D imaging (Lidar, OCT, LDV)



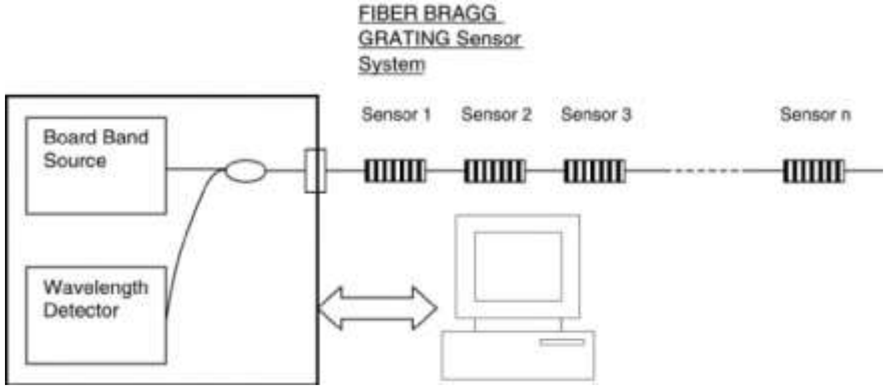
NKT Photonics

Refractive index sensing (biosensing, gas sensing)



PoliMilano

Fiber sensor readout (FBG, Brillouin, Raman)



EXAMPLES OF ABSORPTION SPECTRA

Wavenumber= 1/wavelength

Dyes

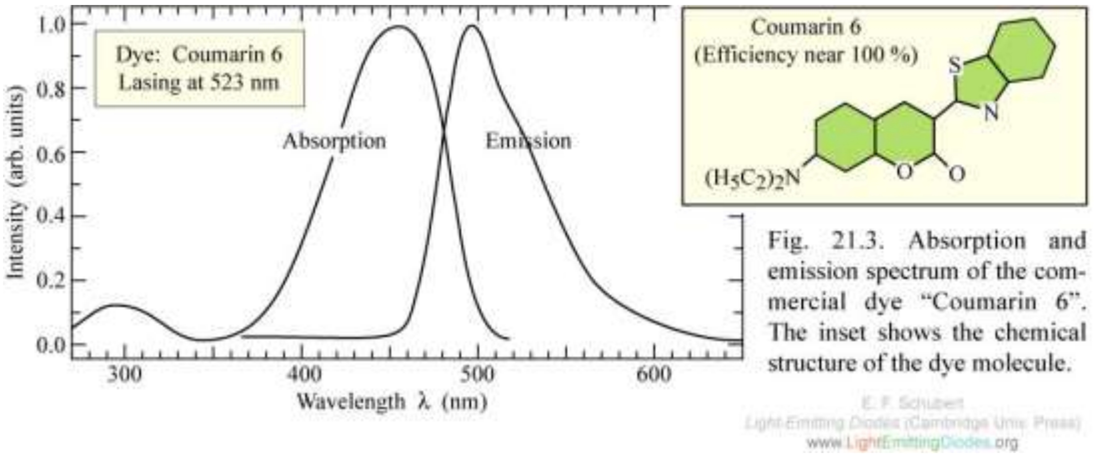
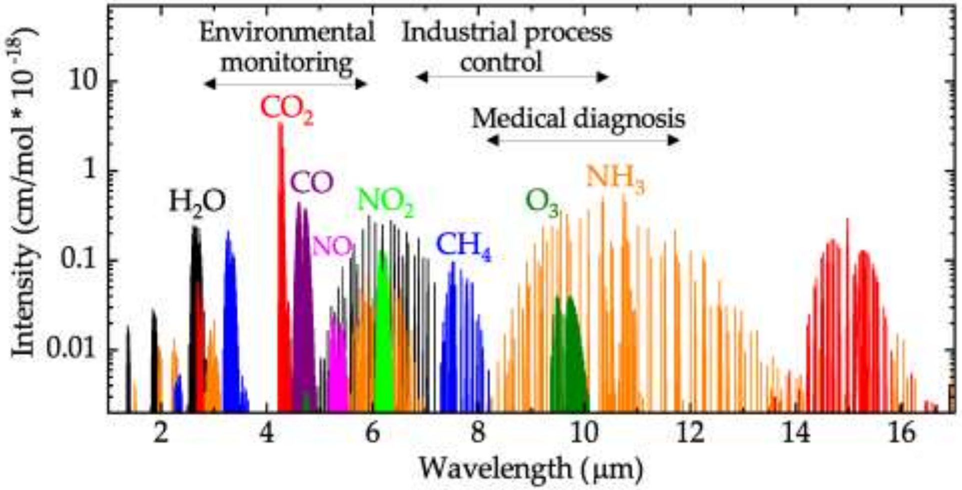


Fig. 21.3. Absorption and emission spectrum of the commercial dye "Coumarin 6". The inset shows the chemical structure of the dye molecule.

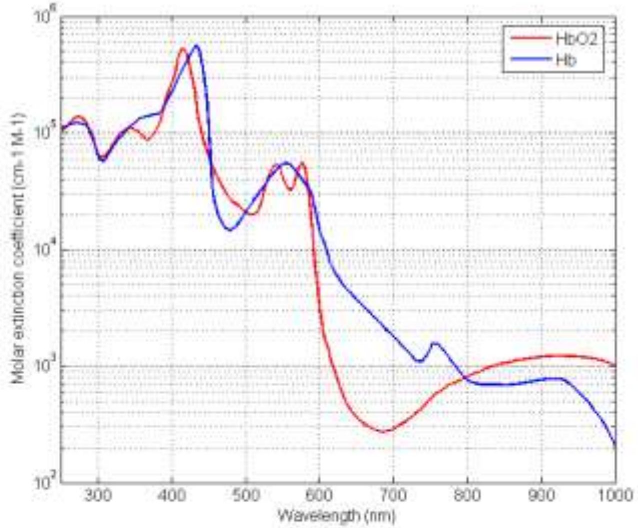
E. Schubert, Light Emitting Diodes (Cambridge UP)

Gases

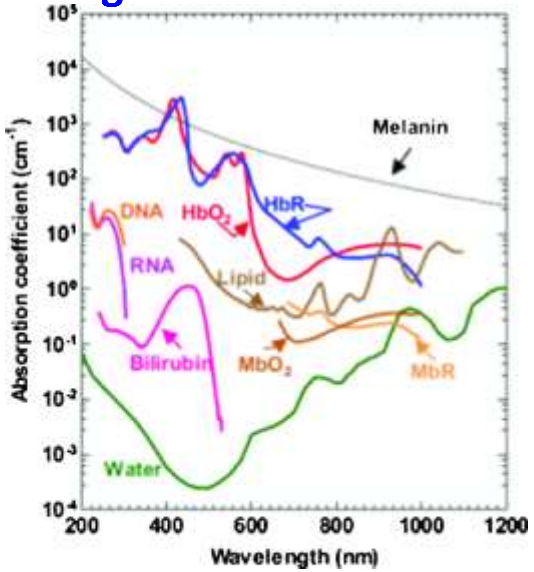


D. Popa, Sensors (2019) doi:10.3390/s19092076

Hemoglobin



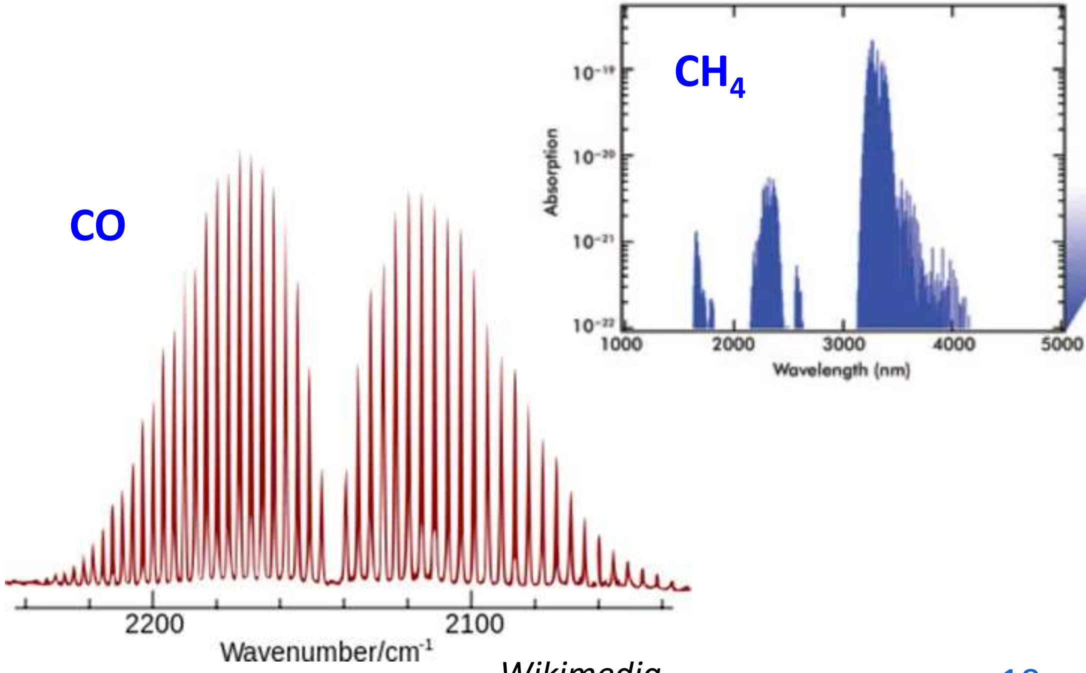
Biological molecules



W. Liu, Photoacoustics (2016) doi:10.1016/j.pacs.2016.05.001

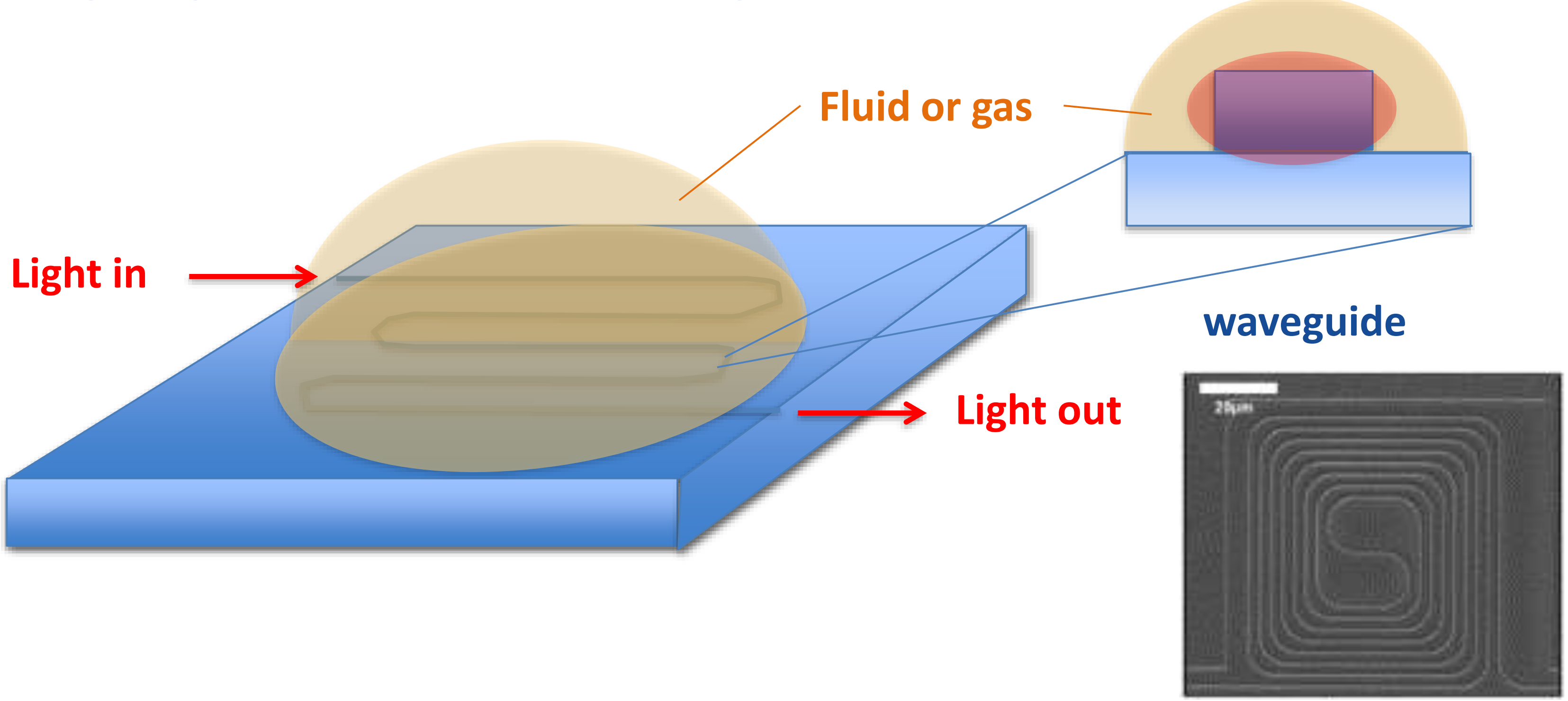
CO

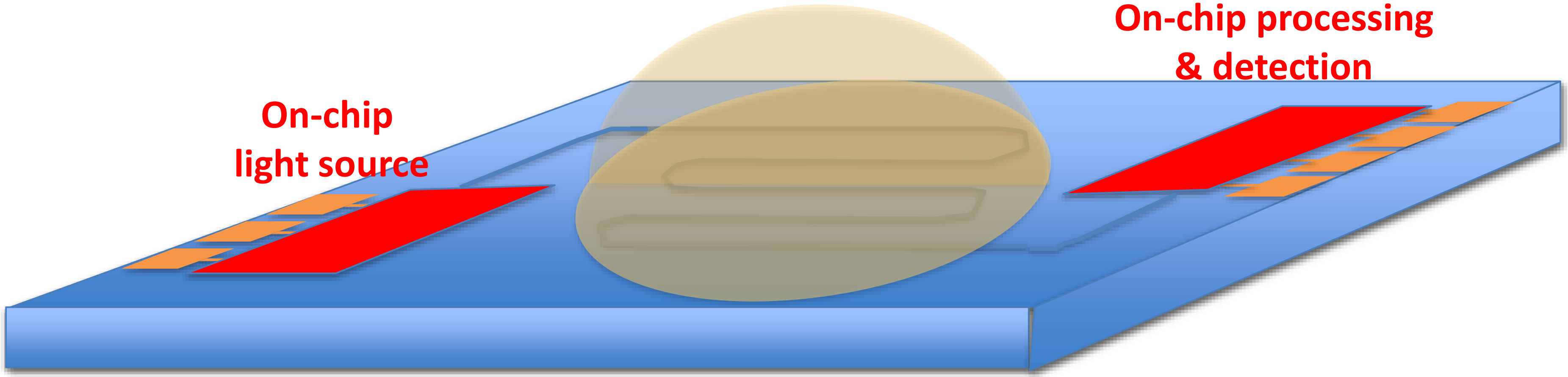
CH_4



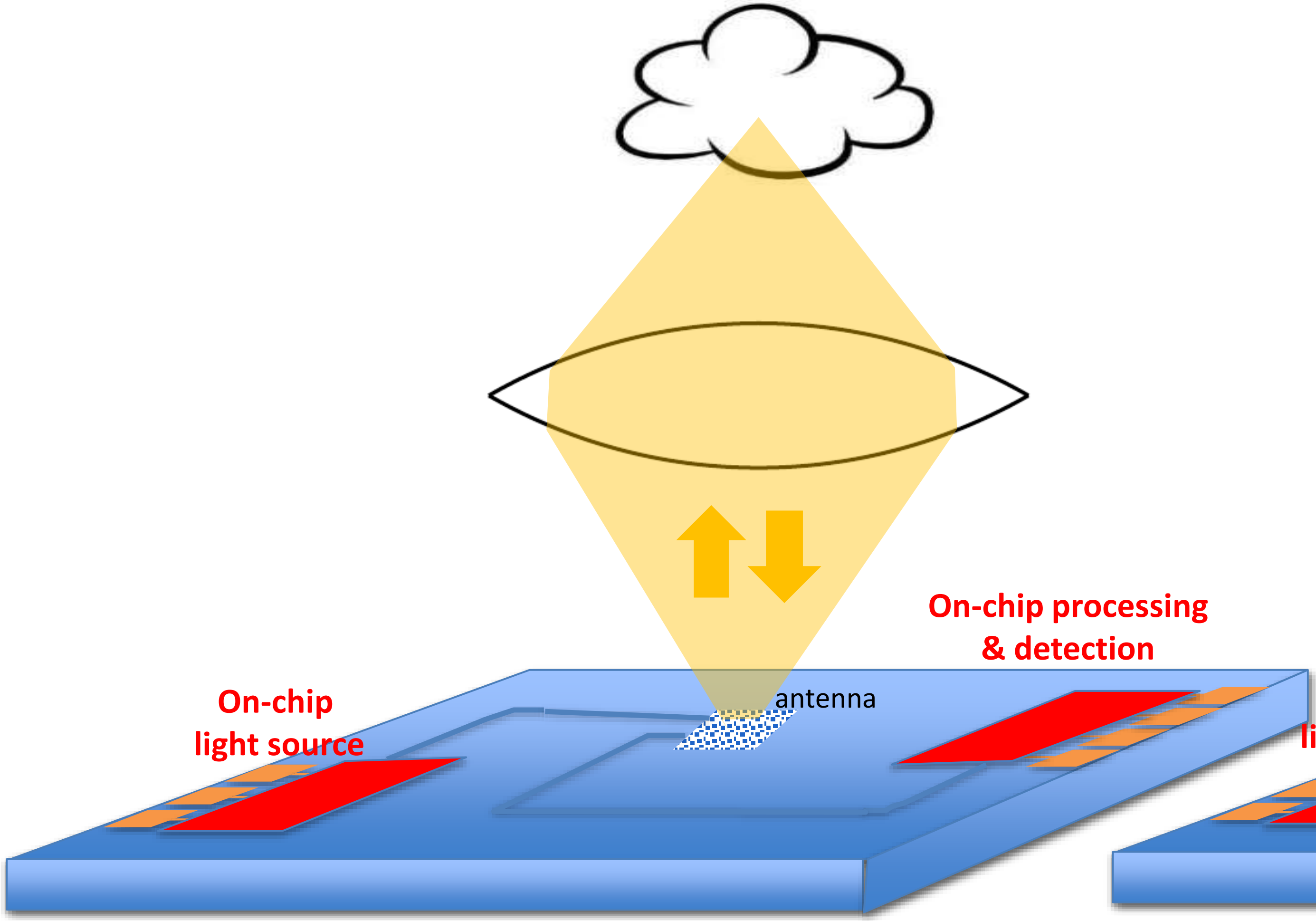
Wikimedia

NEAR FIELD SENSING: ANALYTE IN PROXIMITY

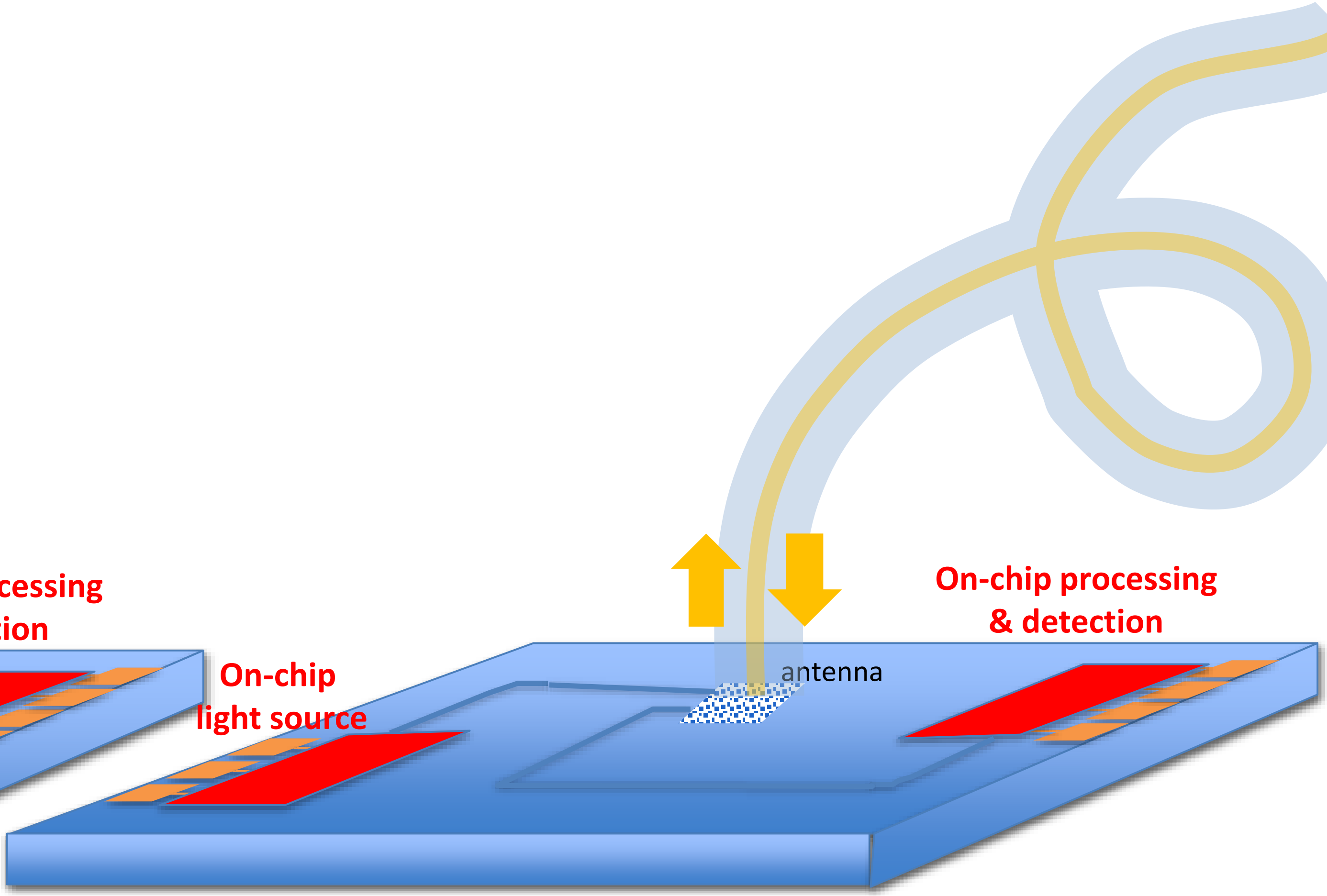




FAR-FIELD SENSING: SENSED AREA IS REMOTE



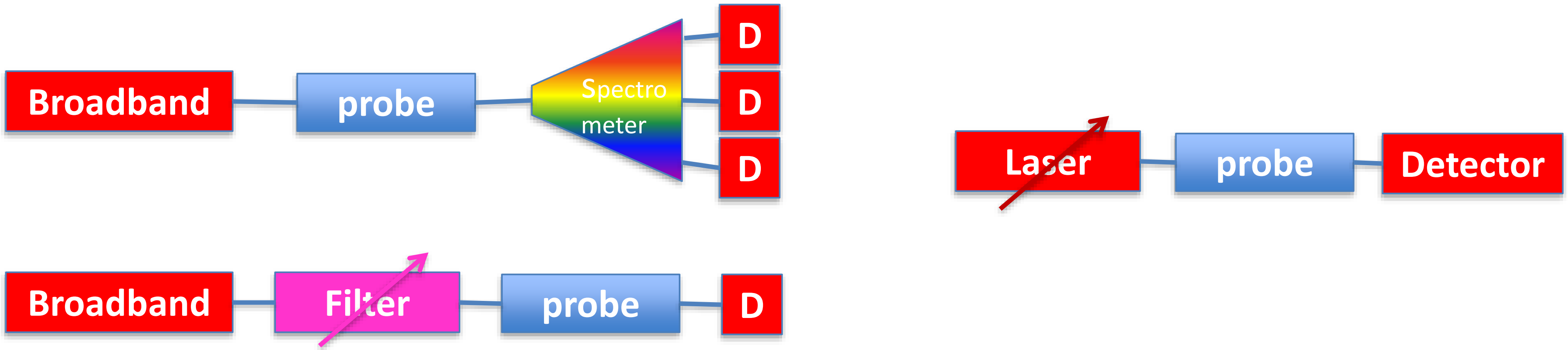
Remote sensing through free space imaging



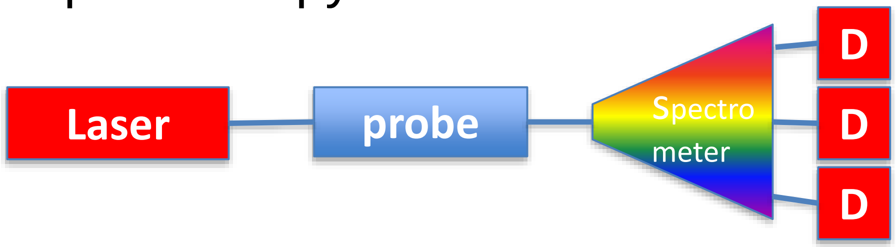
Remote sensing through fiber interconnect

SPECTROSCOPY-ON-CHIP: APPROACHES

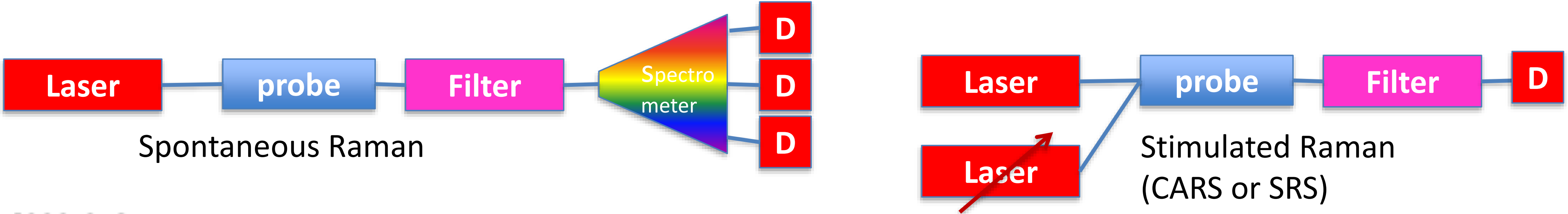
Absorption spectroscopy



Fluorescence spectroscopy



Raman spectroscopy



Spontaneous Raman

Stimulated Raman
(CARS or SRS)

SPECTROSCOPY-ON-CHIP: APPROACHES

Absorption spectroscopy (eg Tunable Diode Laser Absorption Spectroscopy = TDLAS)


Laser
probe
Detector

$$T(\lambda) = e^{-(\alpha(\lambda)+\alpha_s)L}$$

dT/dα max when $(\alpha(\lambda) + \alpha_S)L=1$

Optimal (total) loss: 4.3 dB

When $\alpha_{tot}L<<1$: signal ~ $1- \alpha_{tot}L$

"Indirect" absorption spectroscopy

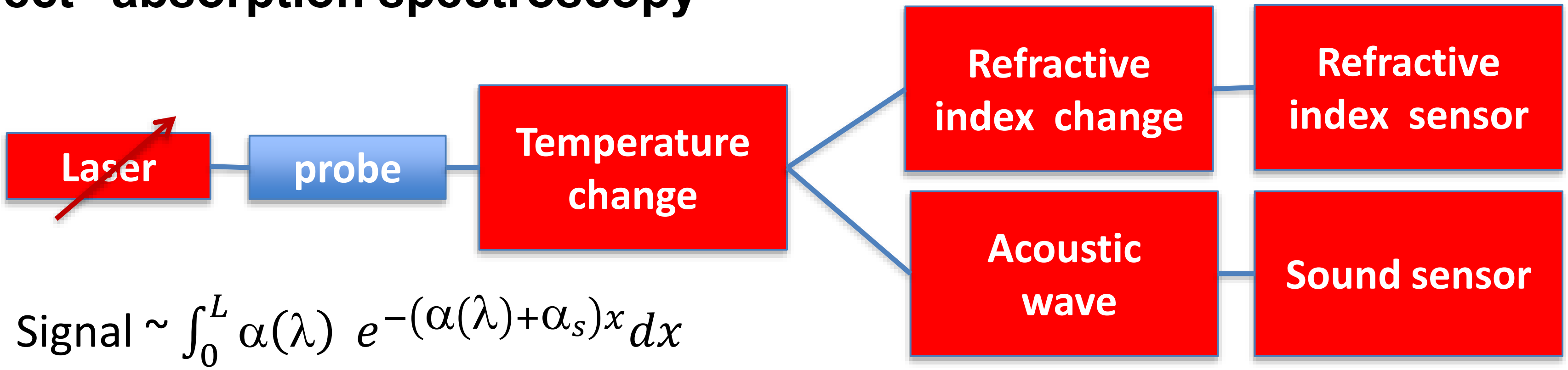

Laser
probe
Temperature change
Refractive index change
Refractive index sensor
Acoustic wave
Sound sensor

Photo-thermal spectroscopy

Photo-acoustic spectroscopy

Signal ~ $\int_0^L \alpha(\lambda)\; e^{-(\alpha(\lambda)+\alpha_s)x} dx$

No optical detector

When $\alpha_{tot}L<<1$: signal ~ $\alpha(\lambda)L$

SPECTROSCOPY-ON-CHIP: APPROACHES

Dispersion spectroscopy

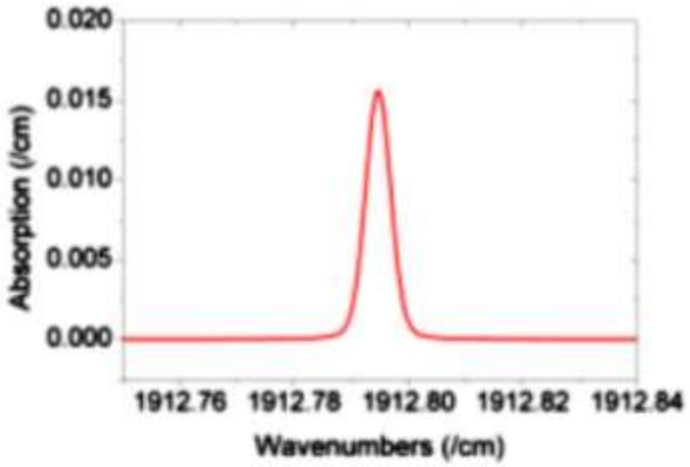
Kramers-Kronig: $$n(\omega) = 1 + \frac{c}{\pi} \int_{0}^{+\infty} \frac{\alpha(\omega')}{\omega'^2 - \omega^2} d\omega'$$

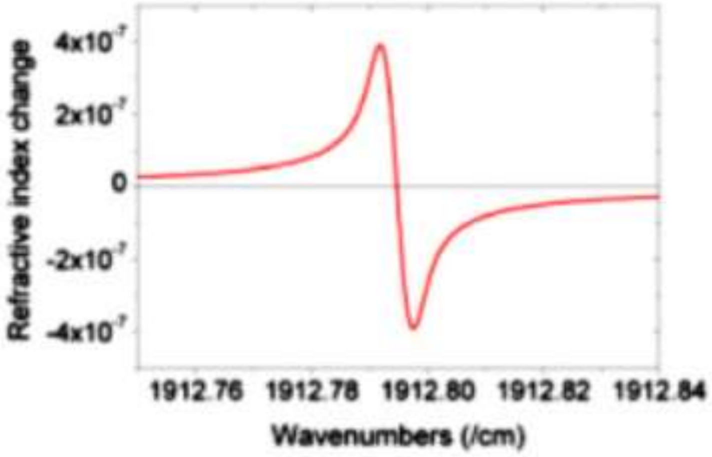
Chirped laser

n(ω) ⇒ delay(ω) ⇒ RF beat frequency (ω)

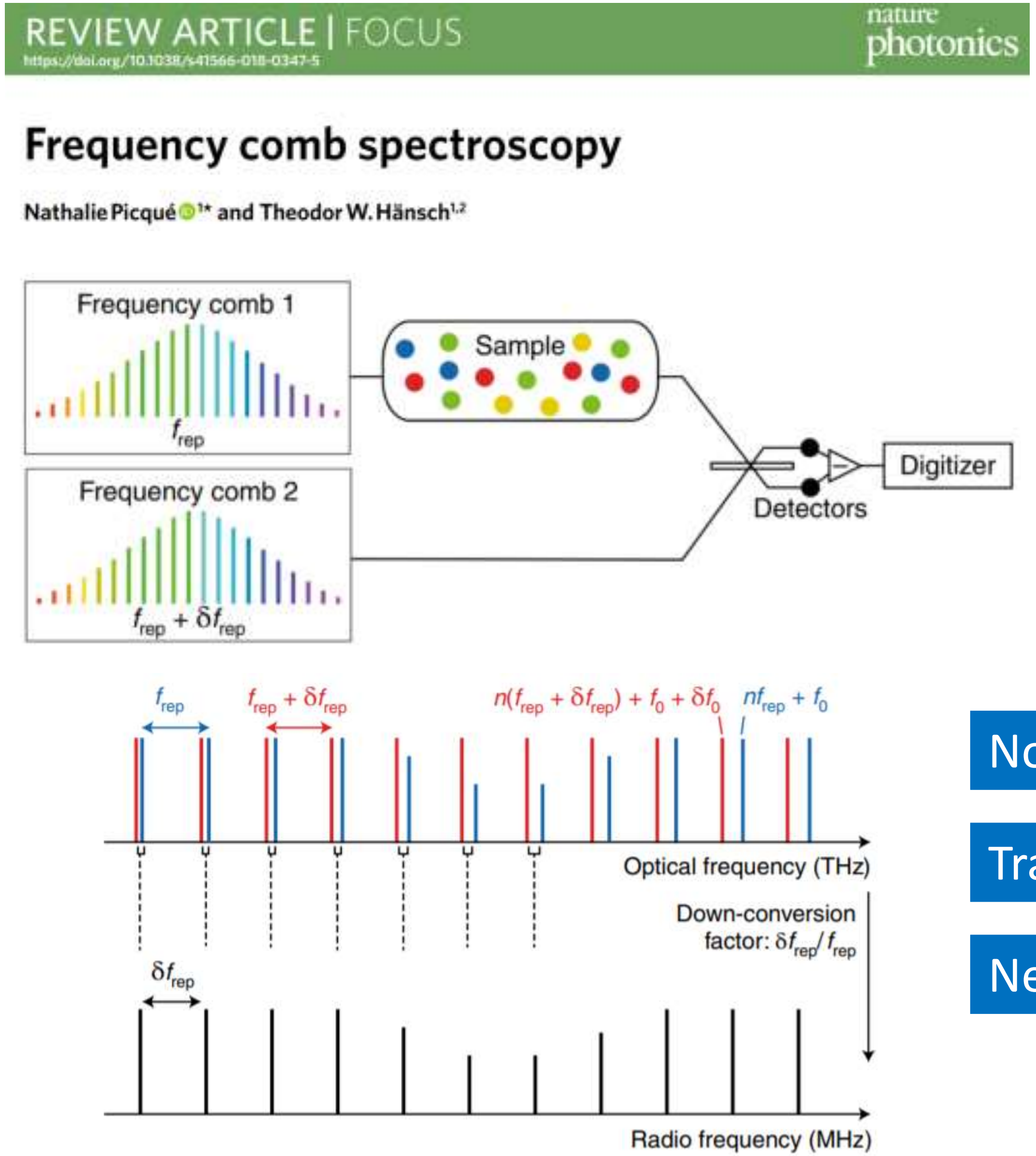
Advantages:

- baseline-free signal
- not prone to amplitude noise of laser source





DUAL COMB ABSORPTION SPECTROSCOPY



REVIEW ARTICLE | FOCUS

https://doi.org/10.1038/s41566-018-0347-5

nature photonics

Frequency comb spectroscopy

Nathalie Picqué[1*] and Theodor W. Hänsch[1,2]

No need for laser tuning

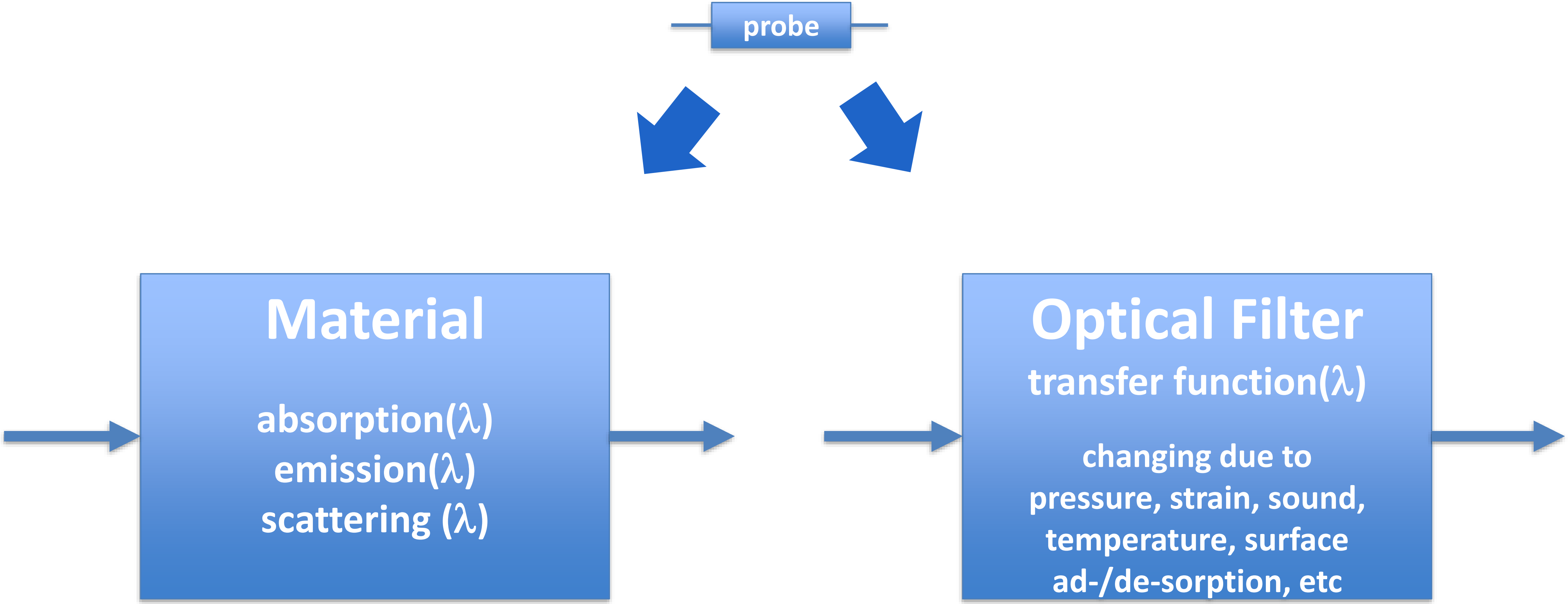
Translation of optical spectrum to RF spectrum

Need for high speed detectors

WHAT IF ABSORPTION IS WEAK?

- increase path length
  - spirals on chip
  - on-chip integrating sphere
  - resonant optical device
- (non-optical) resonant signal enhancement of modulated signals
- densification of analyte
  - adsorption to waveguide surface
  - adsorption in a mesoporous coating covering waveguide

PROBE



probe

Material

absorption(λ)
emission(λ)
scattering (λ)

Optical Filter

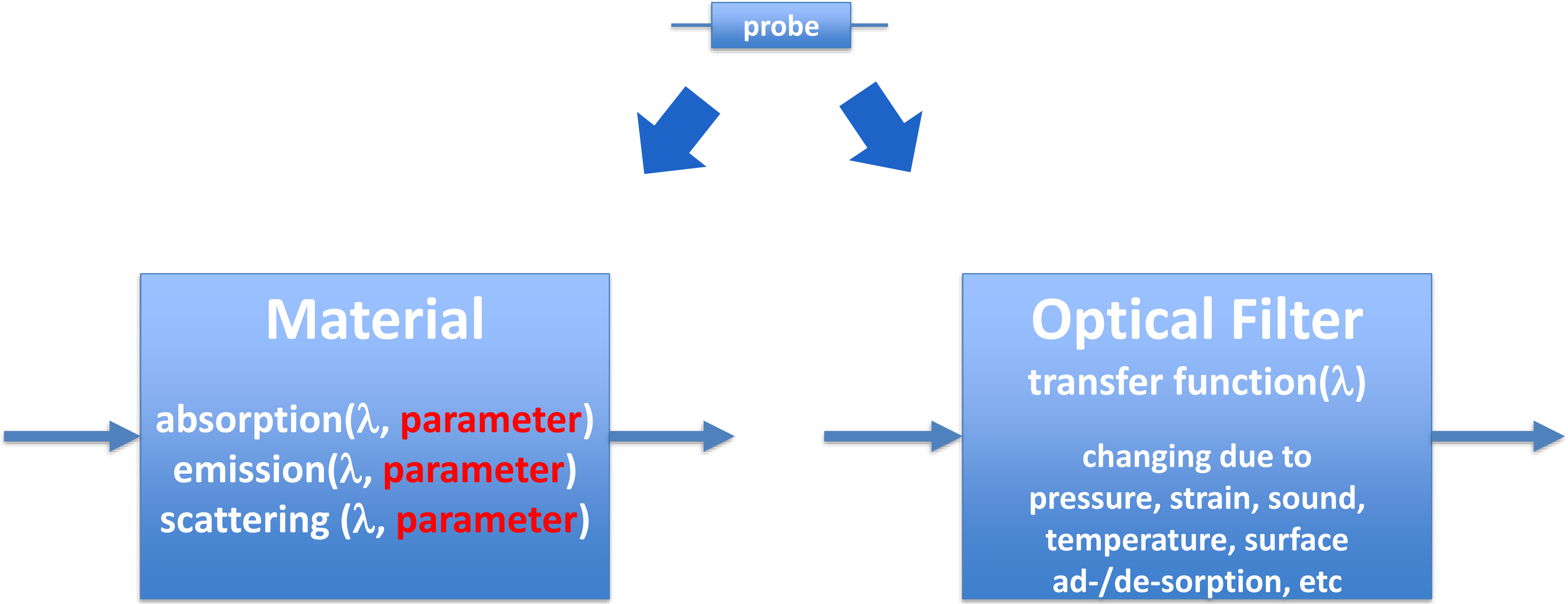
transfer function(λ)

changing due to pressure, strain, sound, temperature, surface ad-/de-sorption, etc

Identify a material
and measure its density

Identify a physical/chemical mechanism
and measure its amplitude

PROBE



probe

Material

absorption(λ, parameter)
emission(λ, parameter)
scattering (λ, parameter)

Optical Filter

transfer function(λ)

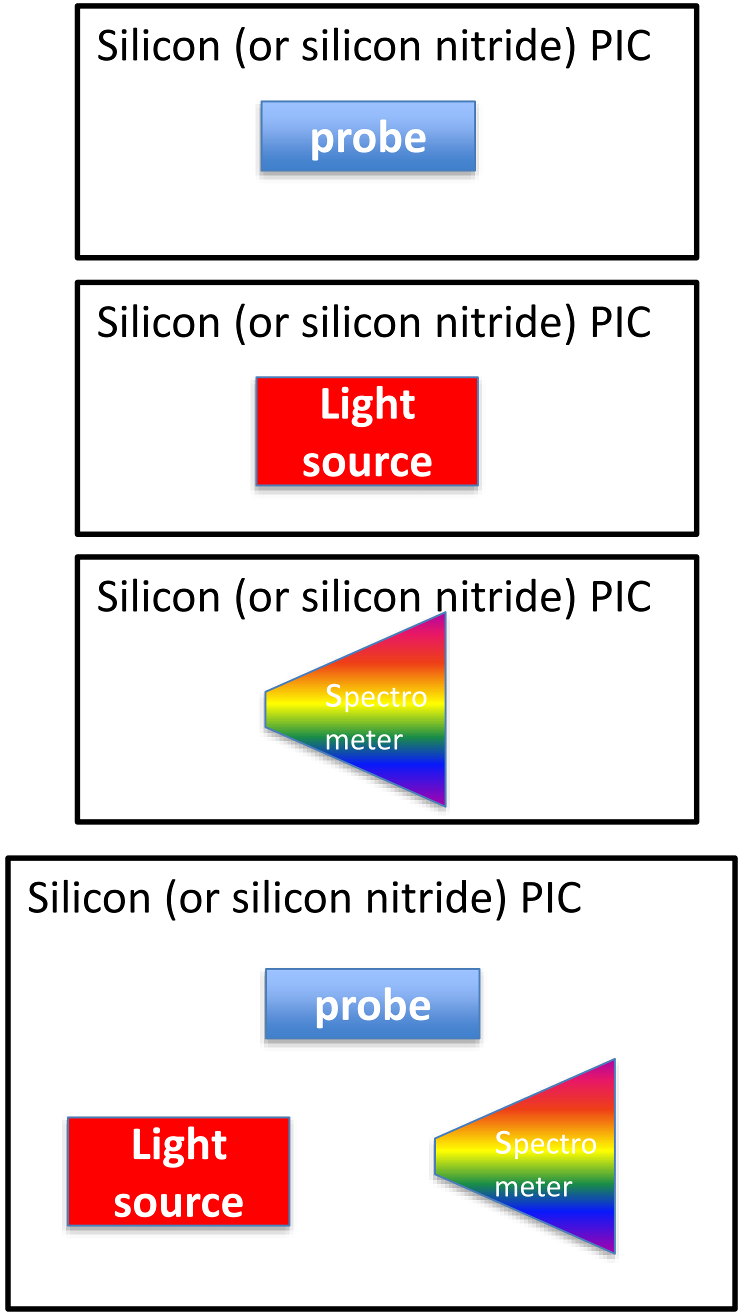
changing due to pressure, strain, sound, temperature, surface ad-/de-sorption, etc

Measure a physical/chemical parameter

Identify a physical/chemical mechanism and measure its amplitude

KEY COMPONENTS NEEDED

probe	Probe on-chip
Spectro meter	Integrated spectrometer
Broadband	Integrated broadband source
Laser	Integrated laser
Laser	Integrated tunable laser
Comb Laser	Integrated comb source



OUTLINE

Brief introduction to silicon and silicon nitride PICs

Spectroscopic sensing modalities

➡ On-chip spectrometers

On-chip tunable lasers

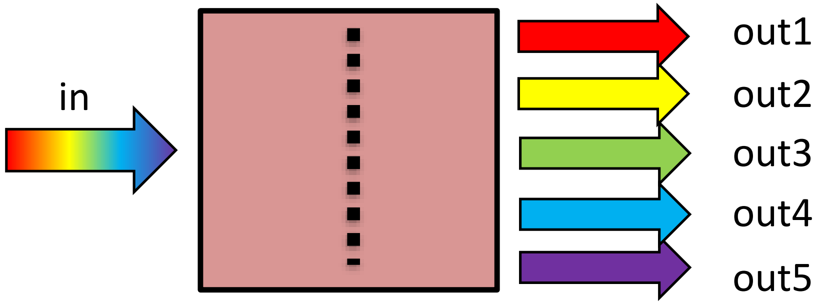
On-chip Raman spectroscopy

Application cases

SPECTROMETERS

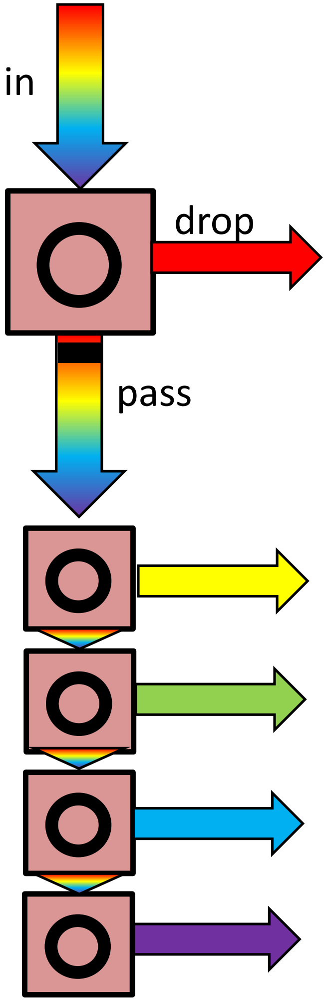
And Combinations!

Dispersive devices



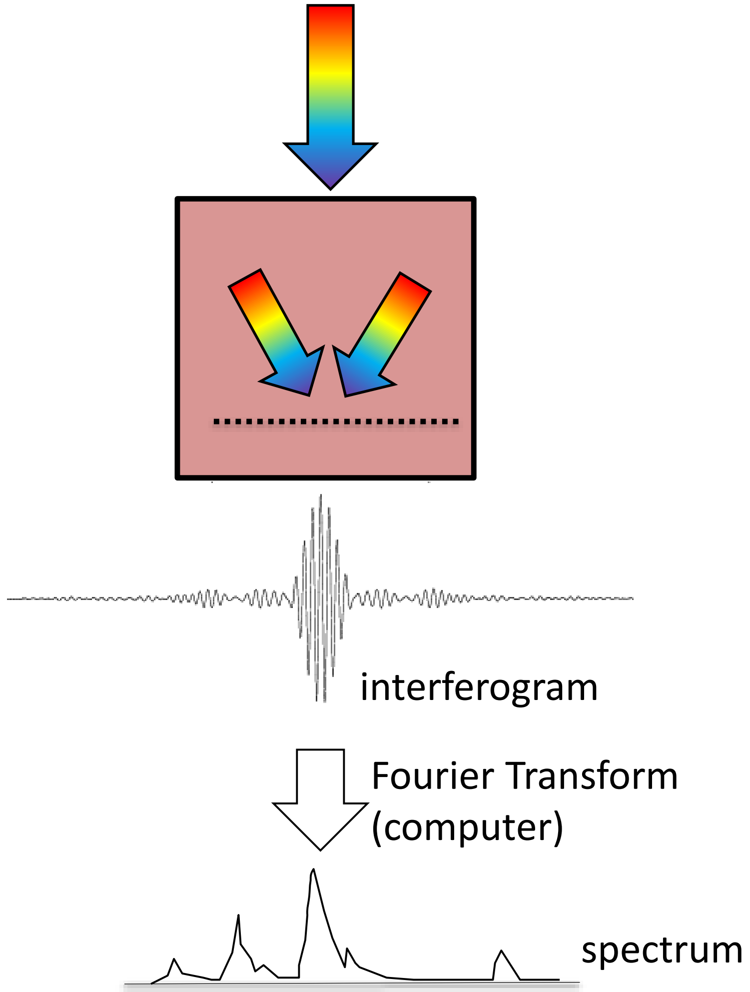
Mechanism used: grating diffraction (multi-beam interference)

Filter cascades



Mechanism used: resonance or interference or Bragg reflection

Fourier Transform



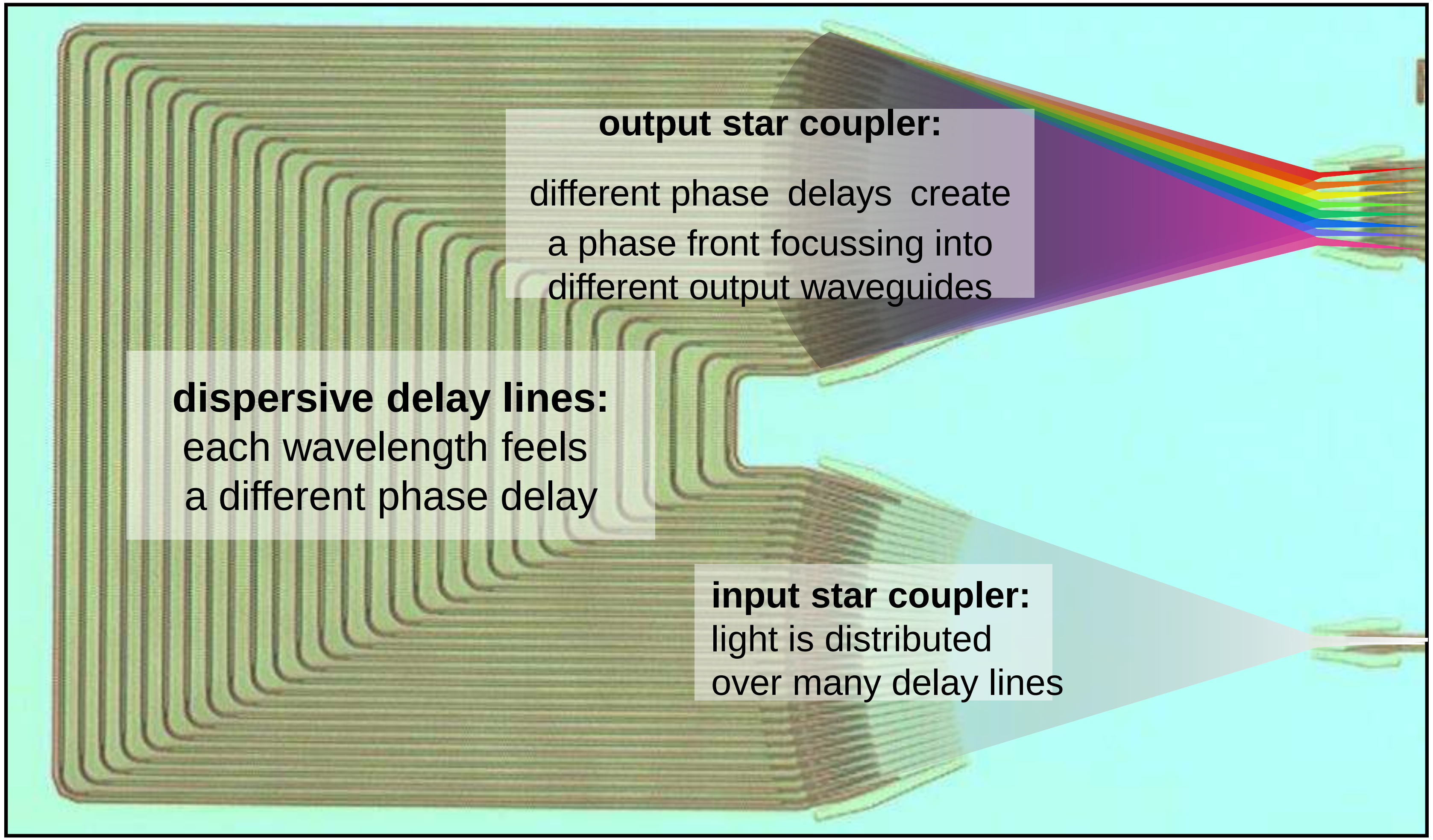
Mechanism used: two-beam interference

FIGURES OF MERIT

- Spectral resolution (channel spacing)
- Overall bandwidth (Free Spectral Range)
- Crosstalk and dynamic range
- Absolute wavelength accuracy
- Polarisation sensitivity
- Chip area needed
- Sensitivity to fabrication error
- Sensitivity to temperature
- Complexity of design

→ Many solutions depending on application context

ARRAYED WAVEGUIDE GRATING (AWG) SPECTROMETER (200 X 350 µM^2)

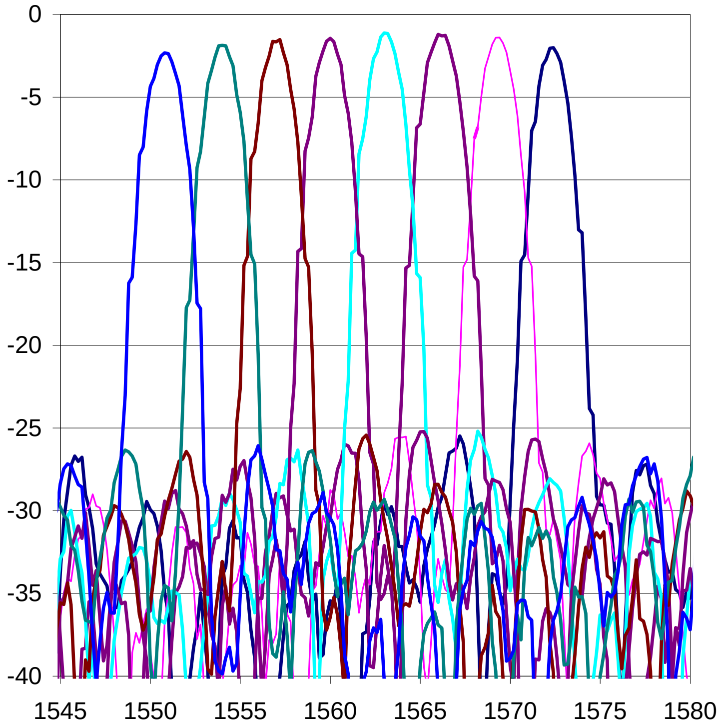


output star coupler:

different phase delays create a phase front focussing into different output waveguides

dispersive delay lines:
each wavelength feels a different phase delay

input star coupler:
light is distributed over many delay lines



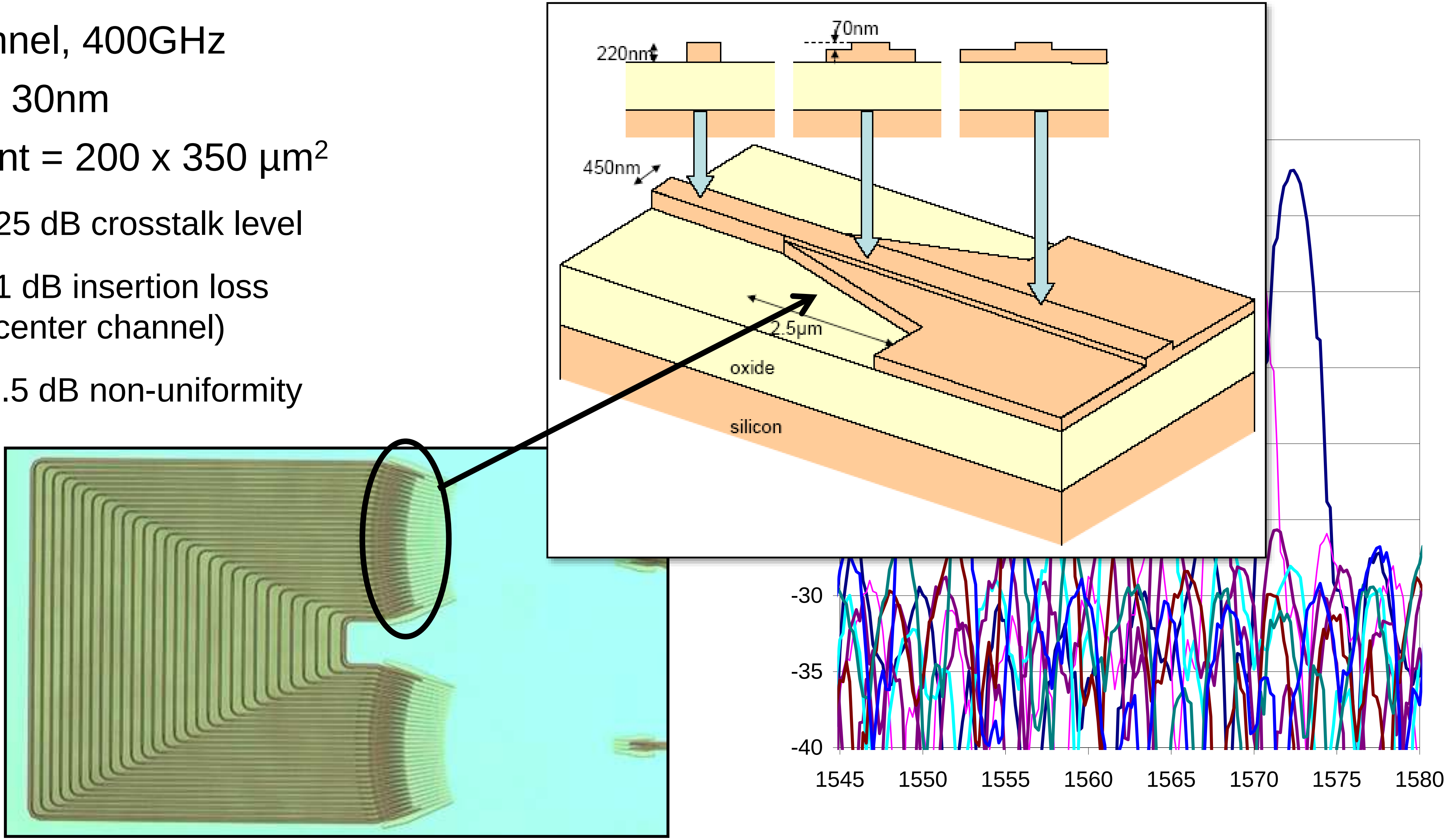
ARRAYED WAVEGUIDE GRATING

8-channel, 400GHz

FSR = 30nm

footprint = 200 x 350 µm^2

- -25 dB crosstalk level
- -1 dB insertion loss (center channel)
- 1.5 dB non-uniformity



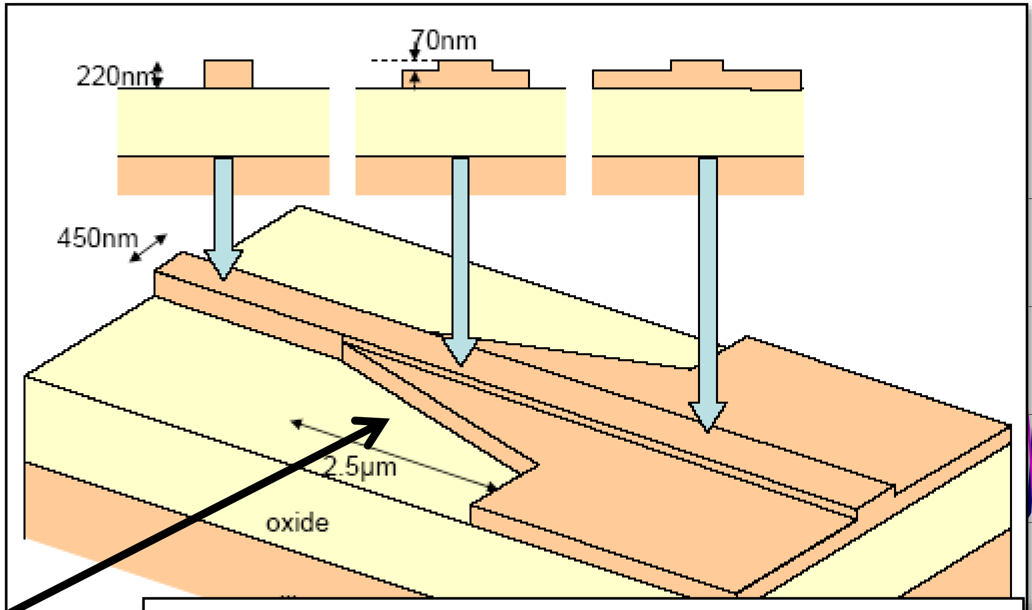
ARRAYED WAVEGUIDE GRATING DESIGN

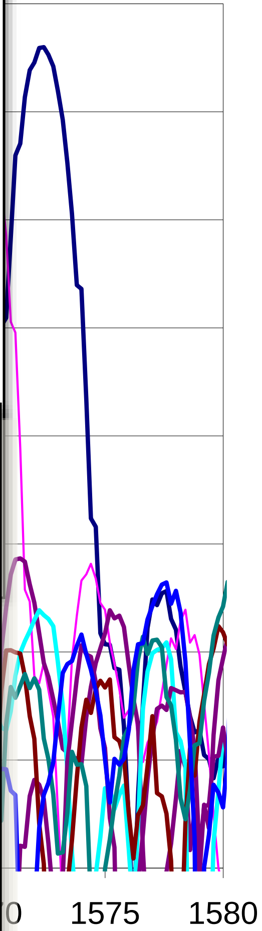
8-channel, 400GHz

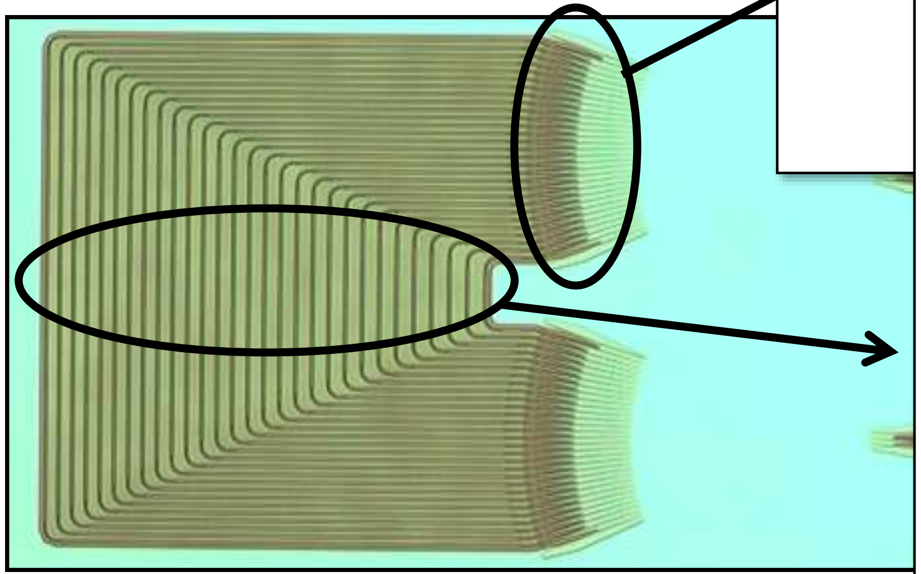
FSR = 30nm

footprint = 200 x 350 µm^2

- -25 dB crosstalk level
- -1 dB insertion loss (center channel)
- 1.5 dB non-uniformity

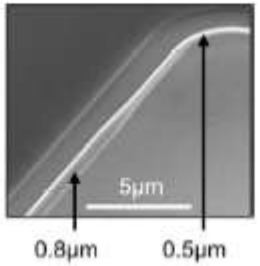






Decrease phase errors

- Use wider waveguides



- Align waveguides to grid
- See also: *P. Dumon, PhD thesis UGent 2007*
  S. Selvaraja, PhD thesis UGent 2014
  (http://photonics.intec.ugent.be)

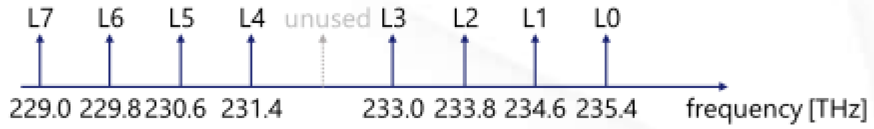
S-shaped AWG for IEEE 400GBase-LR8

Available on LUCEDA ACADEMY

AWG Generation ⇄ Simulation & Analysis ⇄ Finalization

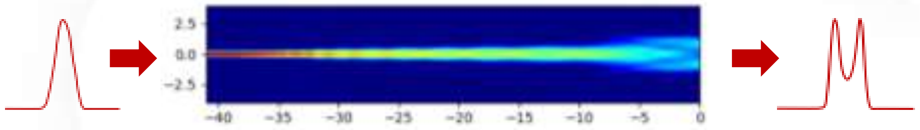
AWG Generation

Specifications

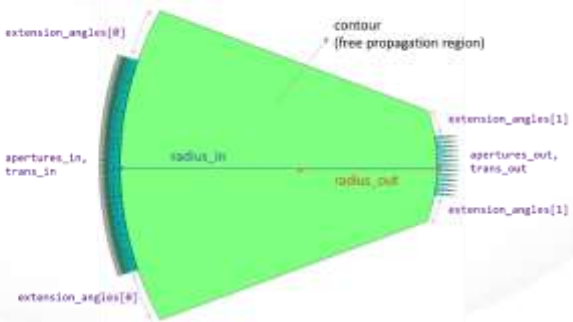


Subcomponents & Synthesis

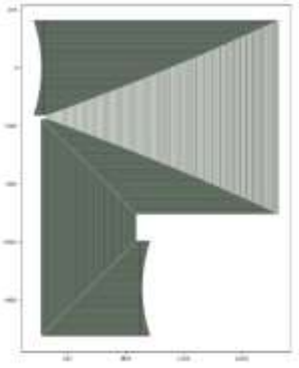
MMI aperture



Assembly



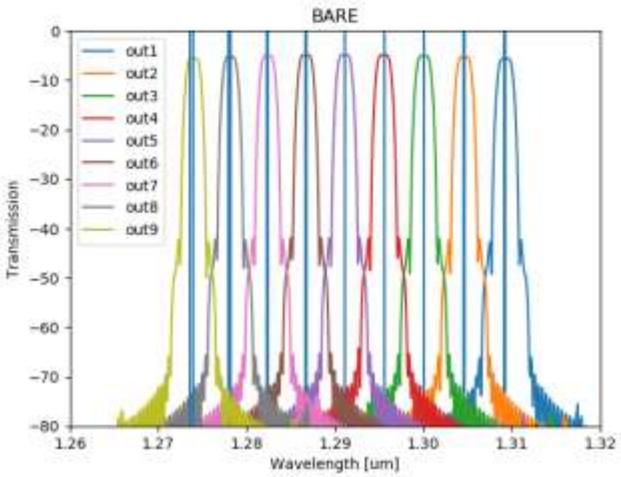
Star coupler



Waveguide array

Simulation & Analysis

Simulation

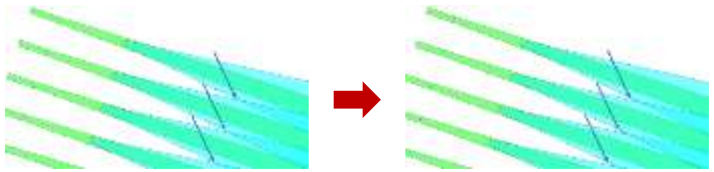


Analysis

- Peaks
- Crosstalk
- Insertion loss
- Nearest-neighbour crosstalk

Finalization

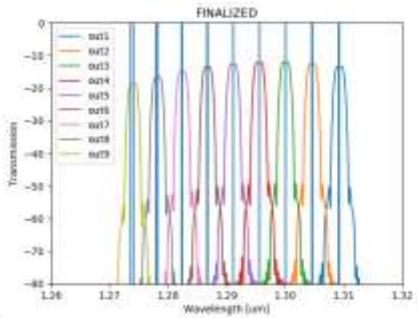
Tape-out prep

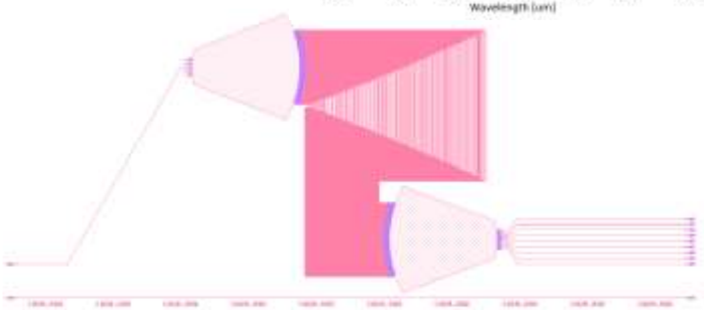


Acute angle patching

Routing

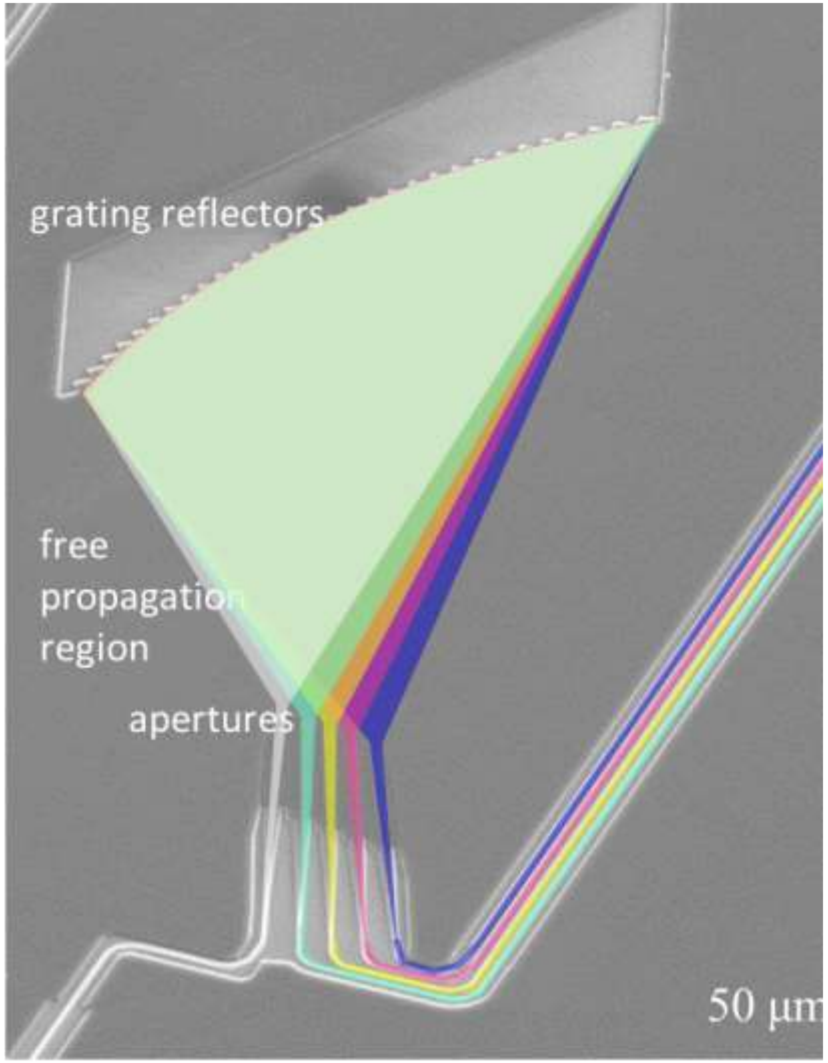
\+ FGC
\+ Ref. WG

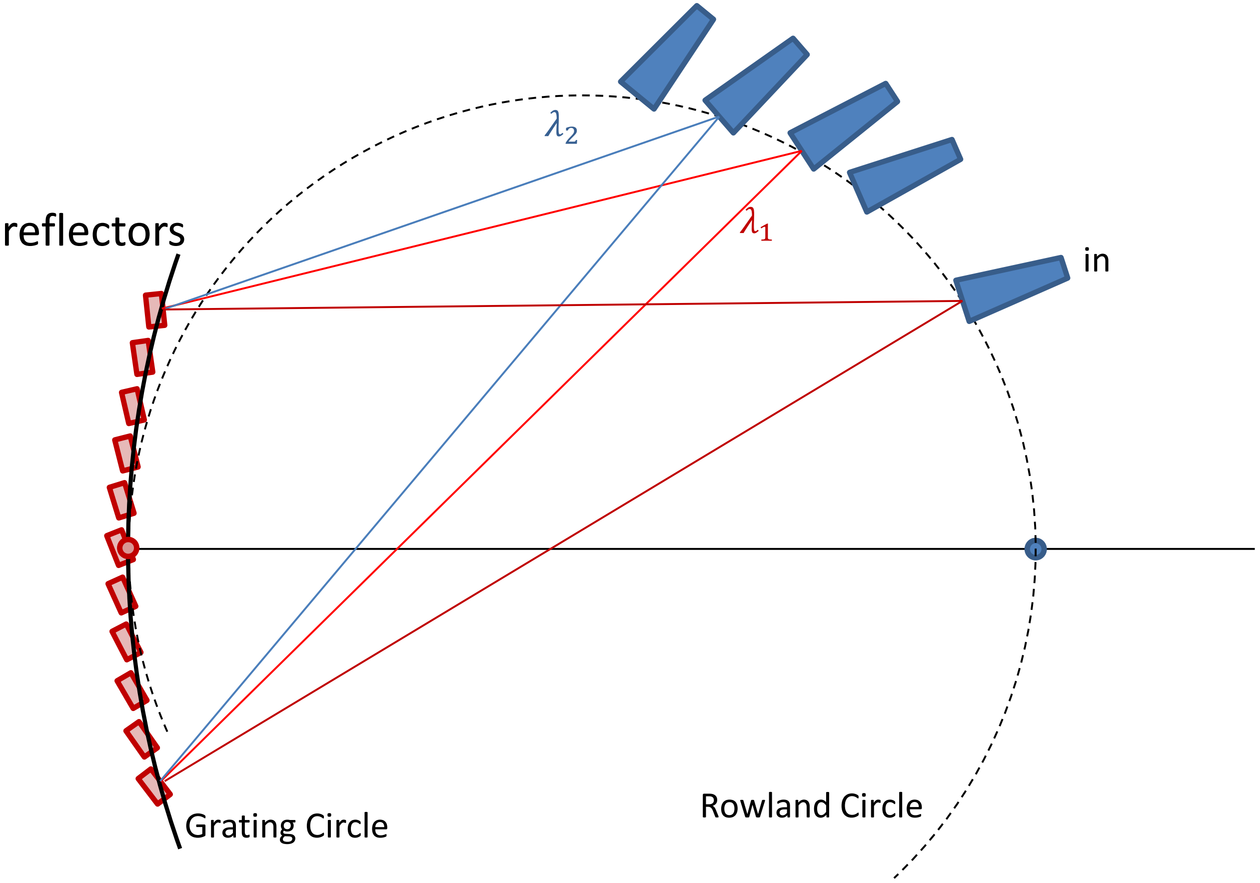




LUCEDA PHOTONICS

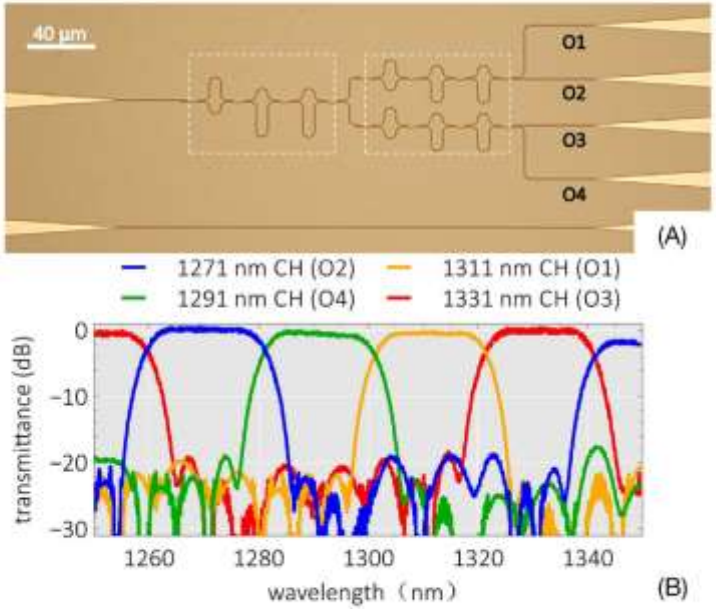
ECHELLE DIFFRACTION GRATINGS (EDG) AKA PLANAR CONCAVE GRATING (PCG)



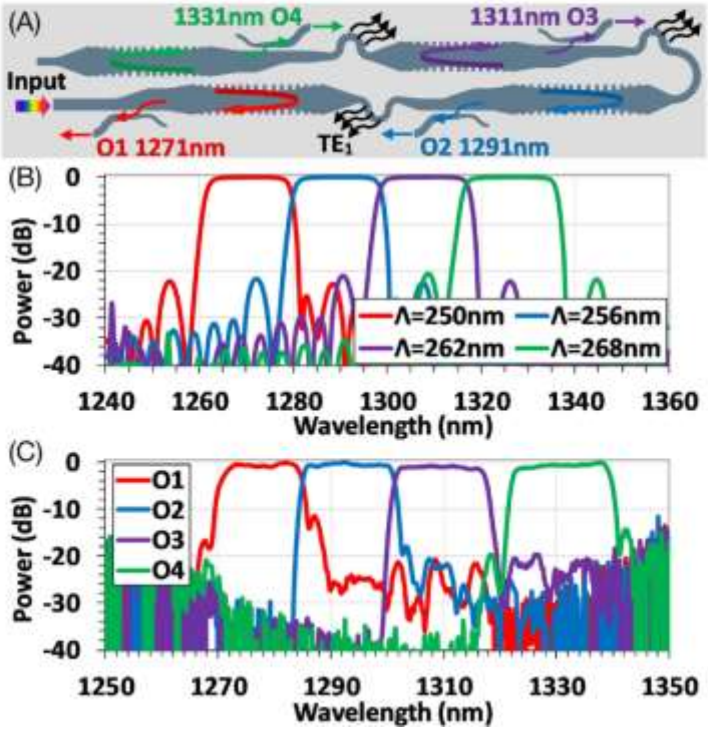


FILTER CASCADES

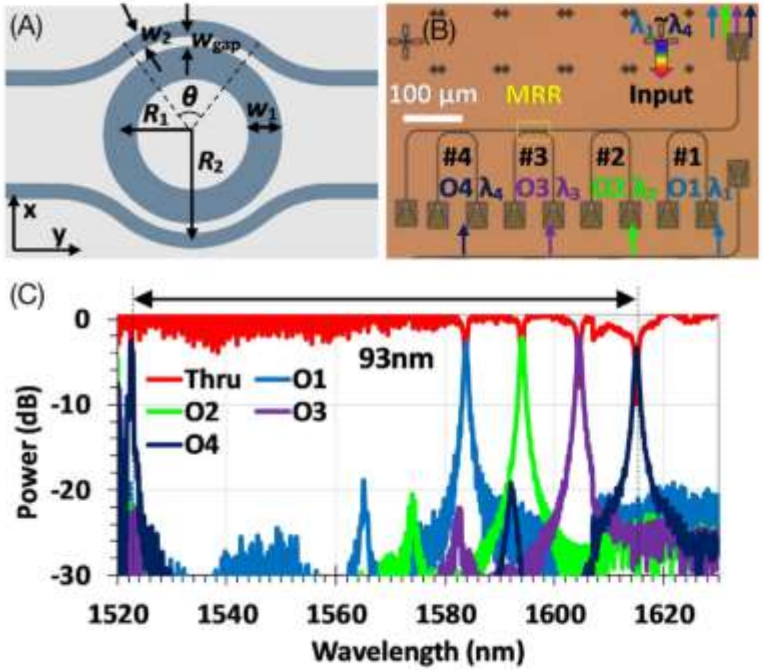
Mach-Zehnder Interferometers (MZI)



Distributed Bragg Reflectors (DBR)



Micro Ring Resonators (MRR)



D. Liu et al, Microw. Opt. Techn. Lett. 2020
https://doi.org/10.1002/mop.32509

REVIEWS OF SILICON MICRO RING RESONATORS

Laser Photonics Rev. **6**, No. 1, 47–73 (2012) / **DOI** 10.1002/lpor.201100017

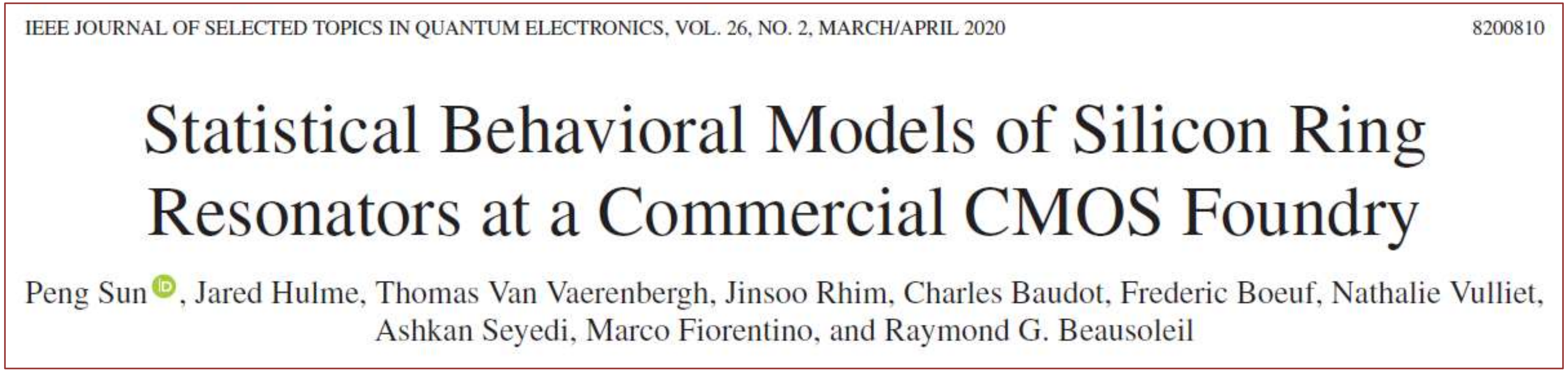
Silicon microring resonators

Wim Bogaerts*, Peter De Heyn, Thomas Van Vaerenbergh, Katrien De Vos, Shankar Kumar Selvaraja, Tom Claes, Pieter Dumon, Peter Bienstman, Dries Van Thourhout, and Roel Baets

IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 24, NO. 6, NOVEMBER/DECEMBER 2018 5900324

Integrated Silicon Photonic Microresonators: Emerging Technologies

Zhanshi Yao, Kaiyi Wu, Bo Xue Tan, Jiawei Wang, Yu Li, Yu Zhang, and Andrew W. Poon, *Member, IEEE*

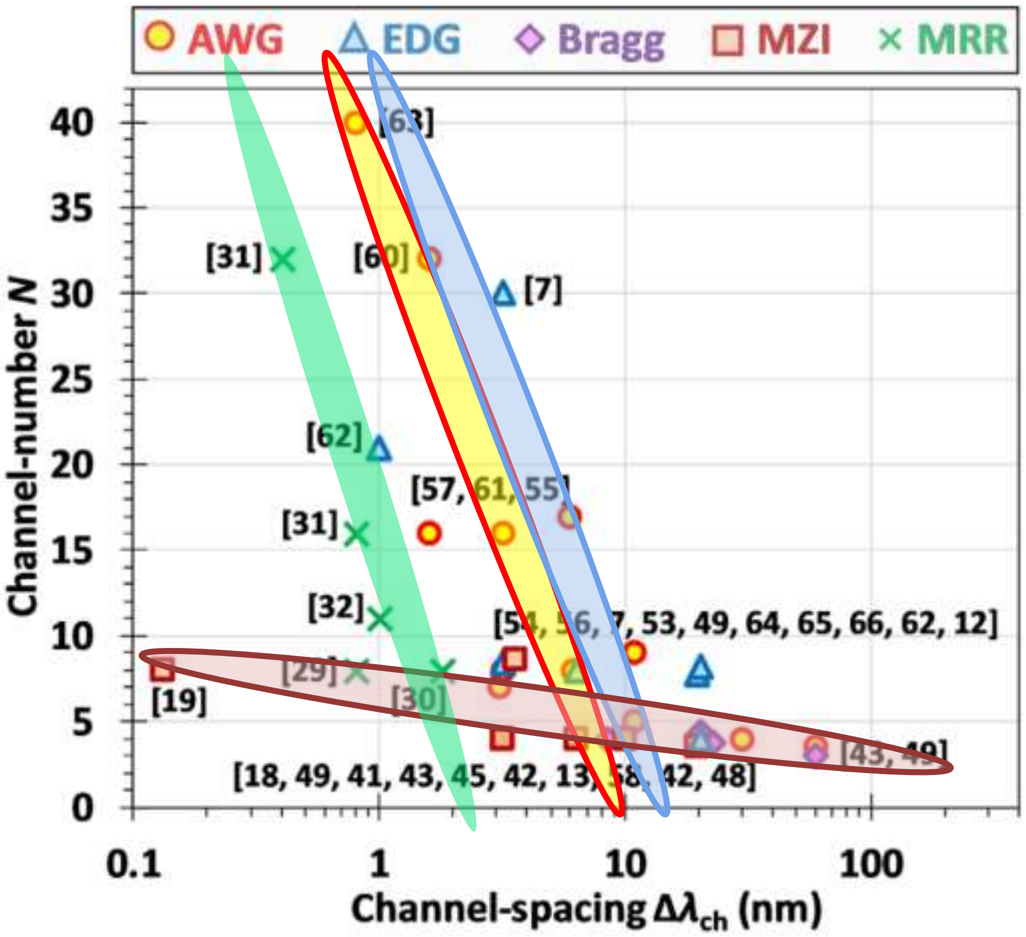


IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 26, NO. 2, MARCH/APRIL 2020 8200810

Statistical Behavioral Models of Silicon Ring Resonators at a Commercial CMOS Foundry

Peng Sun, Jared Hulme, Thomas Van Vaerenbergh, Jinsoo Rhim, Charles Baudot, Frederic Boeuf, Nathalie Vulliet, Ashkan Seyedi, Marco Fiorentino, and Raymond G. Beausoleil

COMPARISONS: CHANNEL # AND SPACING IN SOI-BASED SPECTROMETERS




Received: 5 January 2020
DOI: 10.1002/mop.32509

REVIEW

Silicon photonic filters

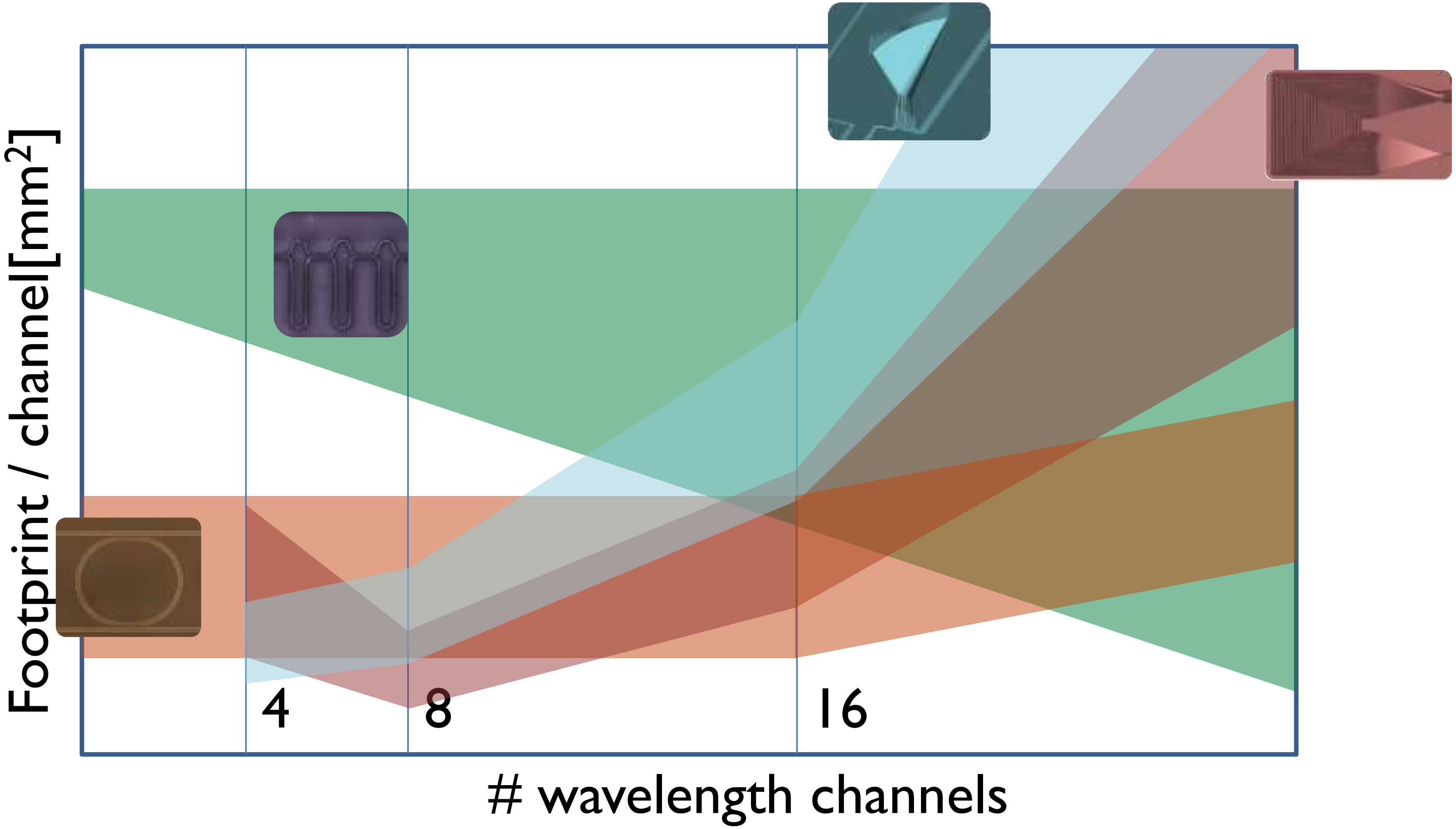
Dajian Liu[1,2] | Hongnan Xu[1,2] | Ying Tan[1,2] | Yaocheng Shi[1,2] | Daoxin Dai[1,2]

[1]Center for Optical and Electromagnetic Research, State Key Laboratory for Modern Optical Instrumentation, International Research Center for Advanced Photonics (Haining), Zhejiang University, Hangzhou, China

[2]Ningbo Research Institute, Zhejiang University, Ningbo, China

D. Liu et al, Microw. Opt. Techn. Lett. 2020
https://doi.org/10.1002/mop.32509

COMPARISONS: FOOTPRINT OF SOI-BASED SPECTROMETERS



W. Bogaerts et al, Proc. SPIE 9365 (2015) doi:10.1117/12.2082785

COMPARISONS: AWGS AND EDG (PCG) ACROSS PLATFORMS

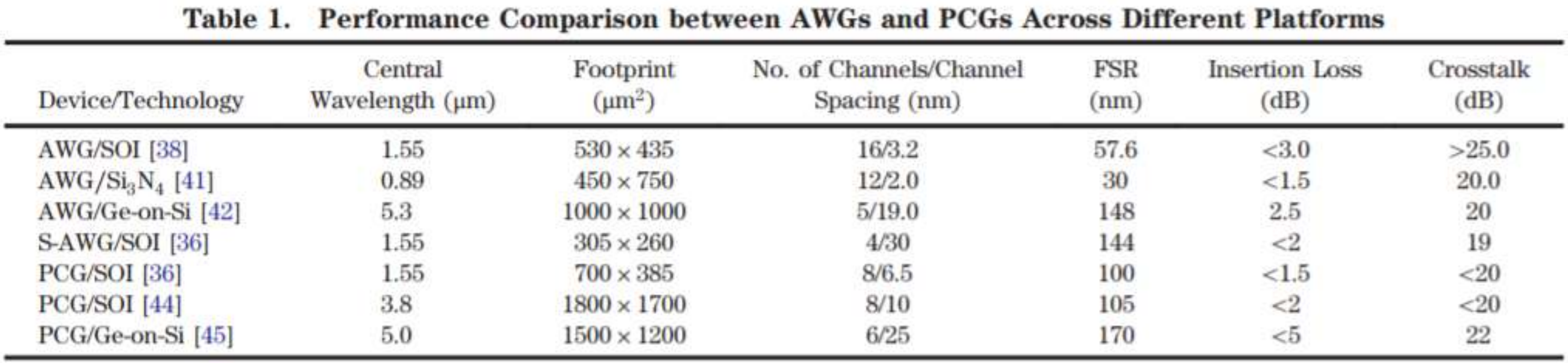


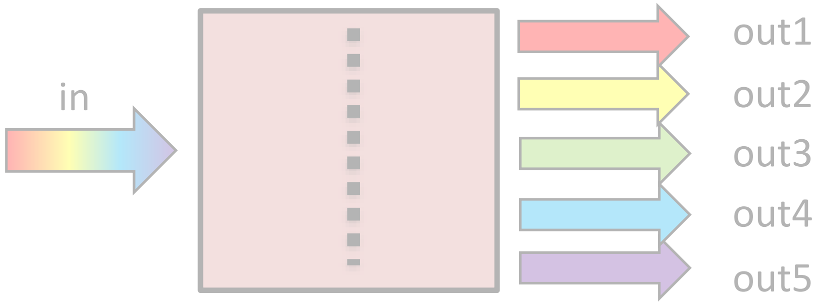
Table 1. Performance Comparison between AWGs and PCGs Across Different Platforms

Device/Technology	Central Wavelength (μm)	Footprint (μm^2)	No. of Channels/Channel Spacing (nm)	FSR (nm)	Insertion Loss (dB)	Crosstalk (dB)
AWG/SOI [38]	1.55	530 × 435	16/3.2	57.6	<3.0	>25.0
AWG/Si_3N_4 [41]	0.89	450 × 750	12/2.0	30	<1.5	20.0
AWG/Ge-on-Si [42]	5.3	1000 × 1000	5/19.0	148	2.5	20
S-AWG/SOI [36]	1.55	305 × 260	4/30	144	<2	19
PCG/SOI [36]	1.55	700 × 385	8/6.5	100	<1.5	<20
PCG/SOI [44]	3.8	1800 × 1700	8/10	105	<2	<20
PCG/Ge-on-Si [45]	5.0	1500 × 1200	6/25	170	<5	22

A. Subramanian et al, Photonics Research (2015) [*doi:10.1364/PRJ.3.000B47*](https://doi.org/10.1364/PRJ.3.000B47)

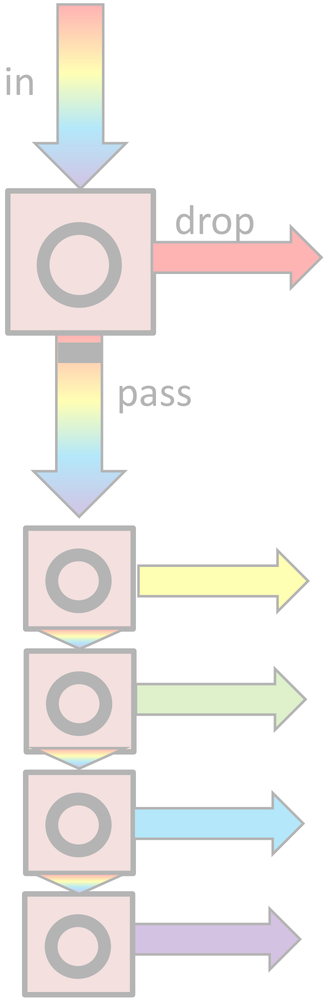
SPECTROMETERS

Dispersive devices



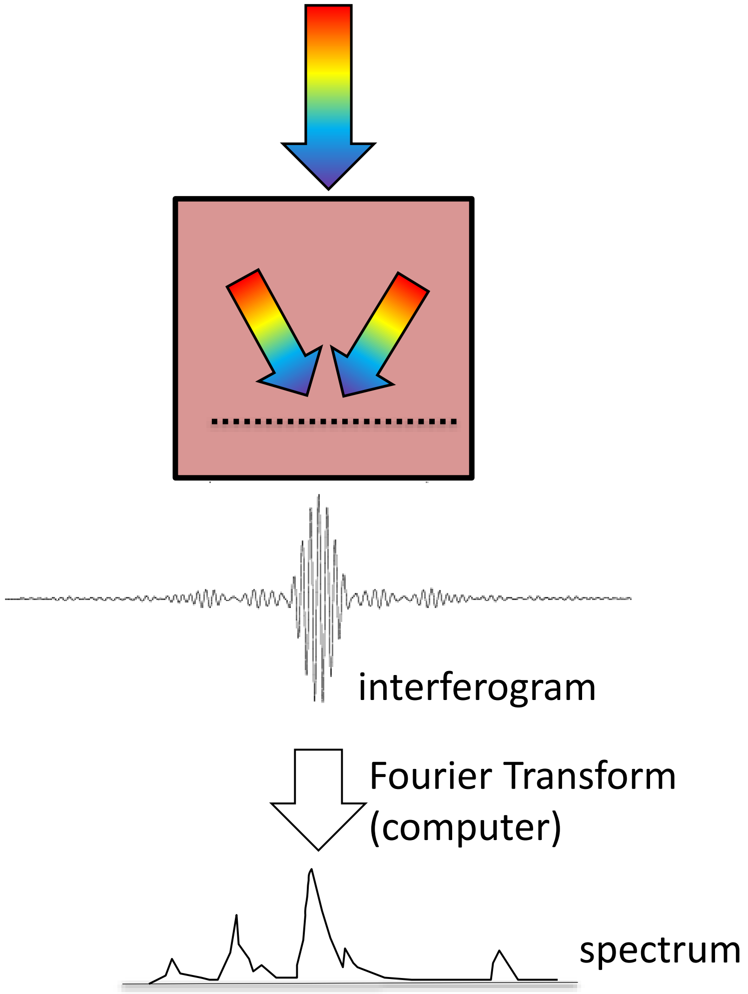
Mechanism used: grating diffraction (multi-beam interference)

Filter cascades



Mechanism used: resonance or interference or Bragg reflection

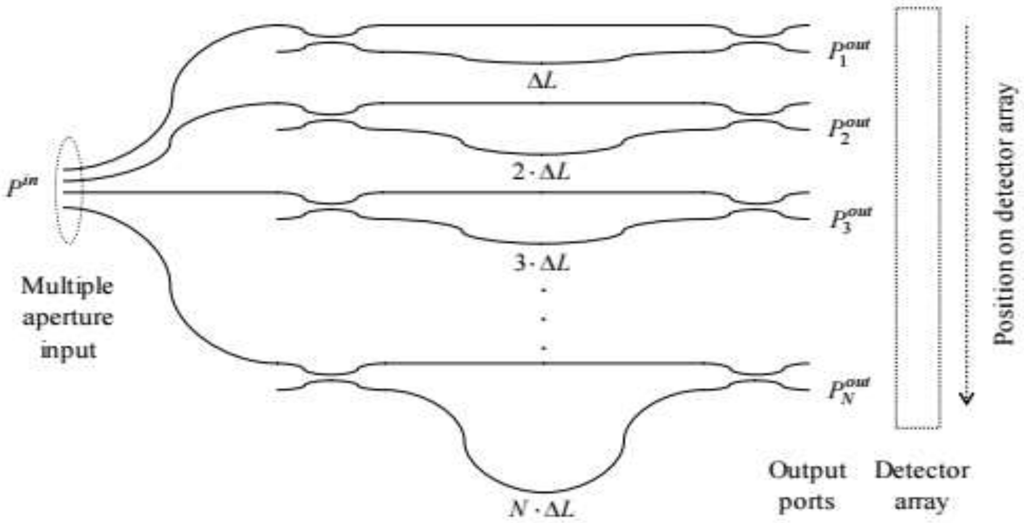
Fourier Transform

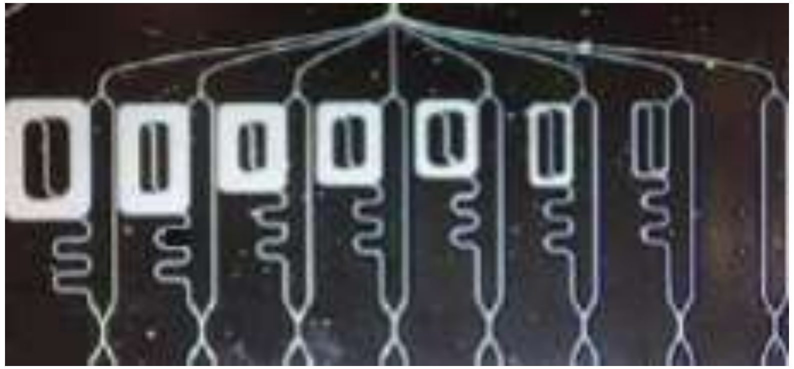


Mechanism used: two-beam interference

SPATIAL HETERODYNE SPECTROMETERS (SHS)

Set of parallel MZIs with increasing pathlength difference





Bandwidth: 0.184 nm
Resolution: 0.023 nm

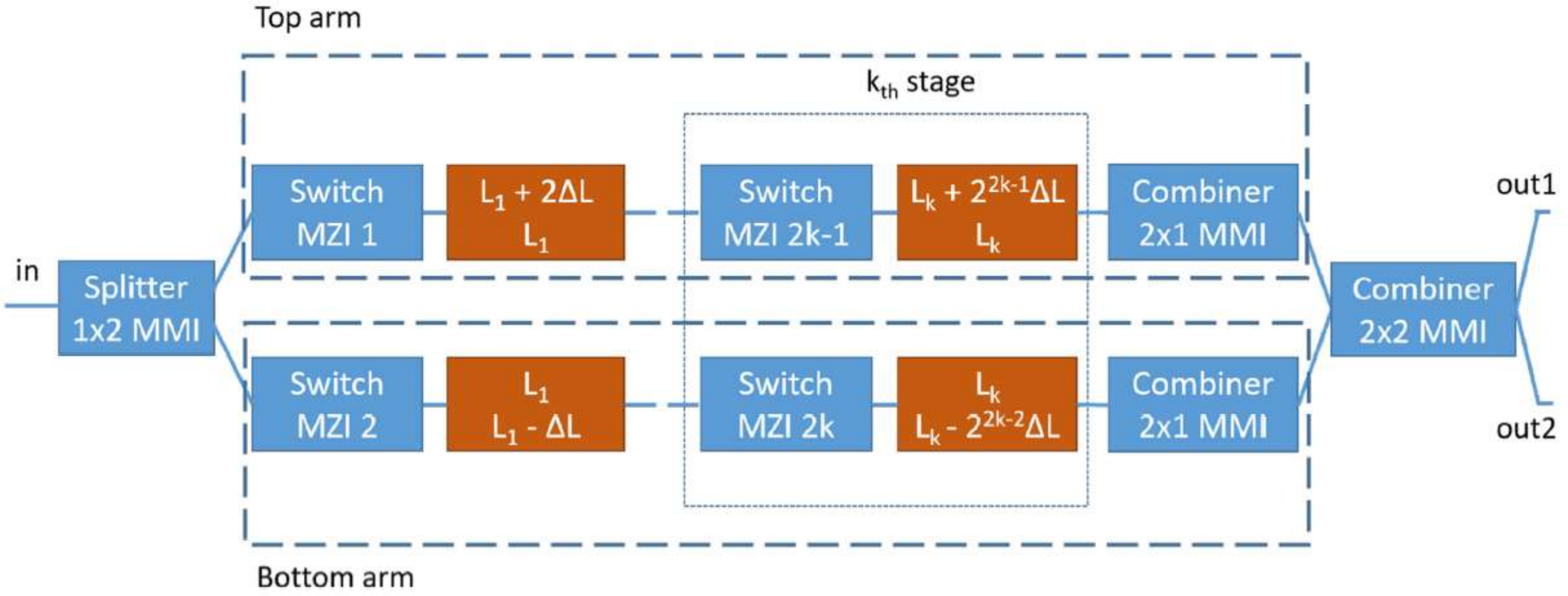
SHS:

- Interferogram is created by **an array of waveguide MZI** with increasing OPD, recorded by a detector array.
- Bandwidth limited by FSR of MZI
- Number of MZI channels: $\mathrm{N} = \frac{2\Delta\lambda}{\delta\lambda}$
- Recent work:
  - SHS on CMOS compatible SiN platform(TriPleX^{TM})
  - Resolution of 0.023nm, bandwidth 0.184nm at 1550nm requires area of 4mm × 8mm.

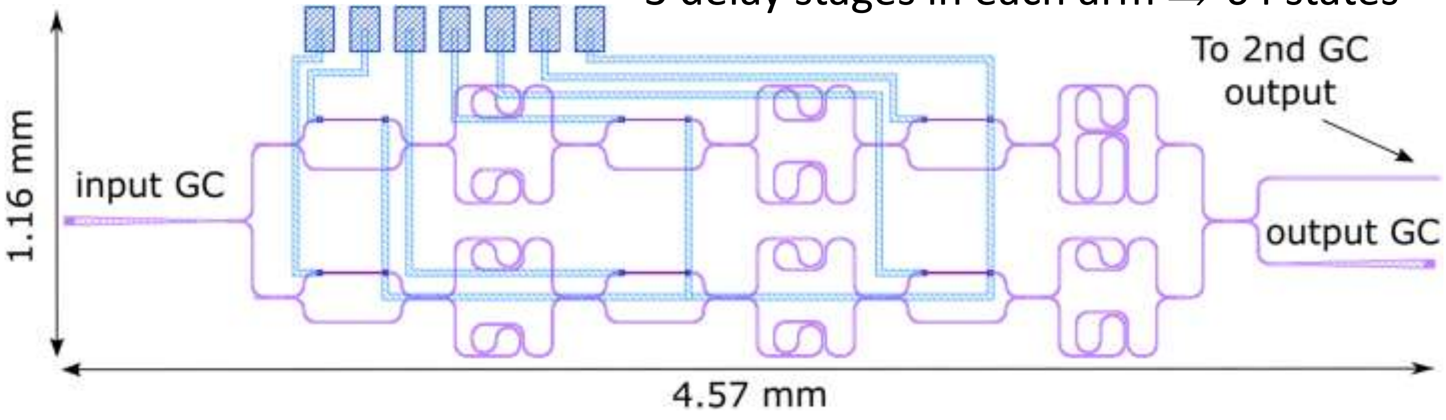
M. Florjanczyk et al., Optics express (2007)
Y. Li et al., IEEE Phot. Tech. Lett. (2016) 10.1109/LPT.2016.2615319

DIGITAL FOURIER TRANSFORM SPECTROMETER

Temporal switching of MZI pathlength difference



3 delay stages in each arm ⇒ 64 states

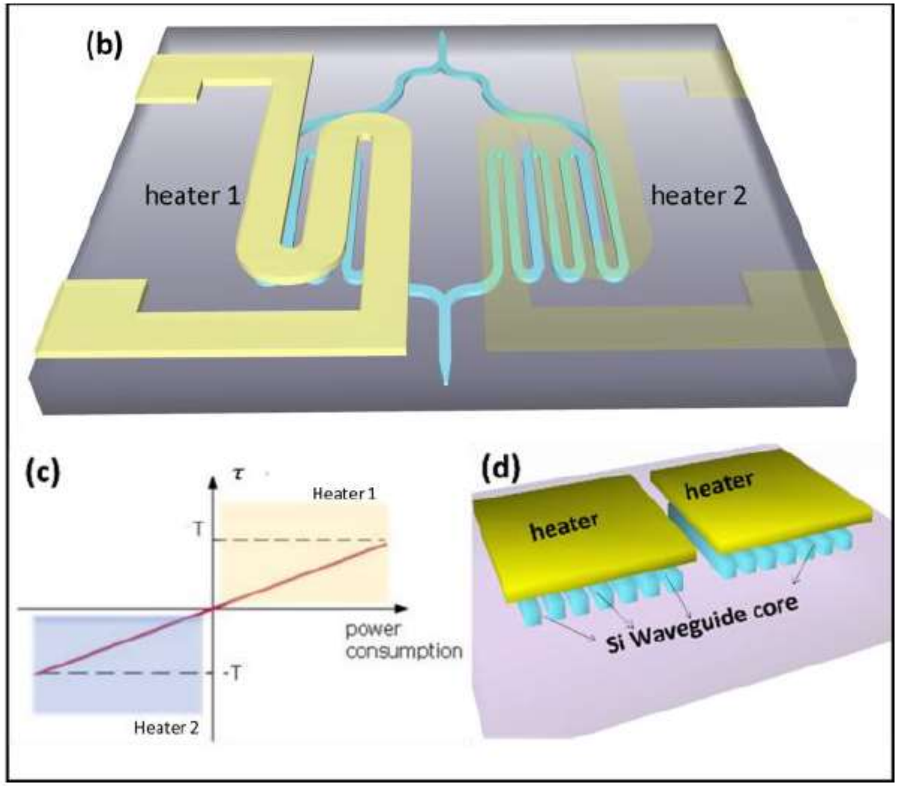


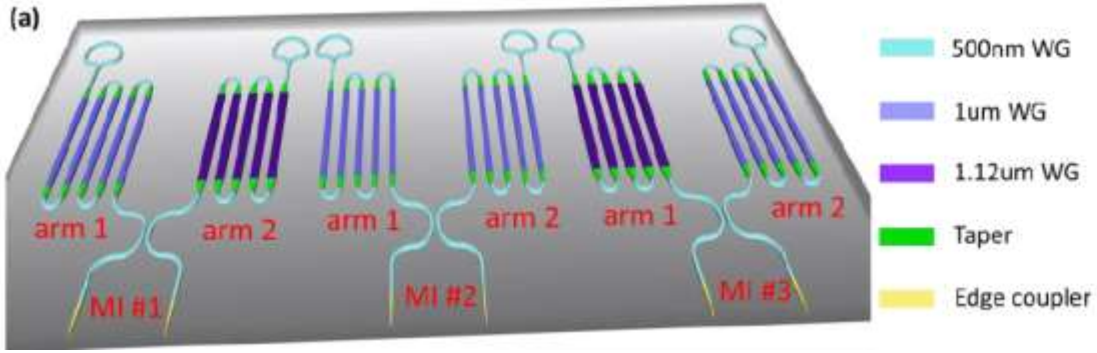
Bandwidth: 130 nm (around 2300 nm)
Resolution: 1.5 nm

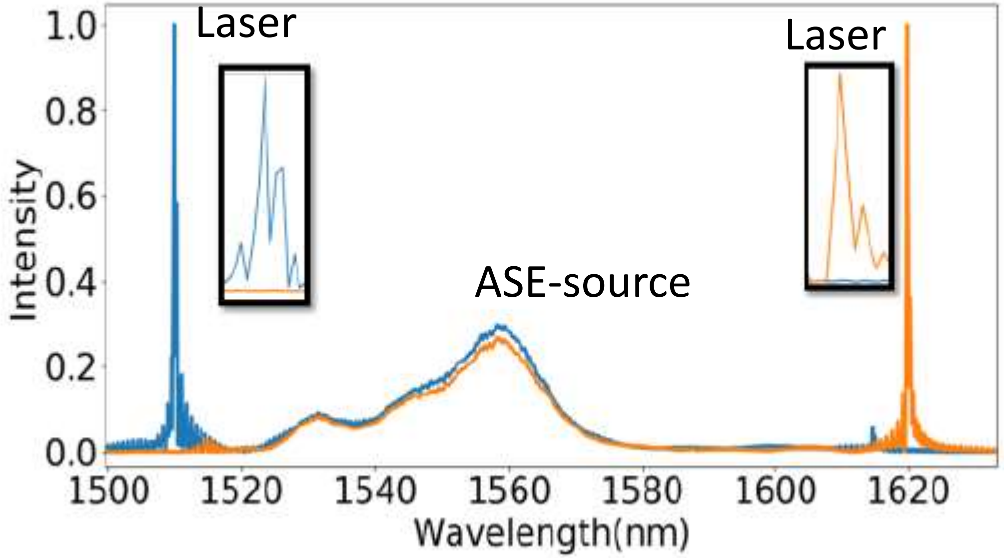
F. Pavanello et al, IEEE Phot. Journ. (2019) 10.1109/JPHOT.2019.2914013

TEMPORAL FOURIER-TRANSFORM SPECTROMETER

Temporal tuning of MZI pathlength difference





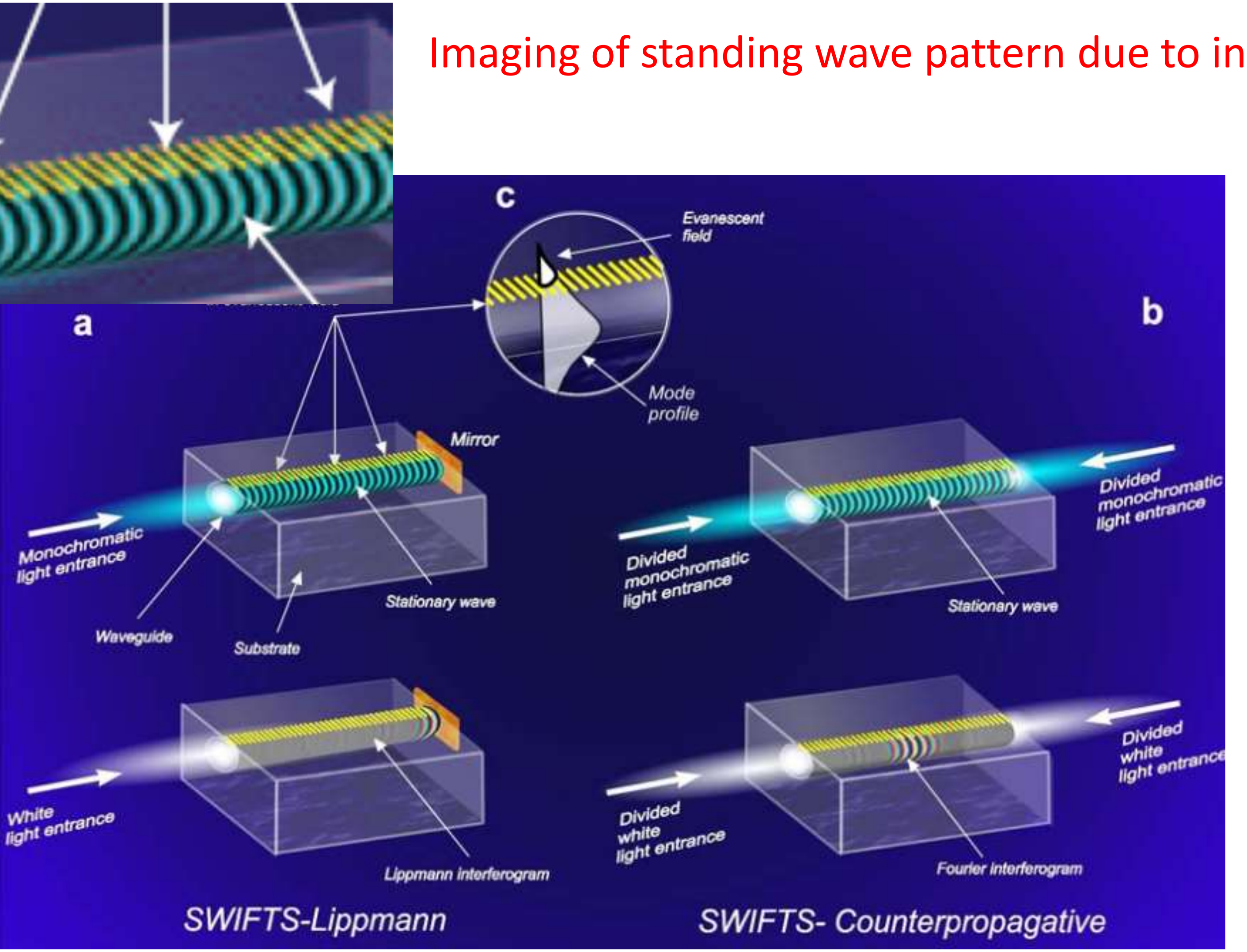


Bandwidth: > 130 nm
Resolution: 0.16 nm

A. Li et al, Lasers and Phot. Rev. (2021) [*doi.org/10.1002/lpor.202000358*](https://doi.org/10.1002/lpor.202000358)

STATIONARY WAVE INTEGRATED FTS (SWIFTS)

Imaging of standing wave pattern due to interference of counterpropagating waves



SWIFTs:

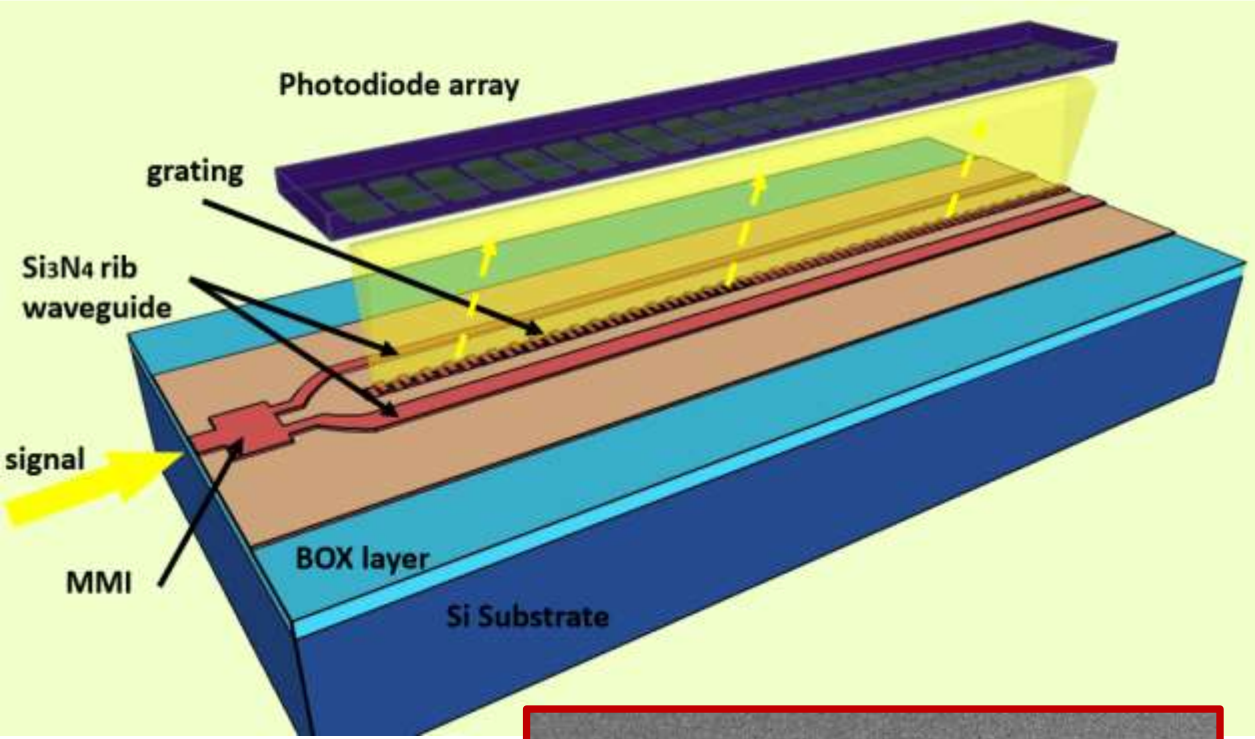
- Interferogram created as **an optical standing wave**, is scattered by Nano-dots loaded on waveguide and recorded by a detector array.
- Increasing waveguide length (L) gives higher resolution: $\delta\lambda = \frac{\lambda^2}{n_{eff}L}$[1]
- Operational bandwidth is limited by **subsampling**:
  - Period of the interferogram = $\frac{\lambda}{2n_{eff}}$ << pixel pitch of commercially available detector array

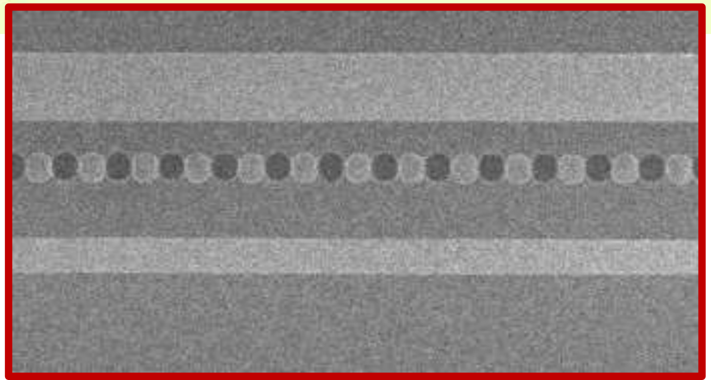
Bandwidth: ~ 100 nm
Resolution: 4 nm

E. Le Coarer, et al. Nature Photonics (2007) doi:10.1038/nphoton.2007.138

CO-PROPAGATIVE STATIONARY FOURIER TRANSFORM SPECTROMETER

Imaging of standing wave pattern due to interference of co-propagating waves





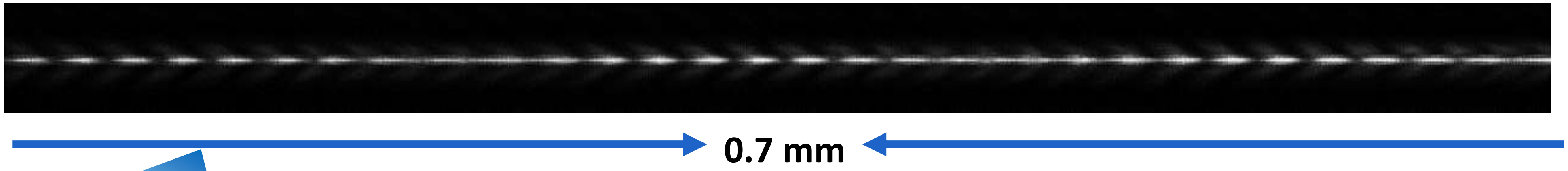
- Interferogram is created by the interference between the **evanescent fields of two waveguide modes propagating at different phase velocity** (due to waveguides with different width)
- Interferogram is diffracted by a grating towards a detector array .
- Subsampling is avoided → broadband operation:
  - Interferogram period = $\frac{\lambda}{\Delta n_{eff}}$
  - Increased by a factor $\frac{2n_{eff}}{\Delta n_{eff}}$ comparing with SWIFTS
- Still allows for moderately high resolution $\frac{\lambda^2}{\Delta n_{eff} L}$

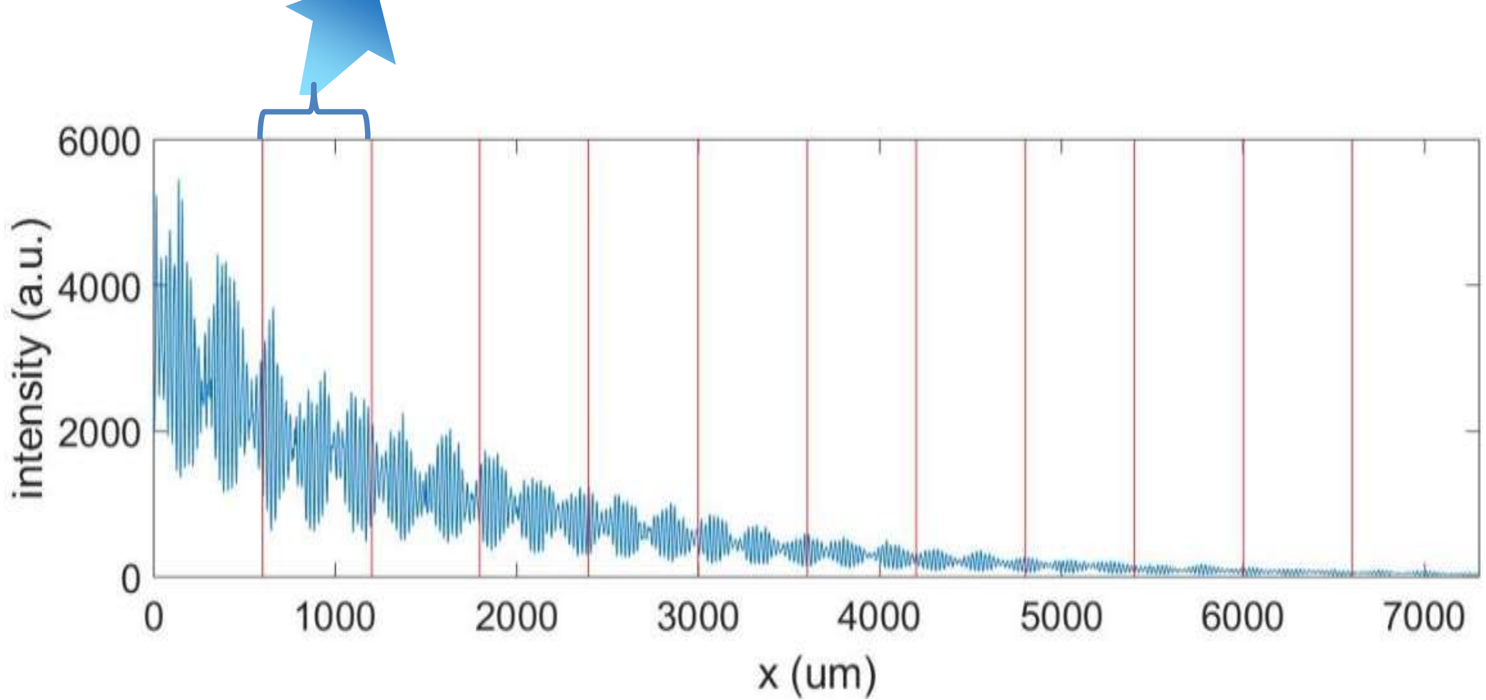
X. Nie et al, Optics Express (2017) *doi:10.1364/OE.25.00A409*

GHENT UNIVERSITY imec

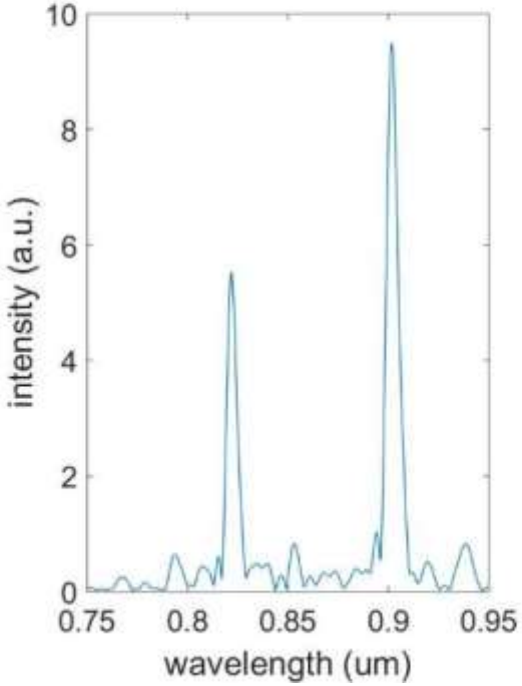
CO-PROPAGATIVE STATIONARY FOURIER TRANSFORM SPECTROMETER

Dual-wavelength injection:





Intensity of the complete interferogram (11 images stitched)



Fourier transform mapped to wavelength axis

Bandwidth: ~ 100 nm
Resolution: 6 nm

X. Nie et al, Optics Express (2017) *[doi:10.1364/OE.25.00A409](doi:10.1364/OE.25.00A409)*

OUTLINE

Brief introduction to silicon and silicon nitride PICs

Spectroscopic sensing modalities

On-chip spectrometers

➡ On-chip tunable lasers

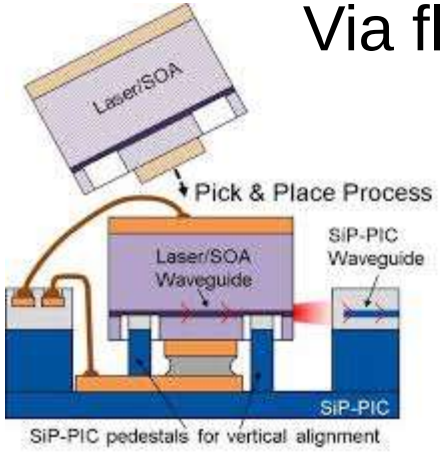
On-chip Raman spectroscopy

Application cases

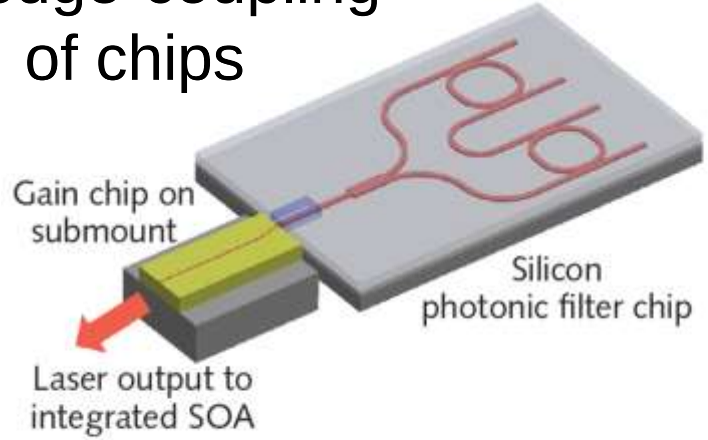
HYBRID INTEGRATION OF III-V LIGHT SOURCES IN SILICON PIC

Via a micro-optic bench

Via flip-chip



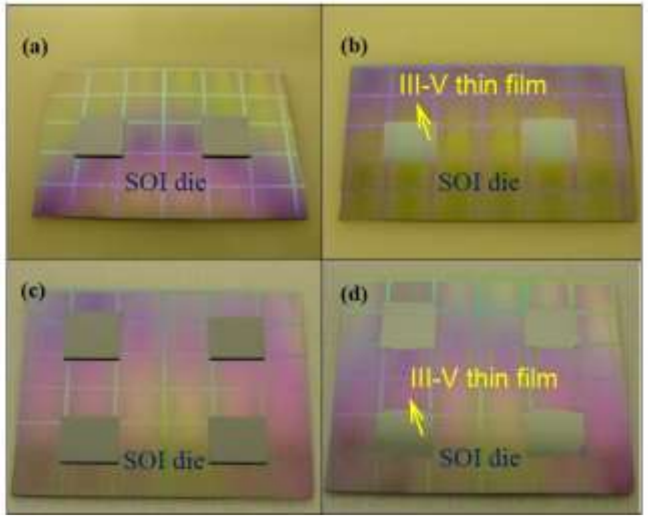
Via edge-coupling of chips



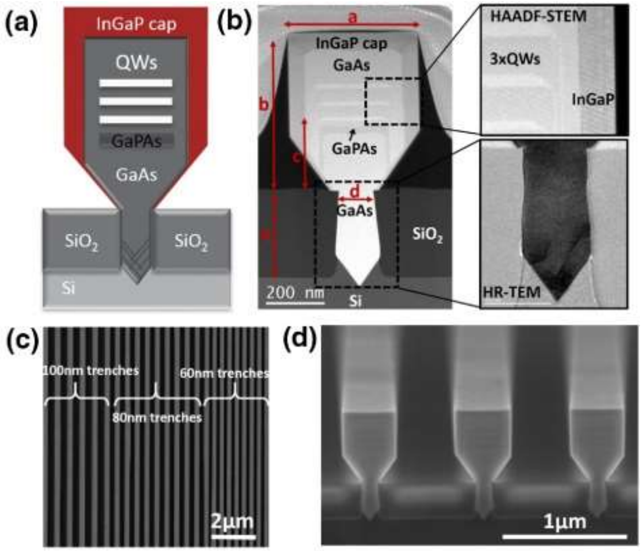
WAFER-LEVEL HETEROGENEOUS INTEGRATION OF III-V LIGHT SOURCES ON SILICON PIC

die-to-wafer bonding

(III-V processing <u>after</u> bonding)

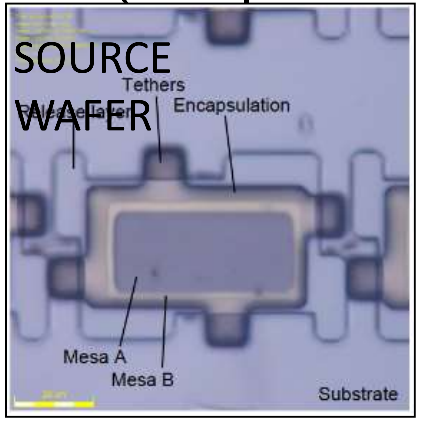


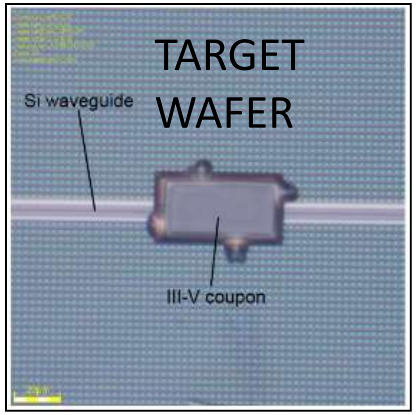
III-V epitaxy on silicon



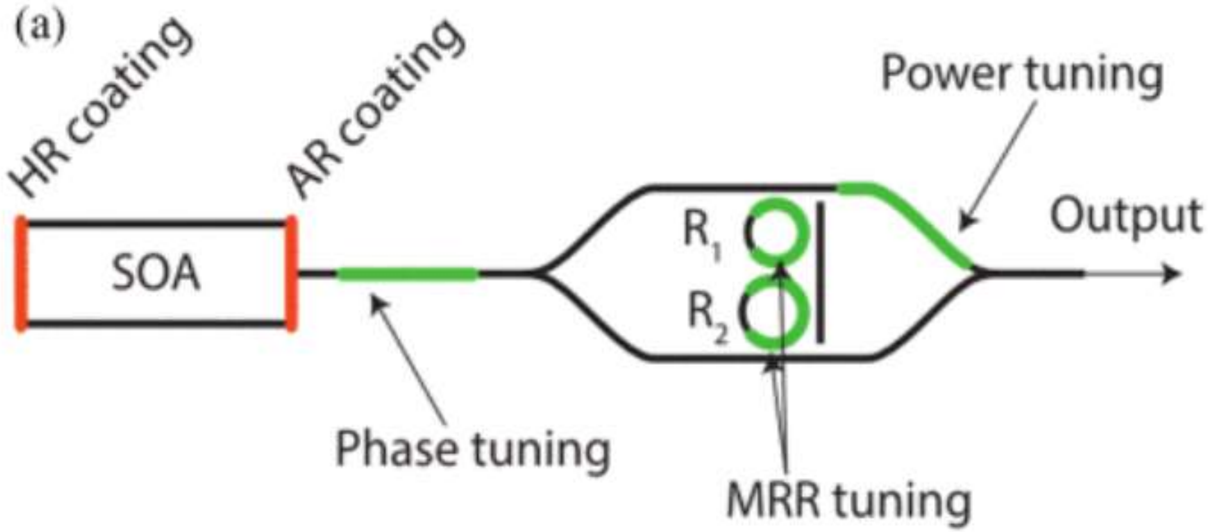
micro transfer printing

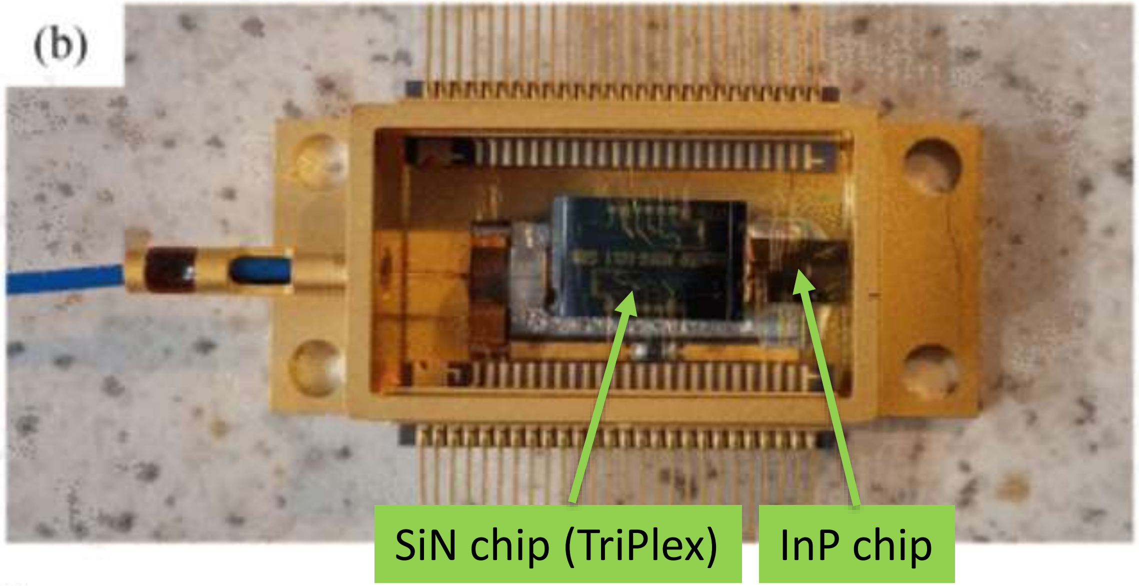
(III-V processing <u>before</u> bonding)





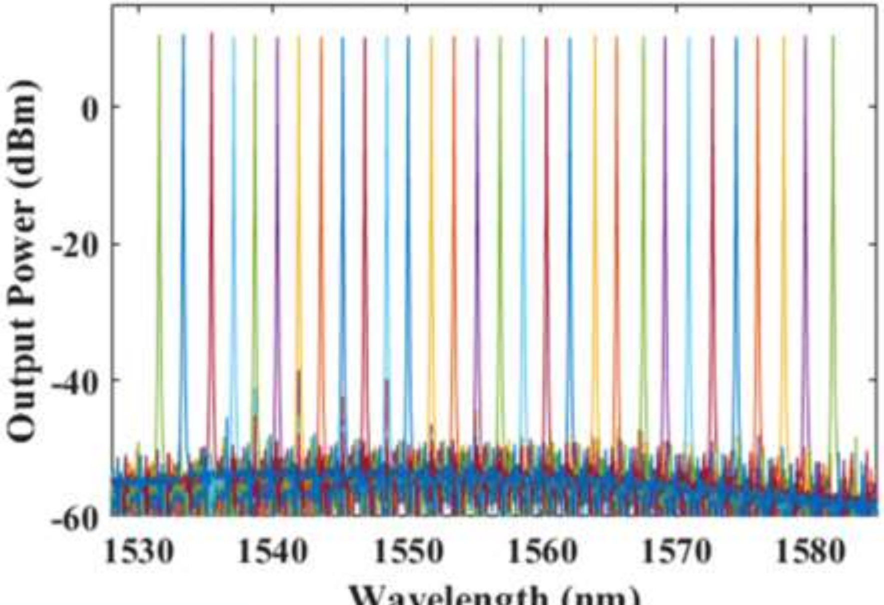
HYBRID INTEGRATION OF INP RSOA AND SIN PIC FOR WIDELY TUNABLE C-BAND LASER





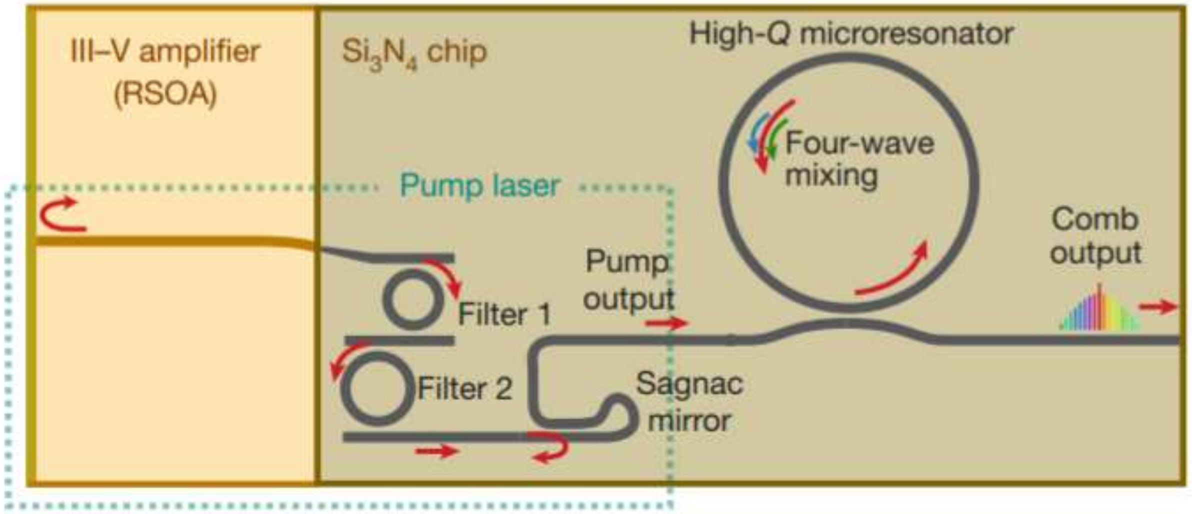
SiN chip (TriPlex)

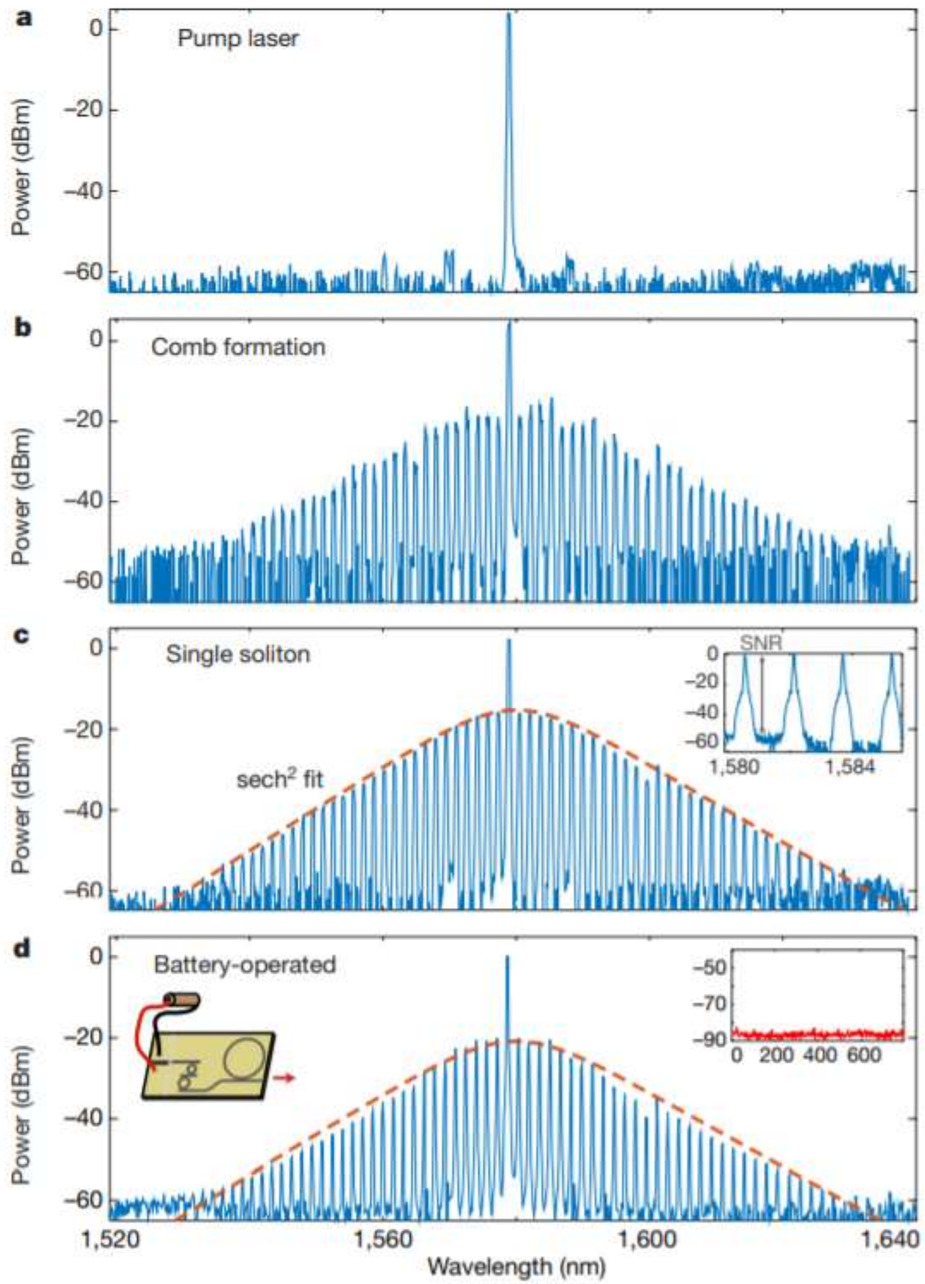
InP chip



Y. Lin et al, IEEE Phot. Journ. (2018)
[10.1109/JPHOT.2018.2842026](https://doi.org/10.1109/JPHOT.2018.2842026)

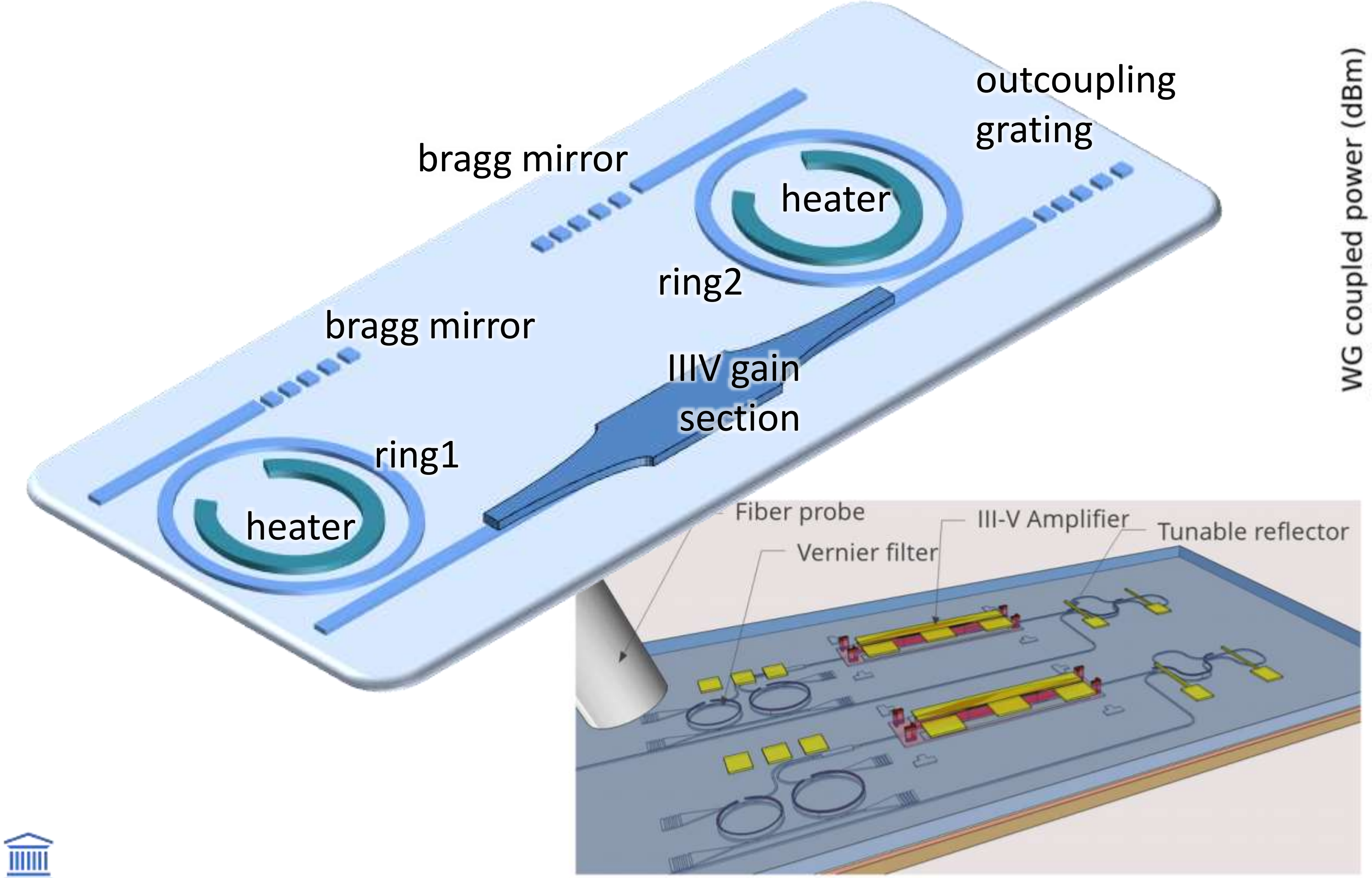
Hybrid integration of InP RSOA and SiN PIC for C-band Kerr comb source

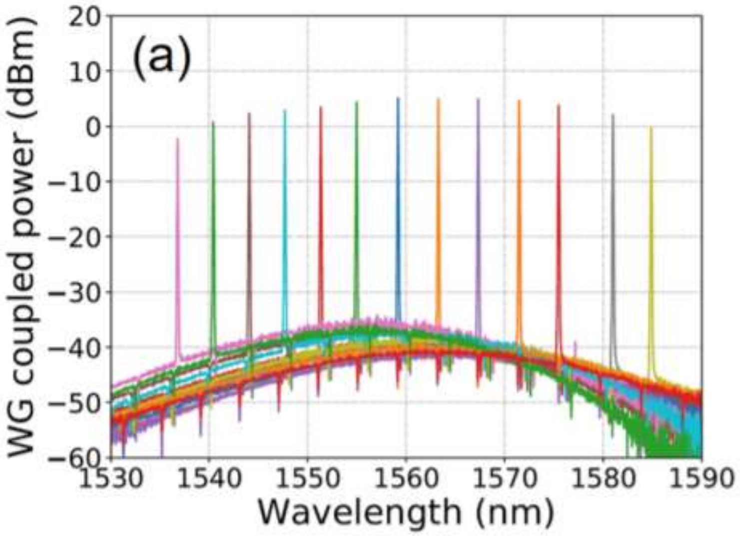




B. Stern et al., Nature (2018)
https://doi.org/10.1038/s41586-018-0598-9

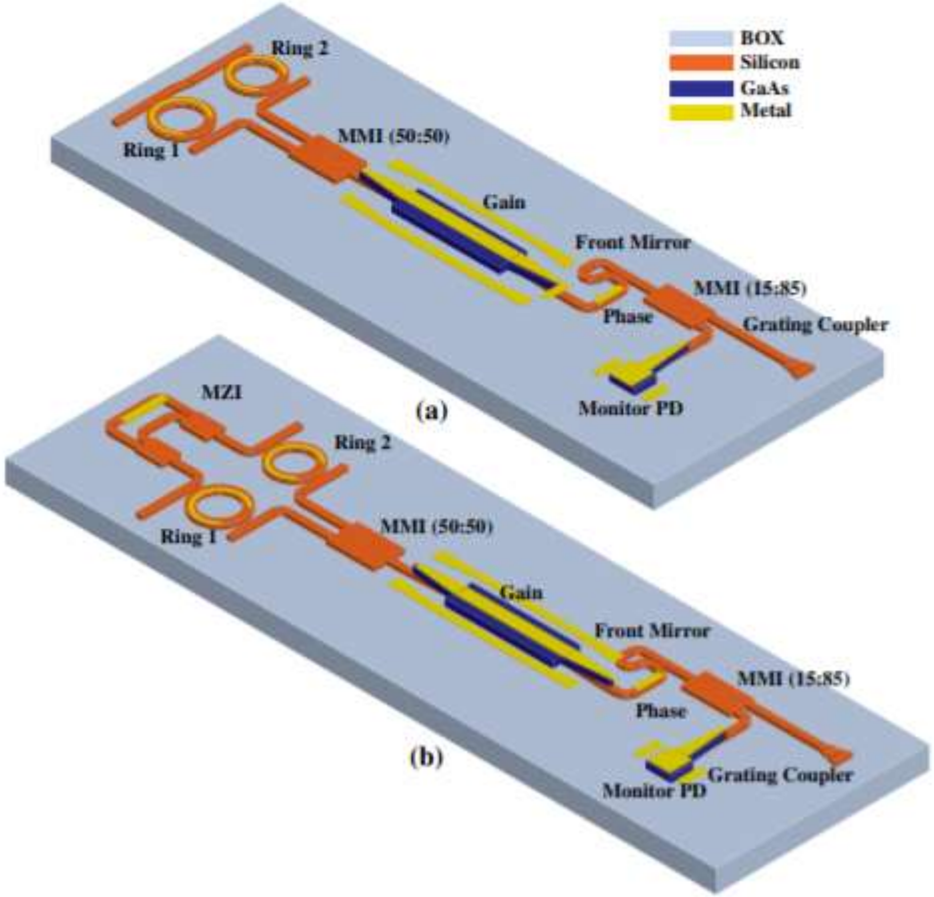
MICRO-TRANSFER-PRINTED WIDELY TUNABLE C-BAND LASER ON SILICON

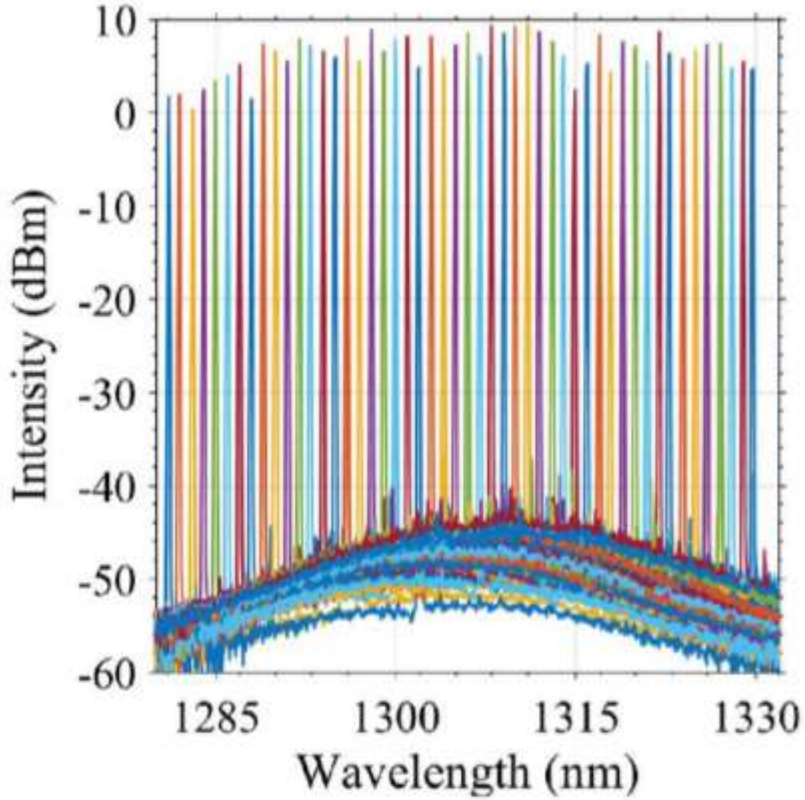




Jing Zhang et al, APL Photonics (2019) doi:10.1063/1.5120004

Epi-bonded widely tunable O-band laser on Silicon





A. Malik et al, Photonics Research (2020) https://doi.org/10.1364/PRJ.394726

OUTLINE

Brief introduction to silicon and silicon nitride PICs

Spectroscopic sensing modalities

On-chip spectrometers

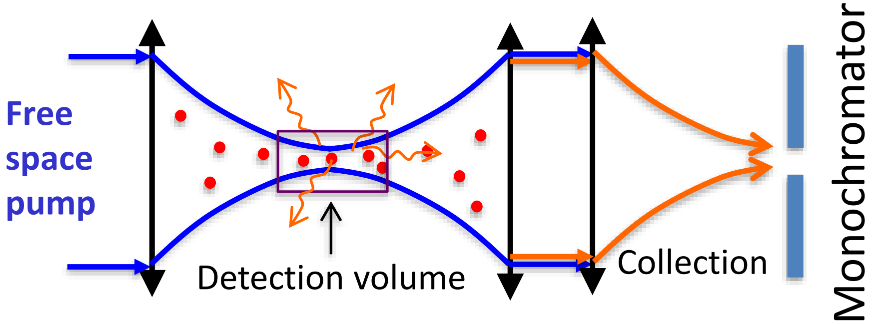
On-chip tunable lasers

➡ On-chip Raman spectroscopy

Application cases

WAVEGUIDE-ENHANCED RAMAN SPECTROSCOPY

Free space excitation and collection in a confocal microscope

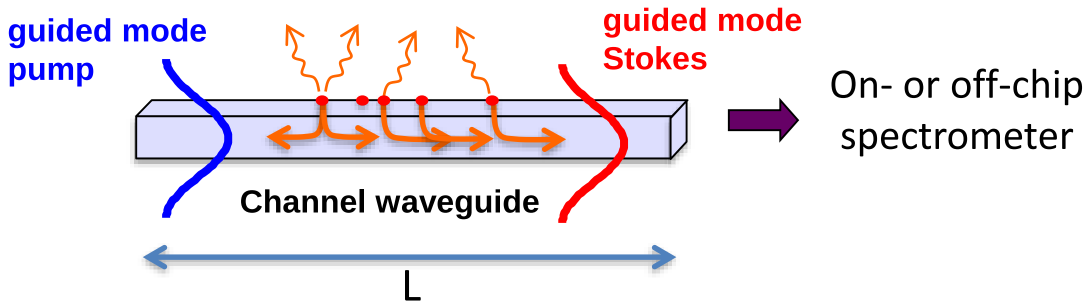


$$\frac{P_{coll}}{P_{pump}} = 2\frac{\lambda_0}{n}\rho\sigma_{scat}$$

density

scattering cross-section

Waveguide-based excitation and collection

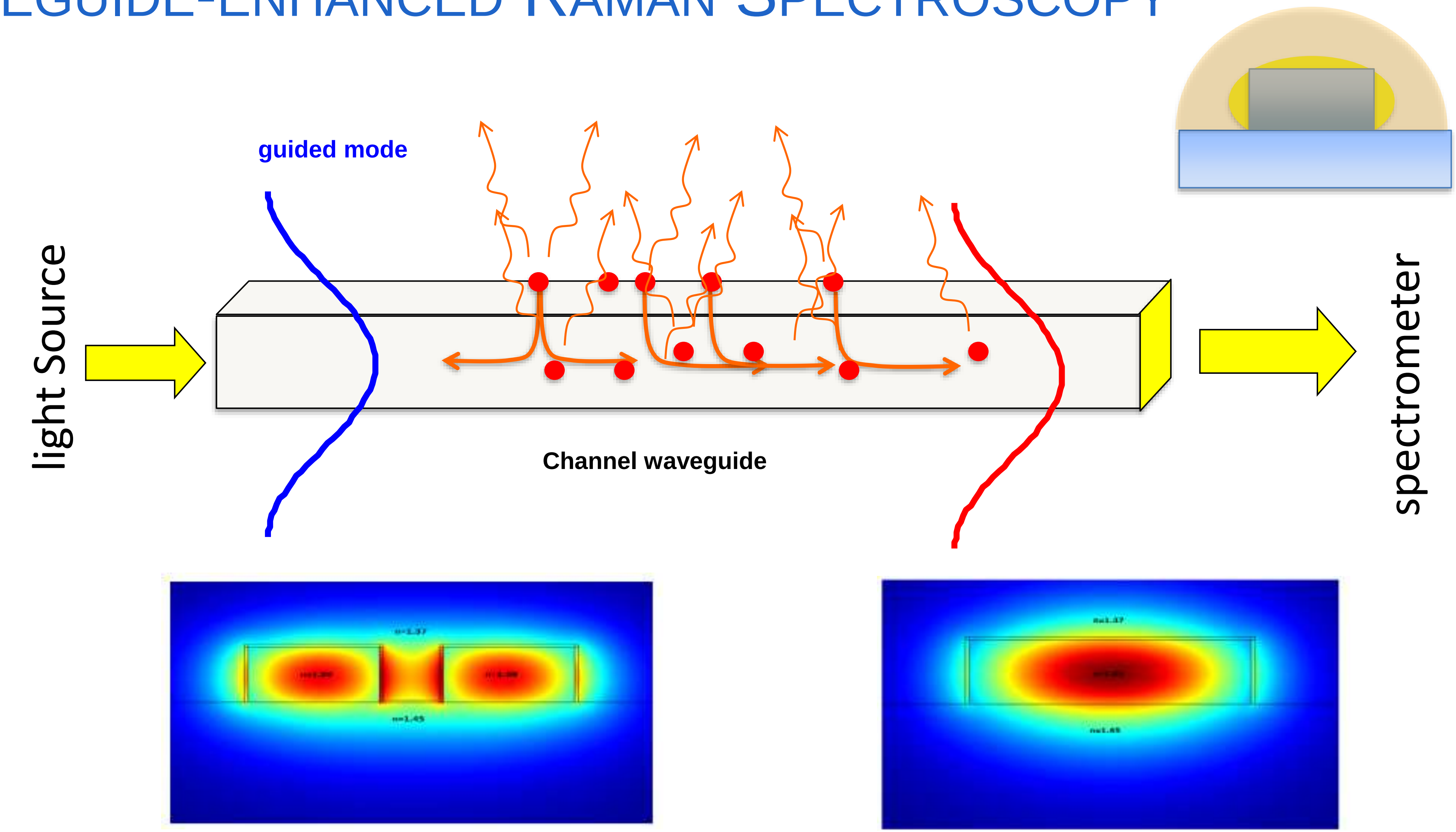


$$\frac{P_{coll}}{P_{pump}} = \boxed{L}\eta_0\rho\sigma_{scat}$$

$$\eta_0 \equiv \frac{1}{n(\vec{r})k_v}\left(\frac{\pi n_g \lambda_0}{\varepsilon_0}\right)^2 \left(\frac{\iint_{Clad} \left|\vec{e}_m(\vec{r})\right|^2 d\vec{r}}{\iint_{\infty} \varepsilon(\vec{r})\left|\vec{e}_m(\vec{r})\right|^2 d\vec{r}}\right)^2$$

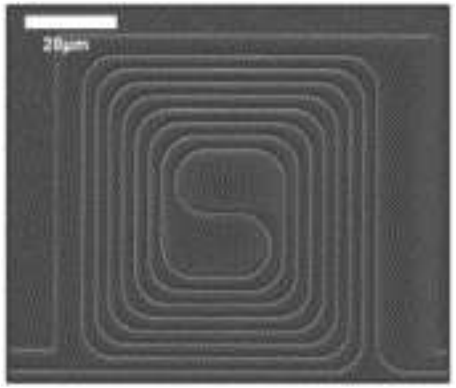
High index contrast matters

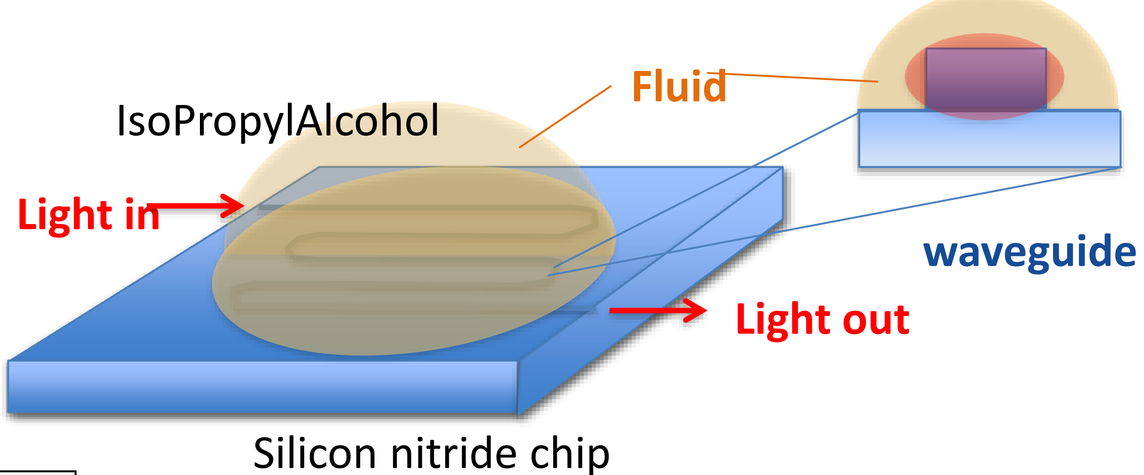
WAVEGUIDE-ENHANCED RAMAN SPECTROSCOPY

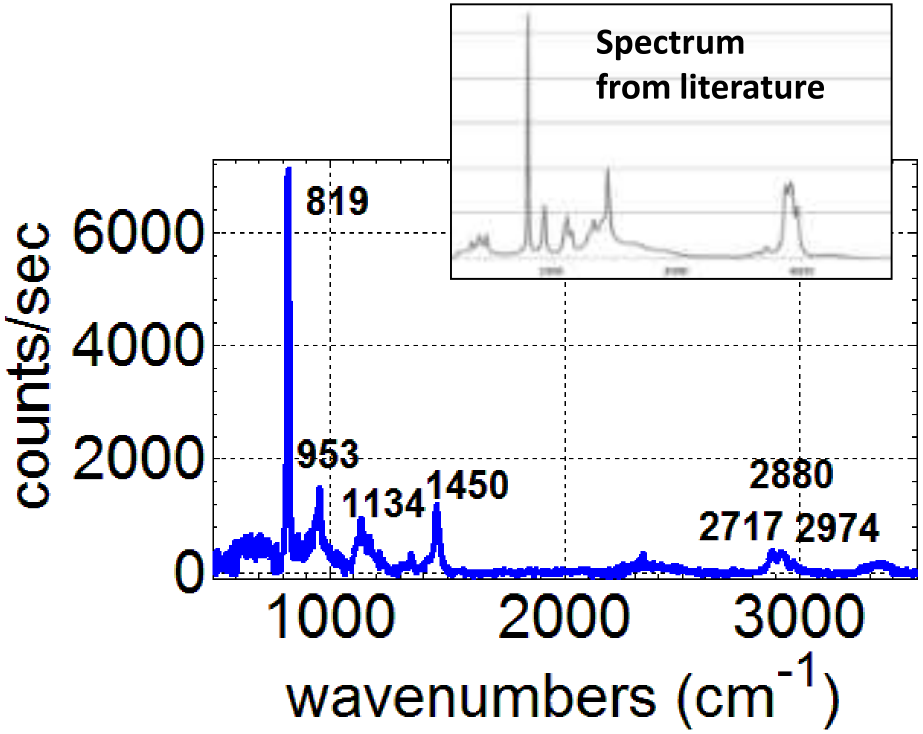


A. Dhakal et al., ACS. Photonics. **3**, 2141-2149 (2016)
Z. Wang et al., Opt. Letters. **41**, 4146-4149 (2016)
C. Evans et al., ACS Photonics 3, 1662-1669 (2016)

RAMAN SPECTRUM OF IPA ON SILICON-NITRIDE WAVEGUIDE





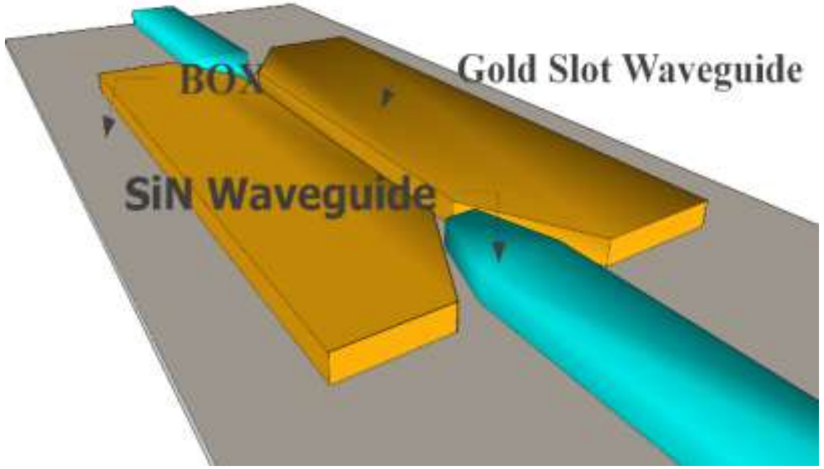


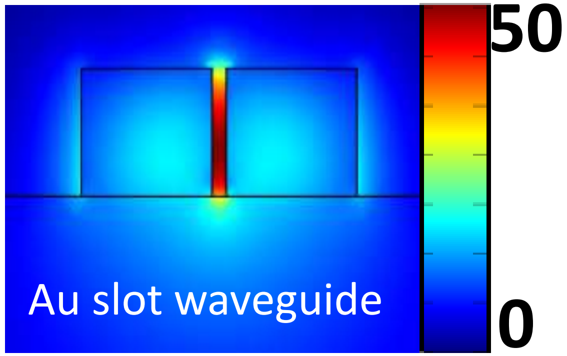
Efficiency of collection 10-100x better than in Raman microscope

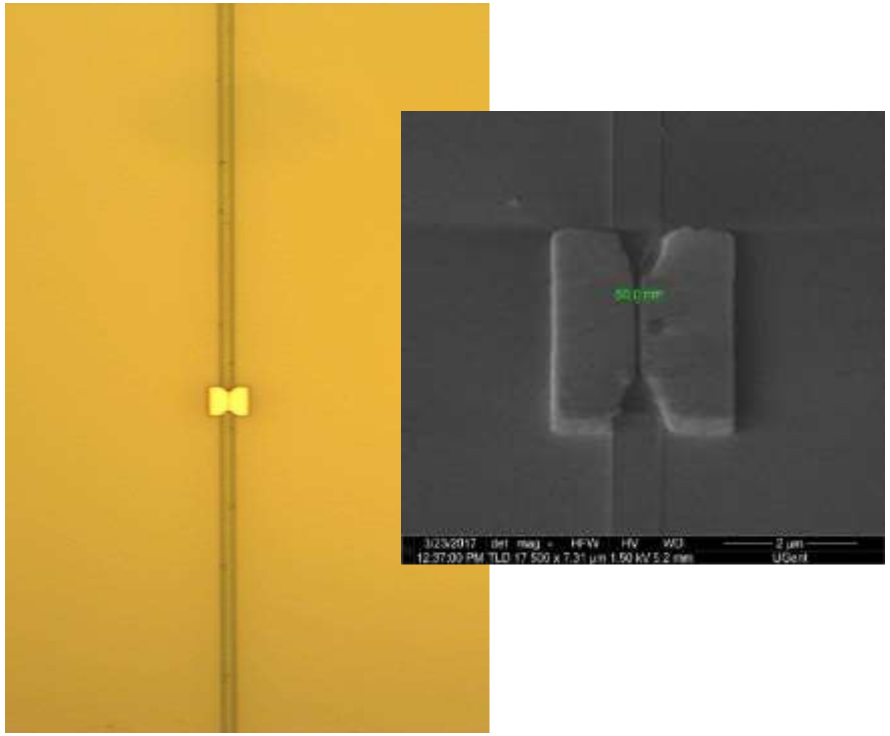
A. Dhakal et al, Opt. Lett. (2014) doi:10.1364/ol.39.004025

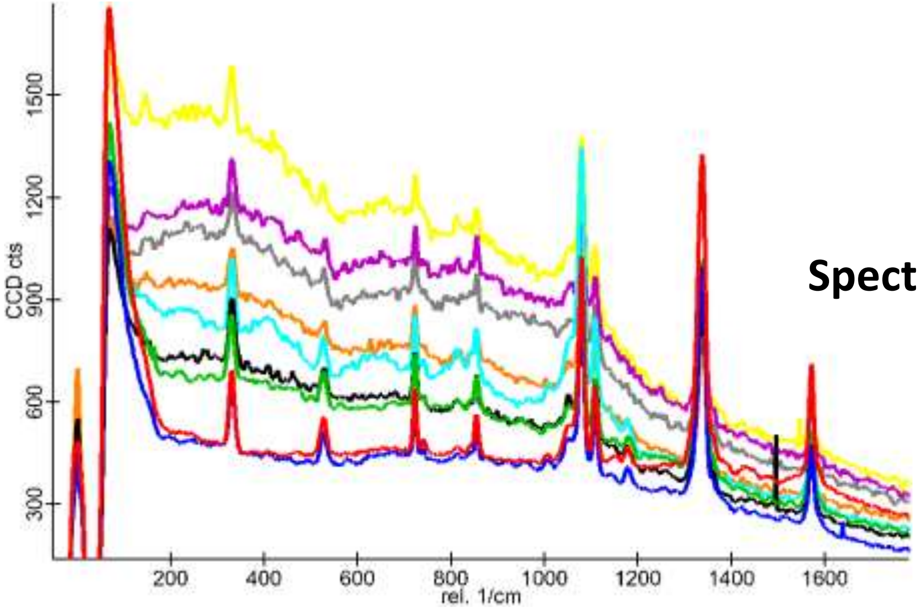
A. Dhakal et al, Optics Express (2015) doi:10.1364/OE.23.027391

USING METAL SLOT WAVEGUIDES TO ENHANCE THE RAMAN SCATTERING









Spectrum of NTP (4-NitroThioPhenol) bound to gold

A. Raza et al, ECIO 2017

A. Raza et al, CLEO2018 *doi:10.1364/CLEO_SI.2018.SW3L.6*

A. Raza et al, APL Photonics 2018 *doi:10.1063/1.5048266*

OUTLINE

Brief introduction to silicon and silicon nitride PICs

Spectroscopic sensing modalities

On-chip spectrometers

On-chip tunable lasers

On-chip Raman spectroscopy

➡ Application cases

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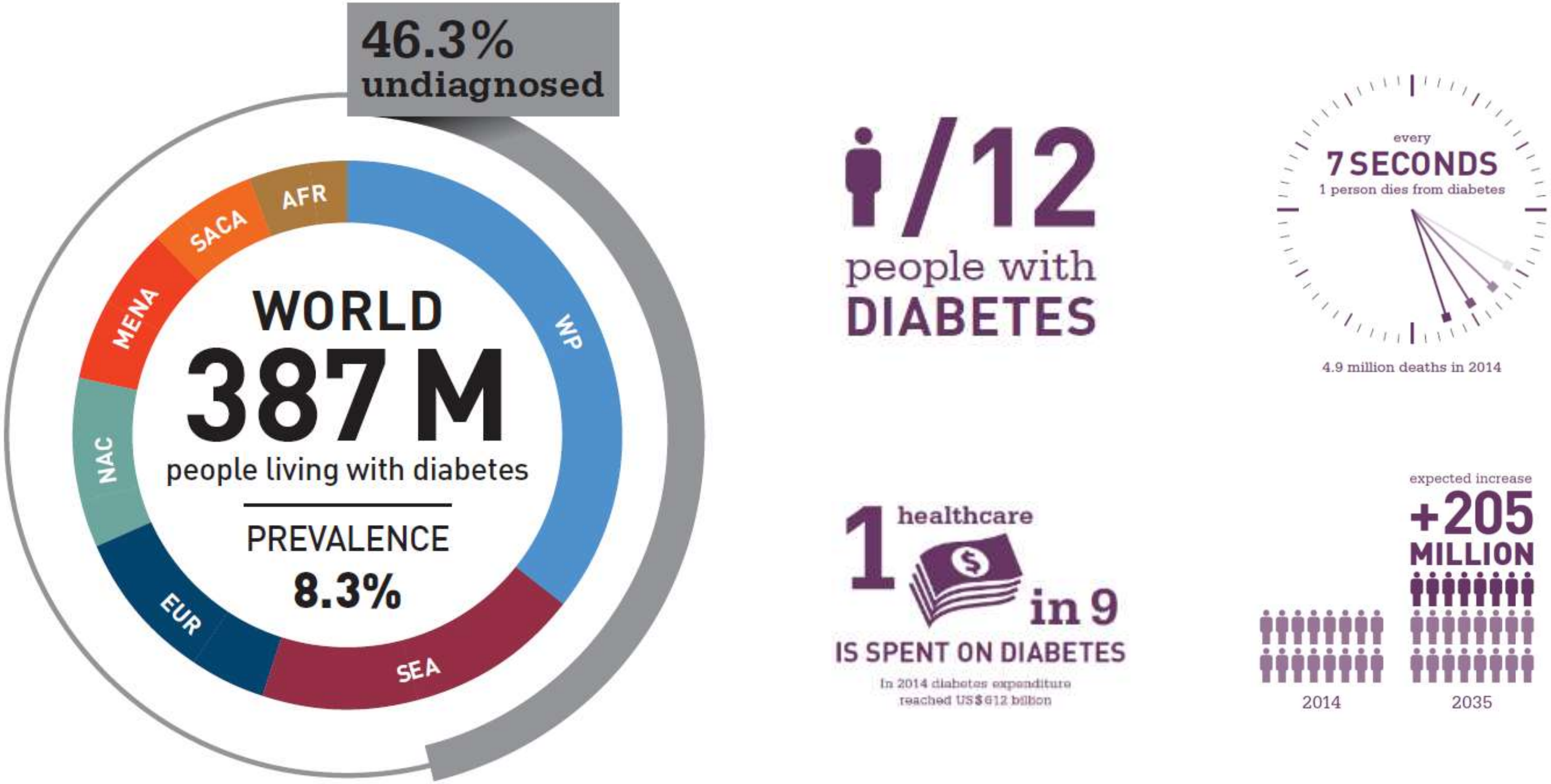
- ➡ Glucose monitoring
- Biosensing
- Gas sensing
- Fiber Bragg Grating readout
- Water pollutant monitoring

DIABETES IS A MAJOR 21ST CENTURY HEALTH CHALLENGE

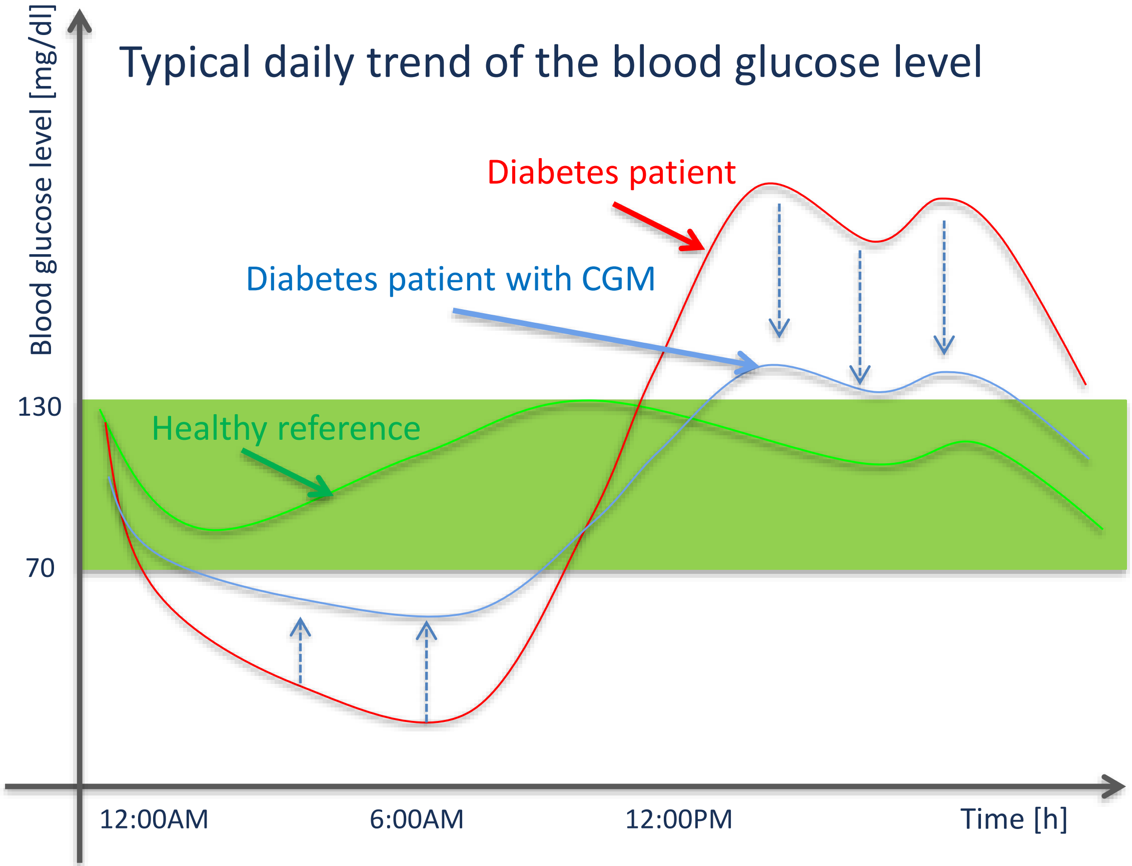


http://www.idf.org/diabetesatlas/update-2014

CONTINUOUS GLUCOSE MONITORING (CGM) HAS PROVEN TO IMPROVE GLYCEMIC CONTROL OF DIABETES PATIENTS

CGM systems show positive health impact *

- lower average blood glucose levels
- decrease of hypoglycemic frequency



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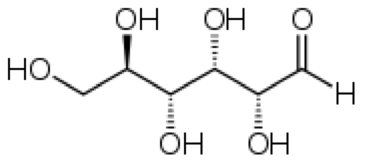
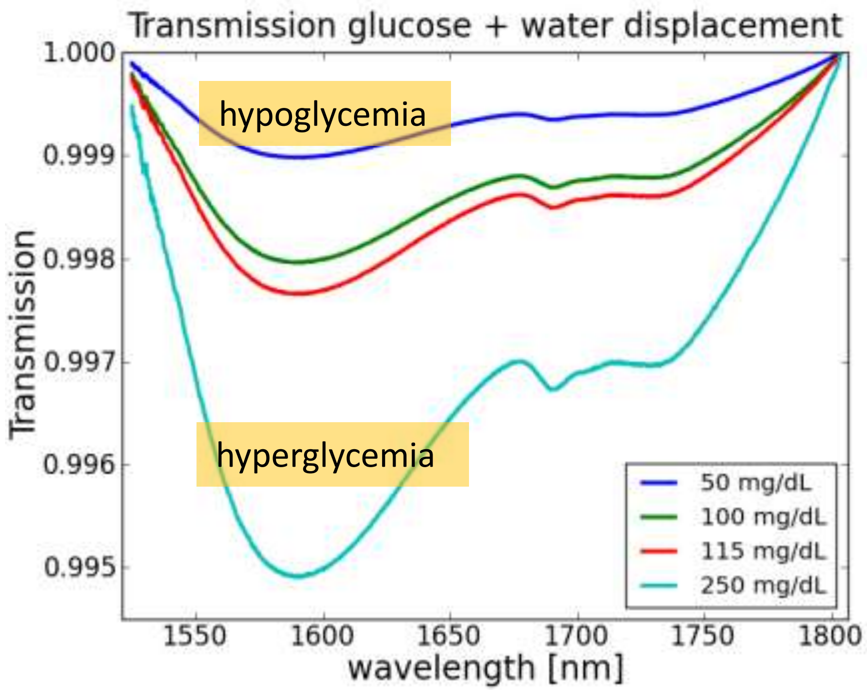
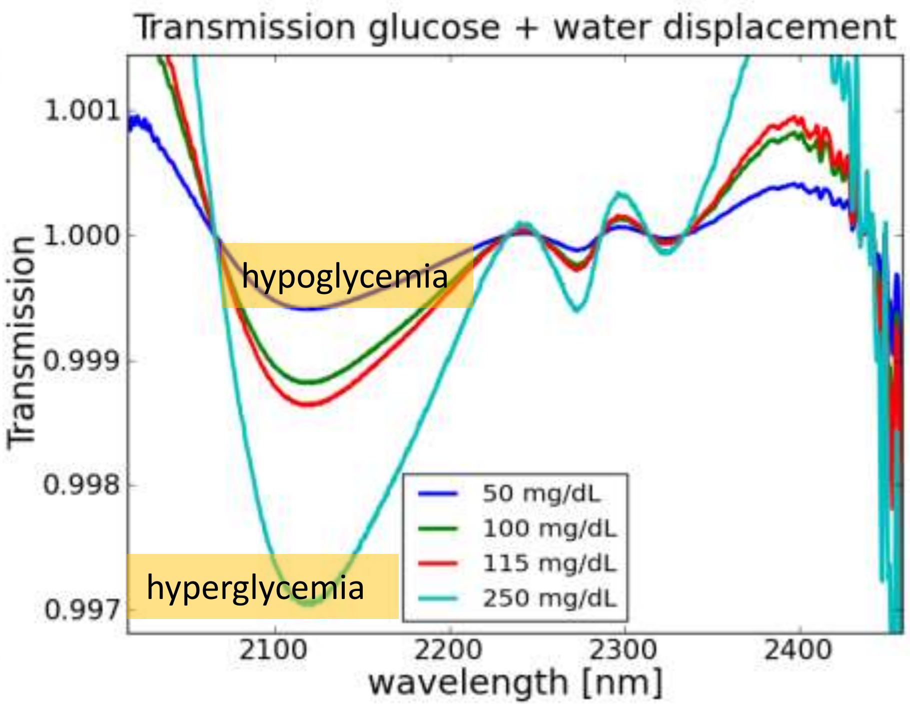
[*] Liebl A, Henrichs HR, Heinemann L, et al. Continuous glucose monitoring: evidence and consensus statement for clinical use. J Diabetes Sci Technol . 2013;7:500-519

GLUCOSE ABSORPTION SPECTROSCOPY





First overtone band: 1500 - 1800 nm

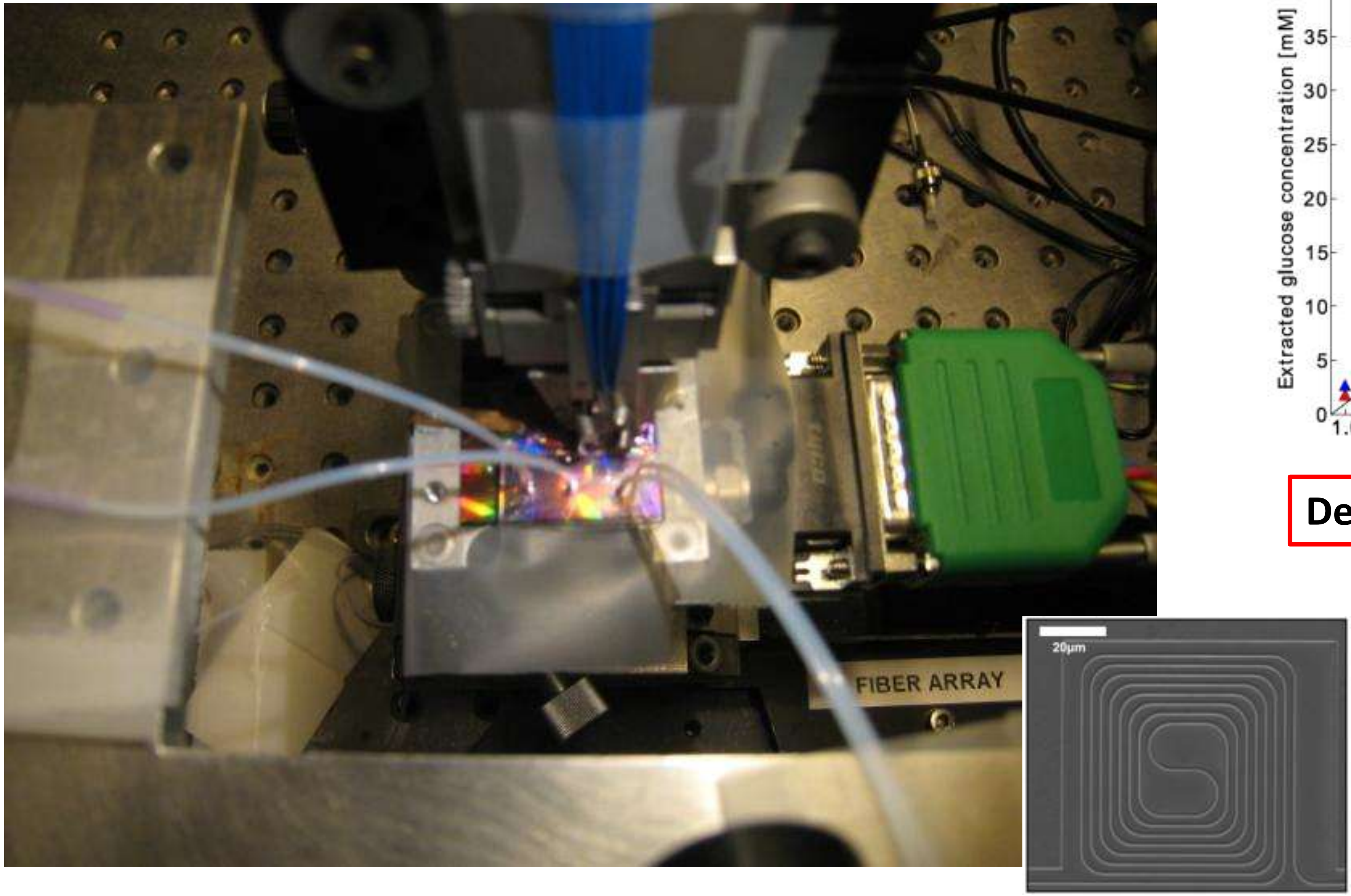


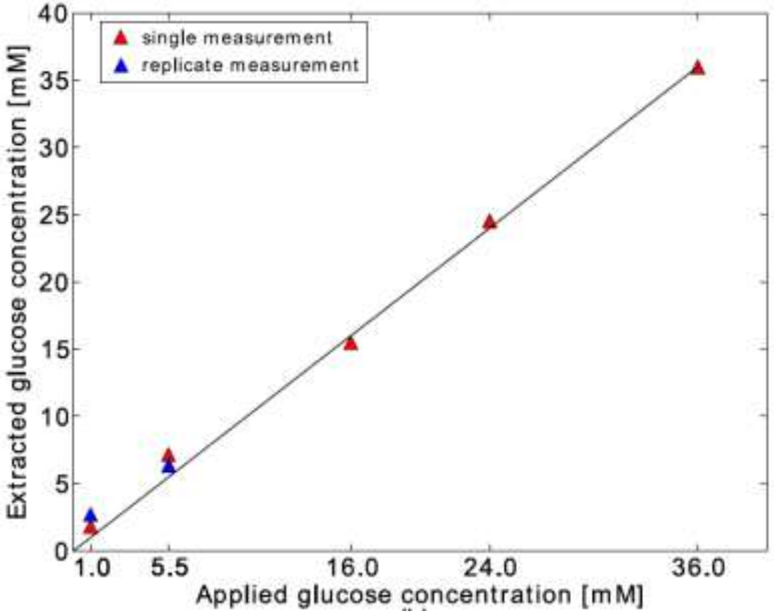
Combination band: 2000 - 2500 nm

For glucose sensing in humans (3-15 mM): Largest change in transmission is 0.5 %

Required sensitivity : 0.02%

PROOF-OF-CONCEPT DEMO OF GLUCOSE SENSING IN THE LAB

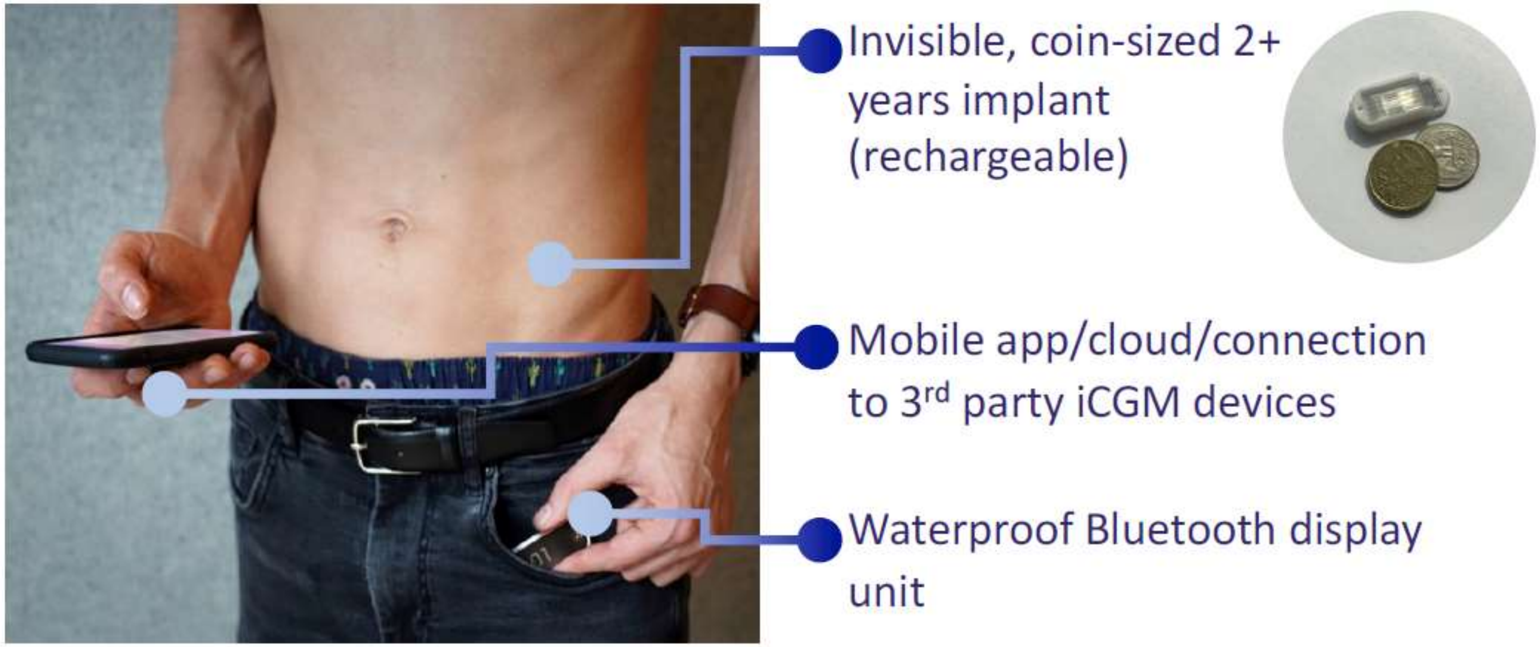




Demonstrated sensitivity of 1mM

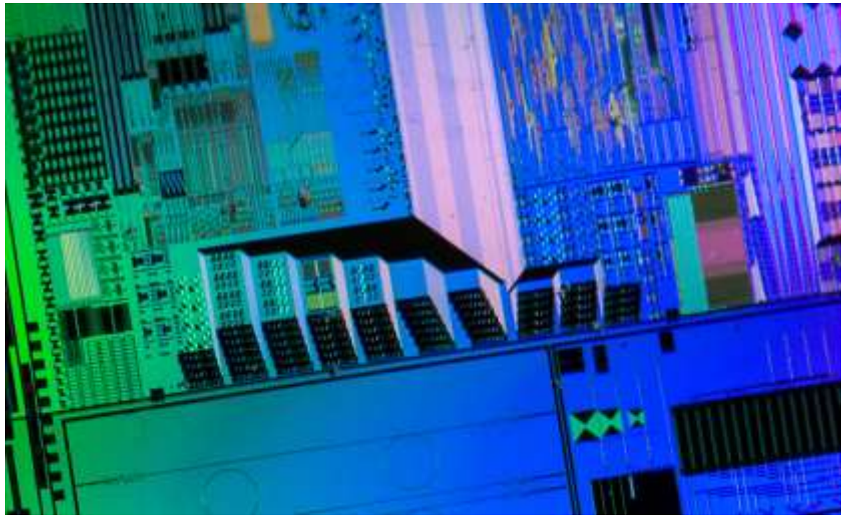
E. Ryckeboer et al, Biomedical Optics Express (2014) *doi:10.1364/boe.5.001636*

CONTINUOUS GLUCOSE MONITORING WITH SUBCUTANEOUS IMPLANT



- Invisible, coin-sized 2+ years implant (rechargeable)
- Mobile app/cloud/connection to 3rd party iCGM devices
- Waterproof Bluetooth display unit

Implant

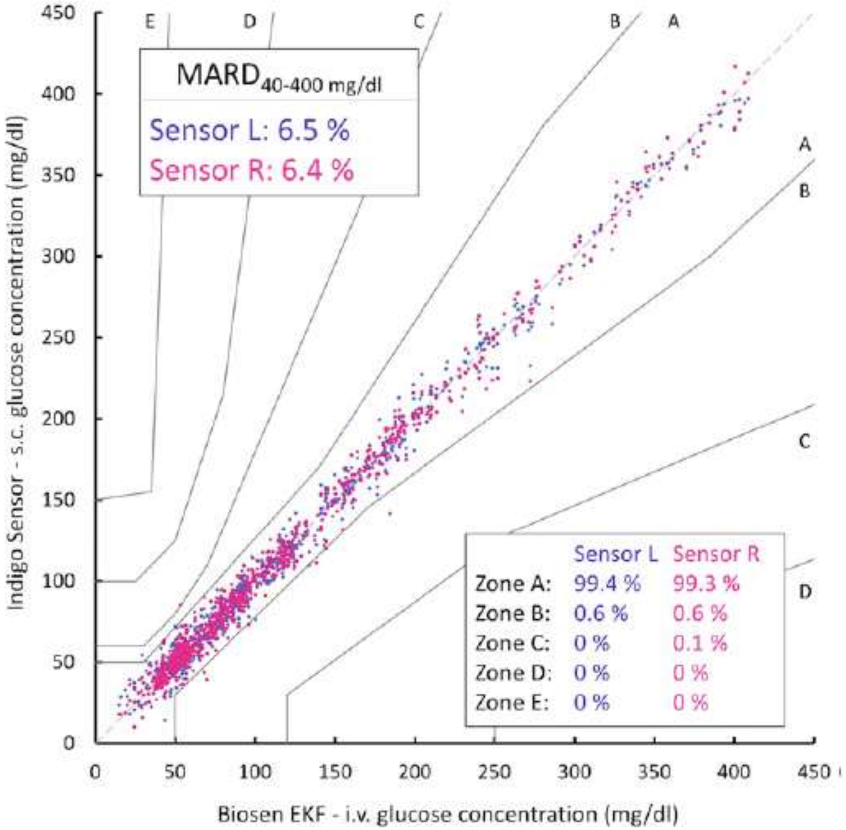


Microspectrometer chip

https://indigomed.com/

indigo

CONTINUOUS GLUCOSE MONITORING WITH SUBCUTANEOUS IMPLANT



MARD$_{40\text{-}400\ mg/dl}$

Sensor L: 6.5 %

Sensor R: 6.4 %

	Sensor L	Sensor R
Zone A:	99.4 %	99.3 %
Zone B:	0.6 %	0.6 %
Zone C:	0 %	0.1 %
Zone D:	0 %	0 %
Zone E:	0 %	0 %

Results on pig model (D. Stocker, EASD 2020)

https://indigomed.com/

indigo

Indigo Diabetes Initiates First Clinical Study of its Continuous Glucose Monitoring Sensor

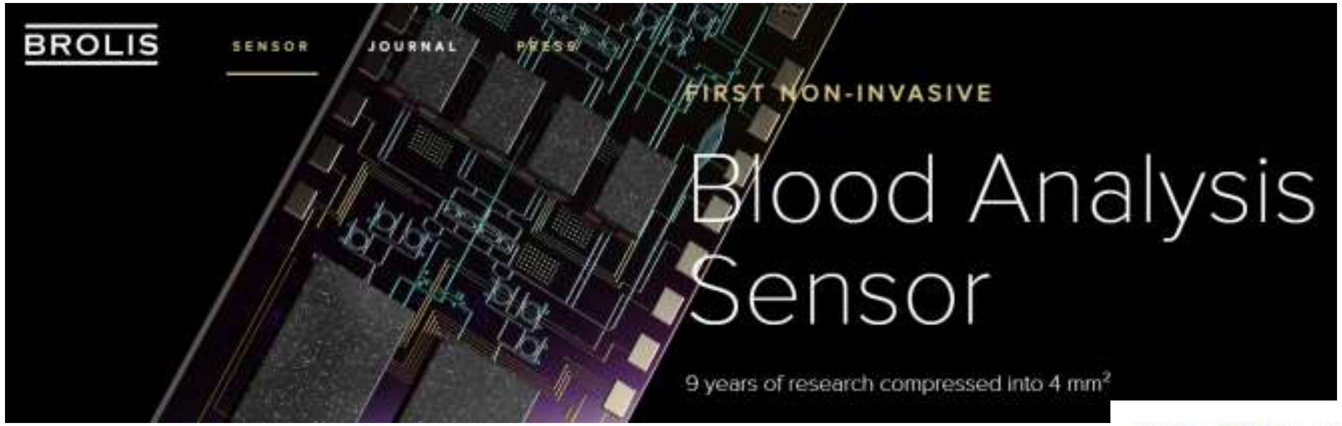
BY INDIGO | MAR 18, 2021 | 2021, NEWS

March 18, 2021 – Ghent, Belgium

> ***Ground-breaking subcutaneous sensor aims to continuously monitor multiple metabolites including ketones in people living with diabetes***

BELGIUM – Ghent, March 18, 2021 – Indigo Diabetes N.V. ('Indigo' or the 'Company'), a pioneering developer of medical solutions using nanophotonics, announces that its continuous multi-metabolite ('CMM') sensor has been successfully implanted subcutaneously in the first three participants of its first clinical study, designed to evaluate the device. Indigo's CMM sensor is in development for the continuous measurement of glucose, ketone and lactate levels in people living with diabetes.

NON-INVASIVE GLUCOSE MONITORING BASED ON SILICON PHOTONICS



FIRST NON-INVASIVE

Blood Analysis Sensor

9 years of research compressed into 4 mm^2

http://brolis.tech

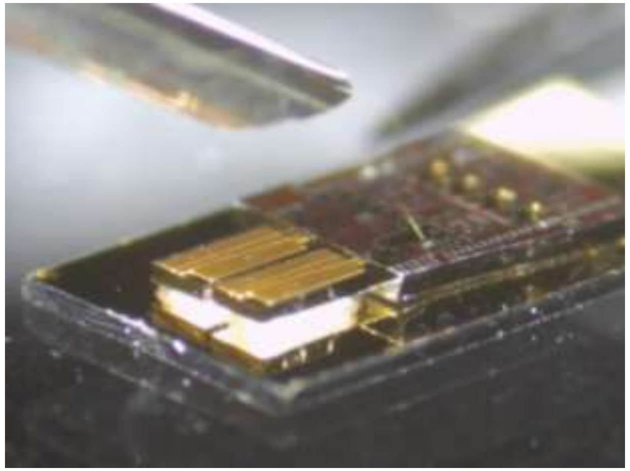
Rockley Photonics to Deliver Glucose Monitoring for Apple Smartwatches

By Nitin Dahad 05.04.2021 0

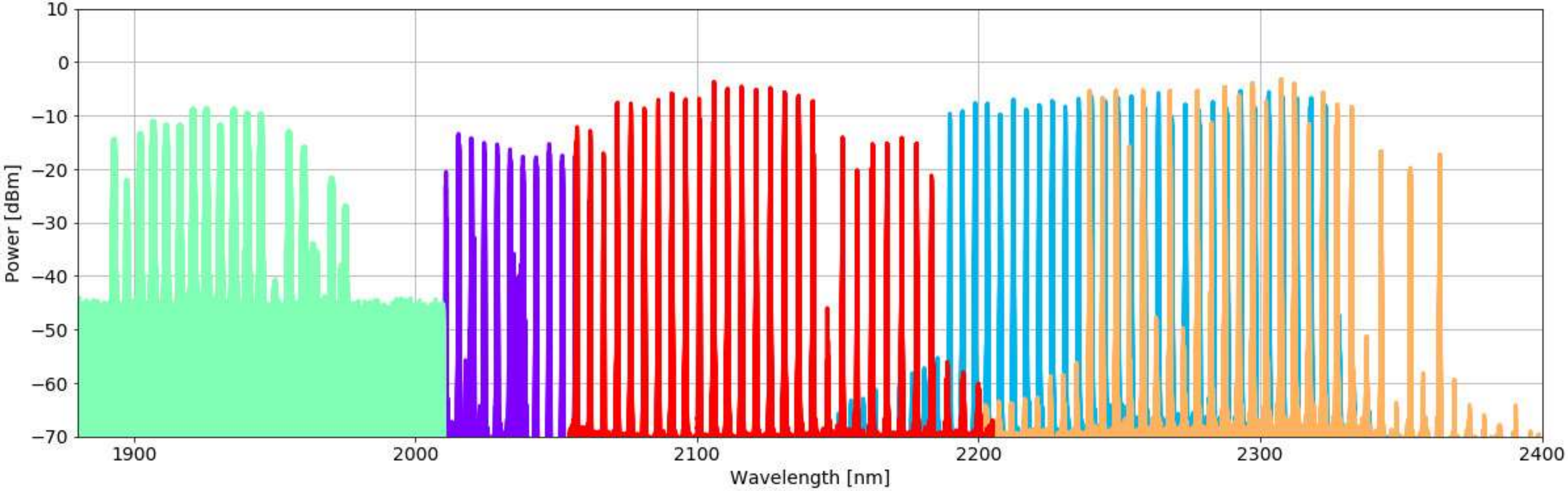
Rockley Photonics, which recently announced a $1.2 billion listing on the New York Stock Exchange via a special purpose acquisition company (SPAC), is thought to be developing advanced health monitoring features for smartwatches including for Apple.

Apple began purchasing products from Rockley in 2017; it is now Rockley's largest customer with $70 million of NRE commitment to date.

Brolis: GaSb tunable laser technology with silicon PIC



- GaSb gain chips hybridly integrated with silicon PIC
- 1880 – 2430 nm
- 0.1- 1 mW output power
- Tuning speed up to 2 kHz
- 120 nm/gain-chip



Current Smartwatch Technology

- ✗ Limited sensor capabilities
- ✗ Legacy LED technology
- ✗ Low resolution & accuracy

Heart Rate & ECG

Blood Oxygen

Current Medical Technology

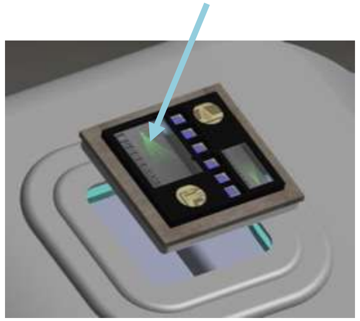
- ✗ In-clinic / in-hospital monitoring only
- ✗ Bulky, high-cost medical lab equipment not available to average consumer
- ✗ Different equipment for different tests

Lactate *Alcohol* *Glucose* *Carbon Monoxide* *Blood Pressure*

Rockley's Multi-Function Clinic-on-the-Wrist Capability

- ✓ **Single sensor for multi-modal biochemical / biophysical marker monitoring**
- ✓ **Functionality of numerous lasers on a single chip**
- ✓ **Unparalleled spectral resolution & accuracy**

Si Photonic PIC



New sensing functions unlocked…

Lactate *Alcohol* *CGM (Glucose)* *Carbon Monoxide* *Blood Pressure* *And more…*

Rockley's integrated optical technology enables miniaturization of sensing devices necessary for the evolution of a wearable spectrometer

OUTLINE

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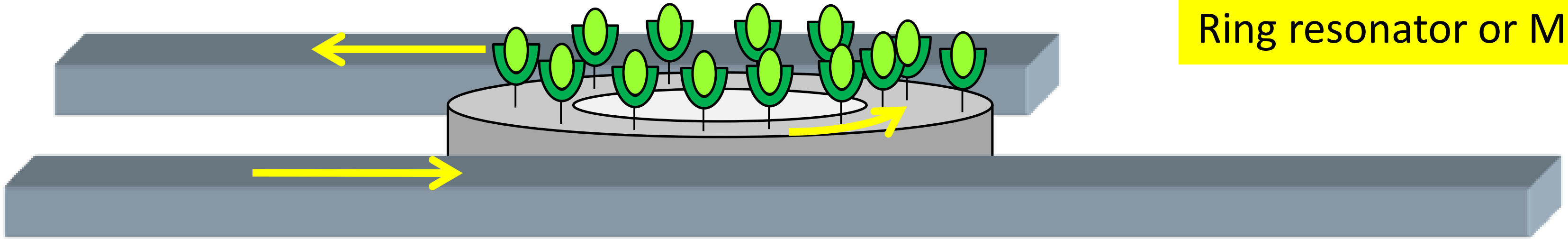
On-chip tunable lasers

On-chip Raman spectroscopy

Application cases

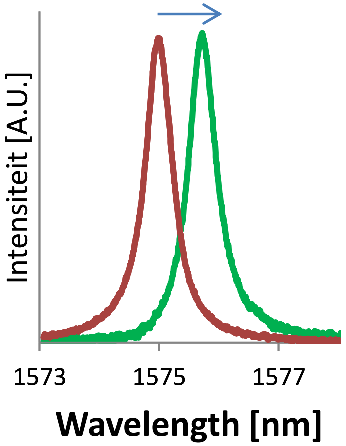
- Glucose monitoring
- ➡ Biosensing
- Gas sensing
- Fiber Bragg Grating readout
- Water pollutant monitoring

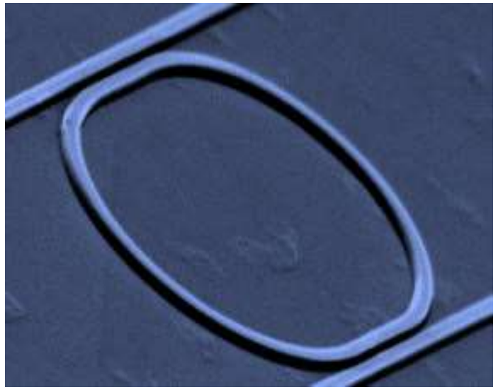
LABEL-FREE BIOSENSOR
THROUGH REFRACTIVE INDEX SENSING OF ANTIGEN-ANTIBODY BINDING



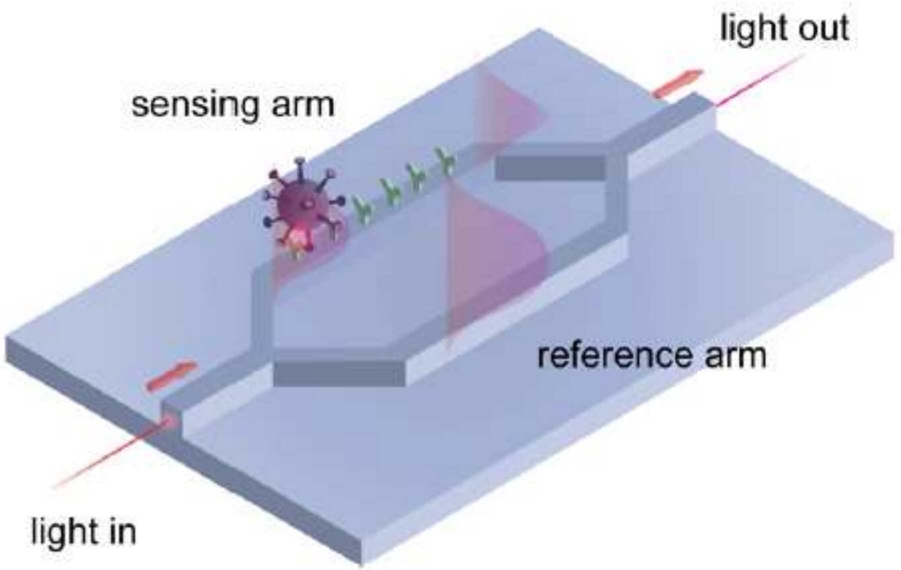
Ring resonator or MZI

Wavelength shift

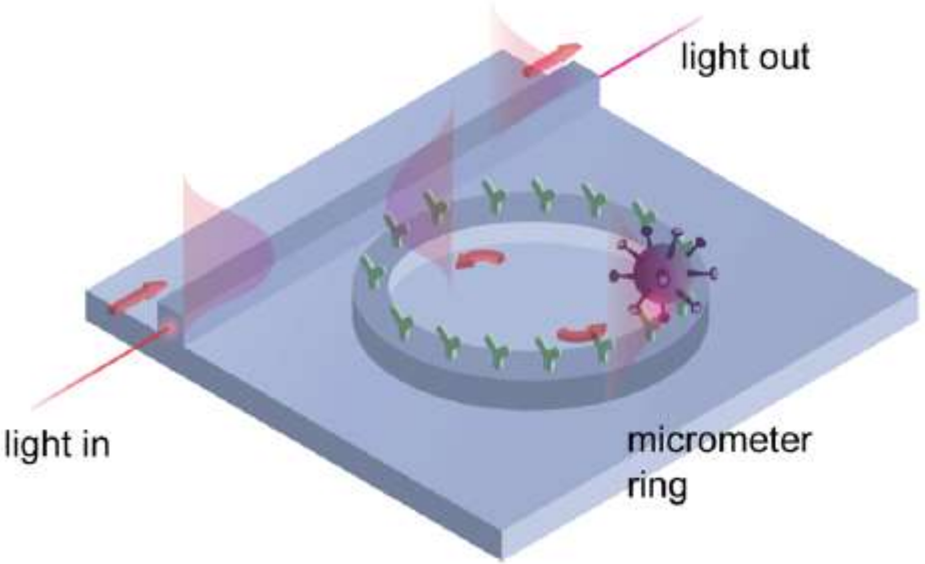




KEY PHOTONIC BIOSENSOR DEVICES



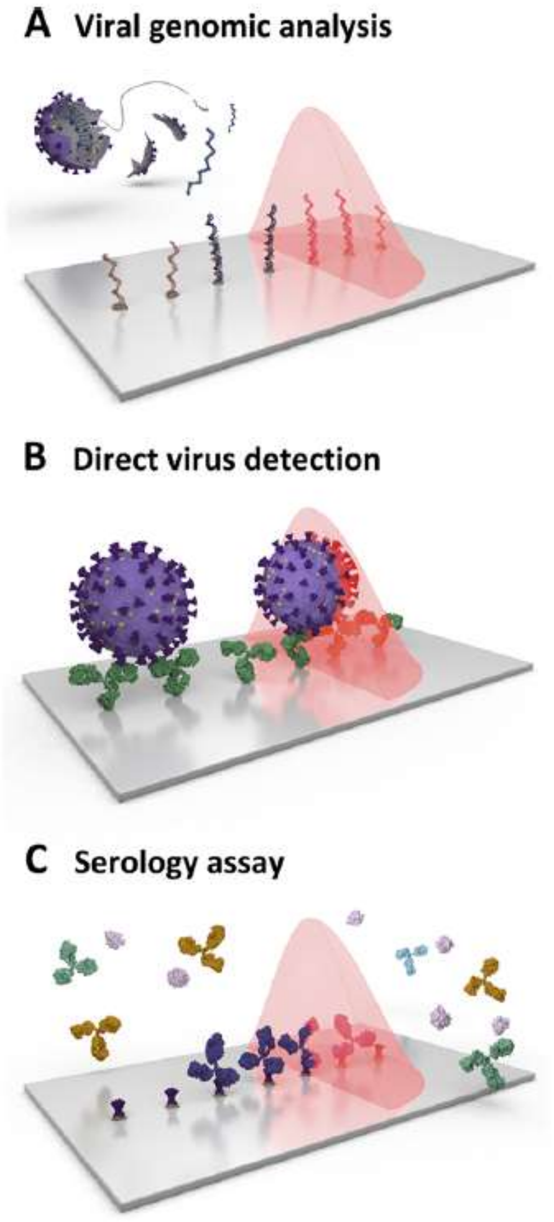
Mach-Zehnder Interferometer (MZI)



Micro-ring resonator (MRR)

M. Soler et al, ACS Sens. (2020) *doi.org/10.1021/acssensors.0c01180*

BIOSENSING STRATEGIES FOR VIRAL INFECTION DIAGNOSIS



A. Genomic detection

Chip is functionalized with short stretches of nucleic acids, with complementary sequence to the viral target

B. Antigen-directed virus detection

Chip is functionalized with antibodies that bind to spike proteins at the surface of the virus

C. Serological test (blood)

Chip is functionalized with antigens that bind to antibodies that result from the body's immune response to the virus

M. Soler et al, ACS Sens. (2020) doi.org/10.1021/acssensors.0c01180

Genalyte

https://www.genalyte.com/

COVID-19 Multi-Antigen Serology Panel

Semi-Quantitative detection of antibodies to SARS-CoV-2

Who We Are

Genalyte is a CAP accredited, CLIA certified lab specializing in large scale serology testing. Our Maverick™ SARS-CoV-2 Multi-Antigen Serology Panel uses a multiplex format to test patient samples for antibodies to five SARS-CoV-2 proteins. The result is unparalleled accuracy across a variety of patient populations.

Our Platform

The Maverick™ Diagnostic System (MDS) uses silicon chip based photonic ring resonance technology to perform multiple simultaneous rapid tests on a small volume of whole blood. The system is cloud-connected for assay protocol retrieval and clinical oversight. Results are available in 20 minutes. FDA Cleared in 2019 .

General Population: 7-14 days

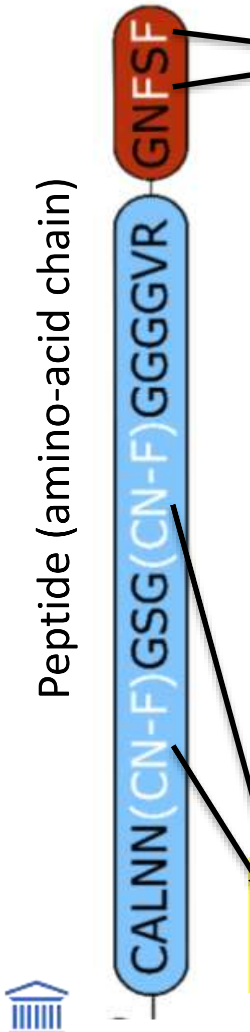
	PCR Result		
MAVERICK	Pos	Neg	
Pos	46	0	46
Neg	7	303	310
	53	303	

Post Seroconversion: >14 days

	PCR Result		
MAVERICK	Pos	Neg	
Pos	86	0	86
Neg	2	303	305
	88	303	

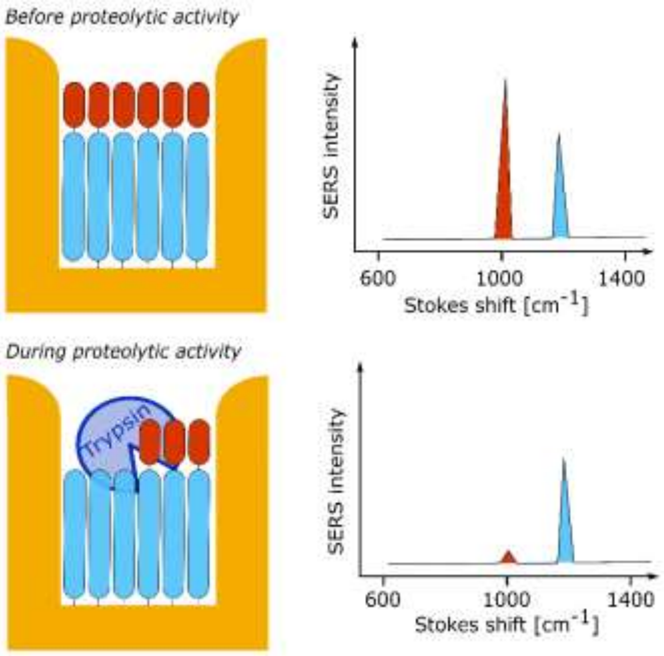
ON-CHIP RAMAN SPECTROSCOPY FOR MONITORING OF ENZYMATIC ACTIVITY

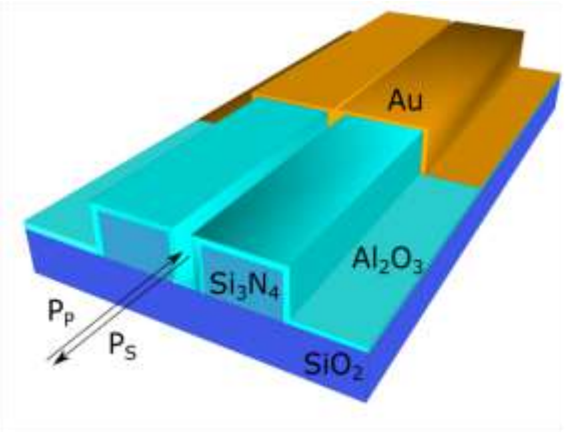
Proteases play an important role in signaling pathways in relation to various diseases

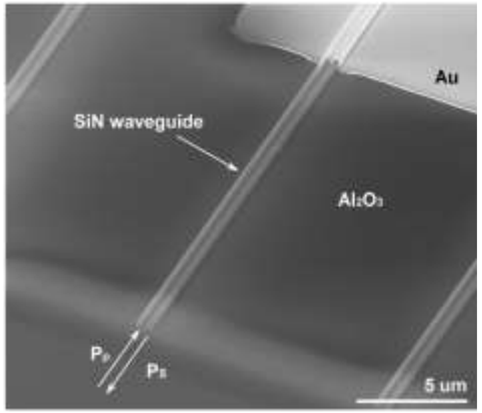


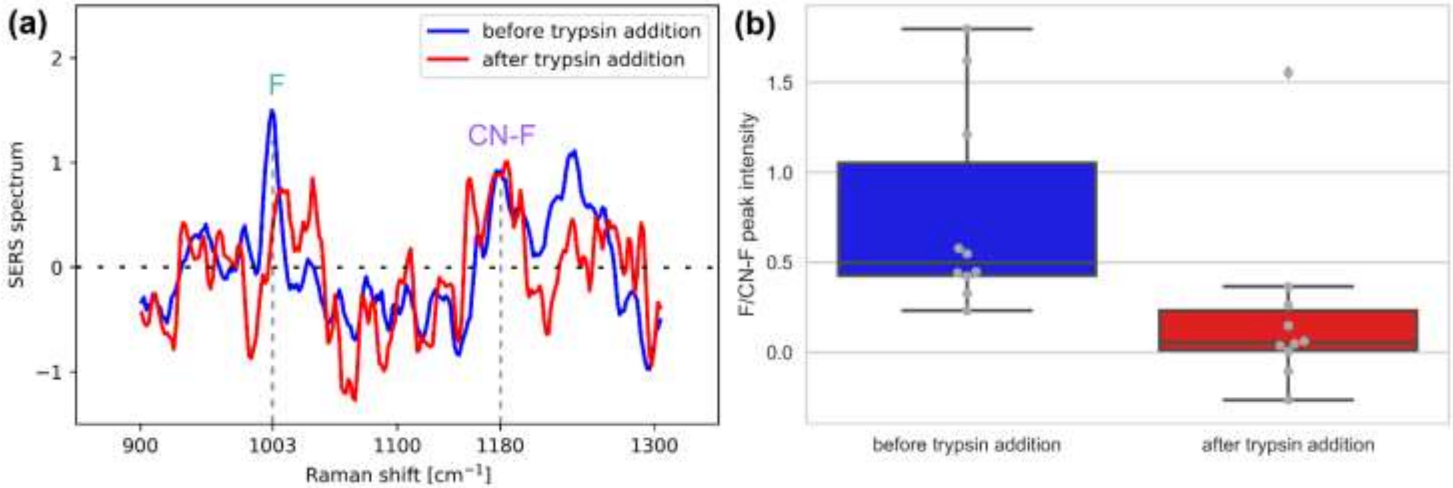
F: natural amino-acid phenylalanine

CN-F: non-natural amino-acid 4-cyano-phenylalanine









N. Turk et al, Biomed. Opt. Expr. (2020) doi:10.1364/BOE.398038

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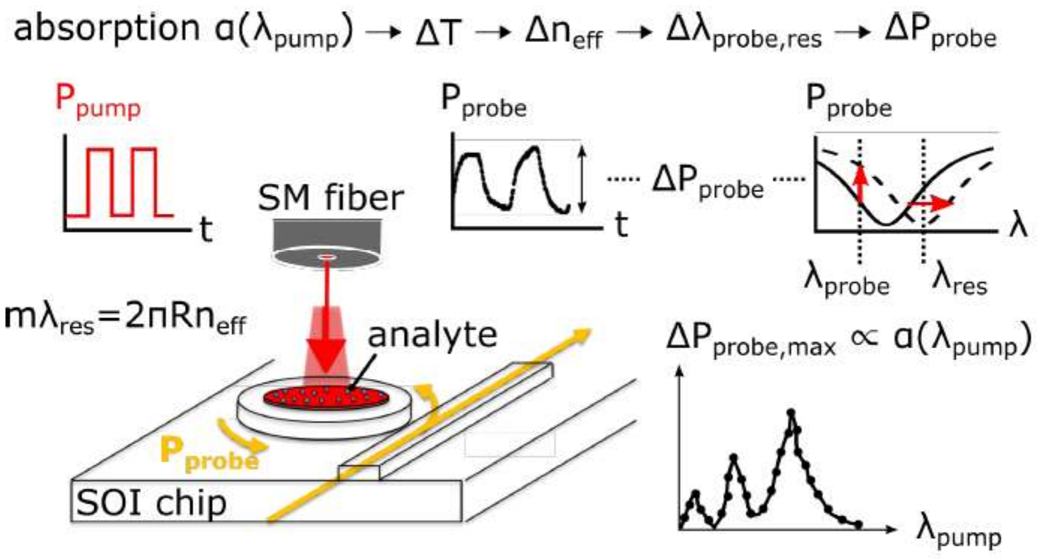
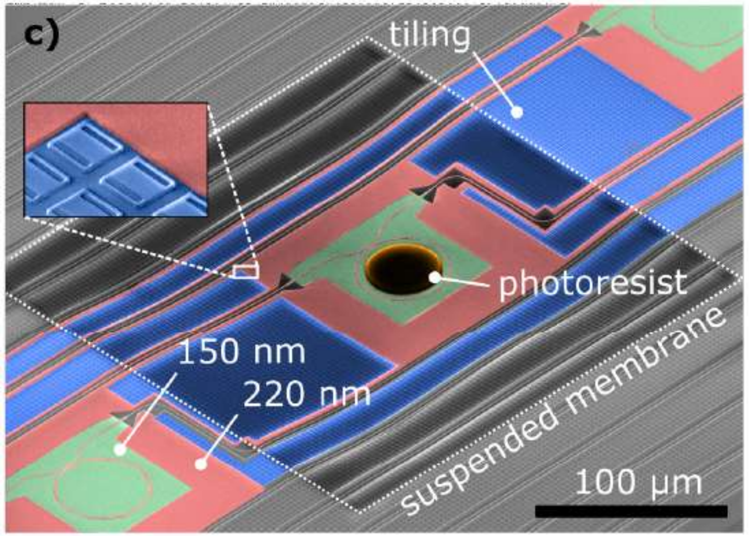
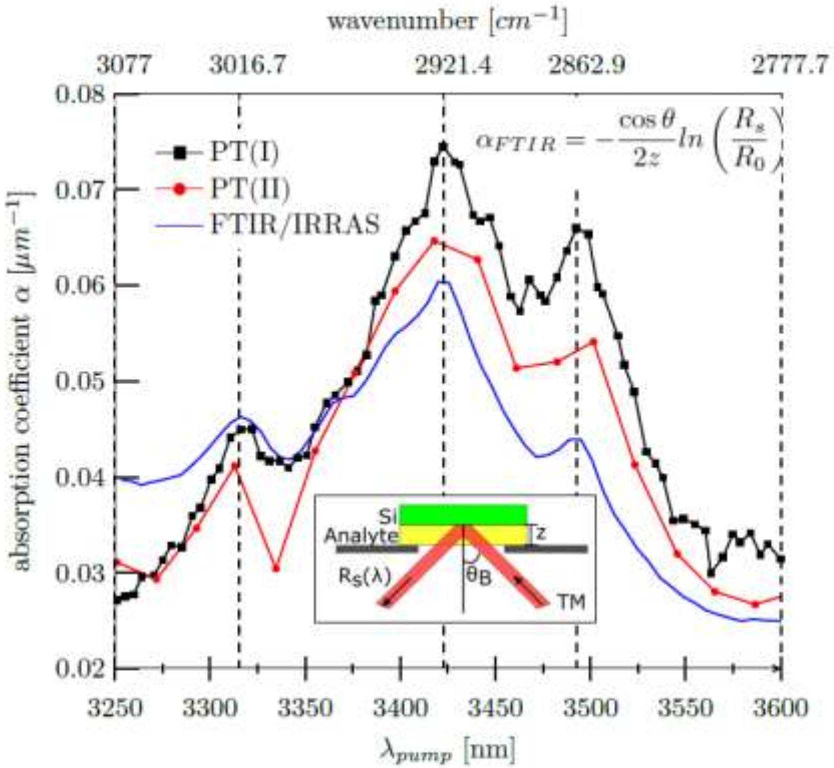
- Water pollutant monitoring

MID-IR PHOTOTHERMAL ABSORPTION SPECTROSCOPY WITH SOI RING



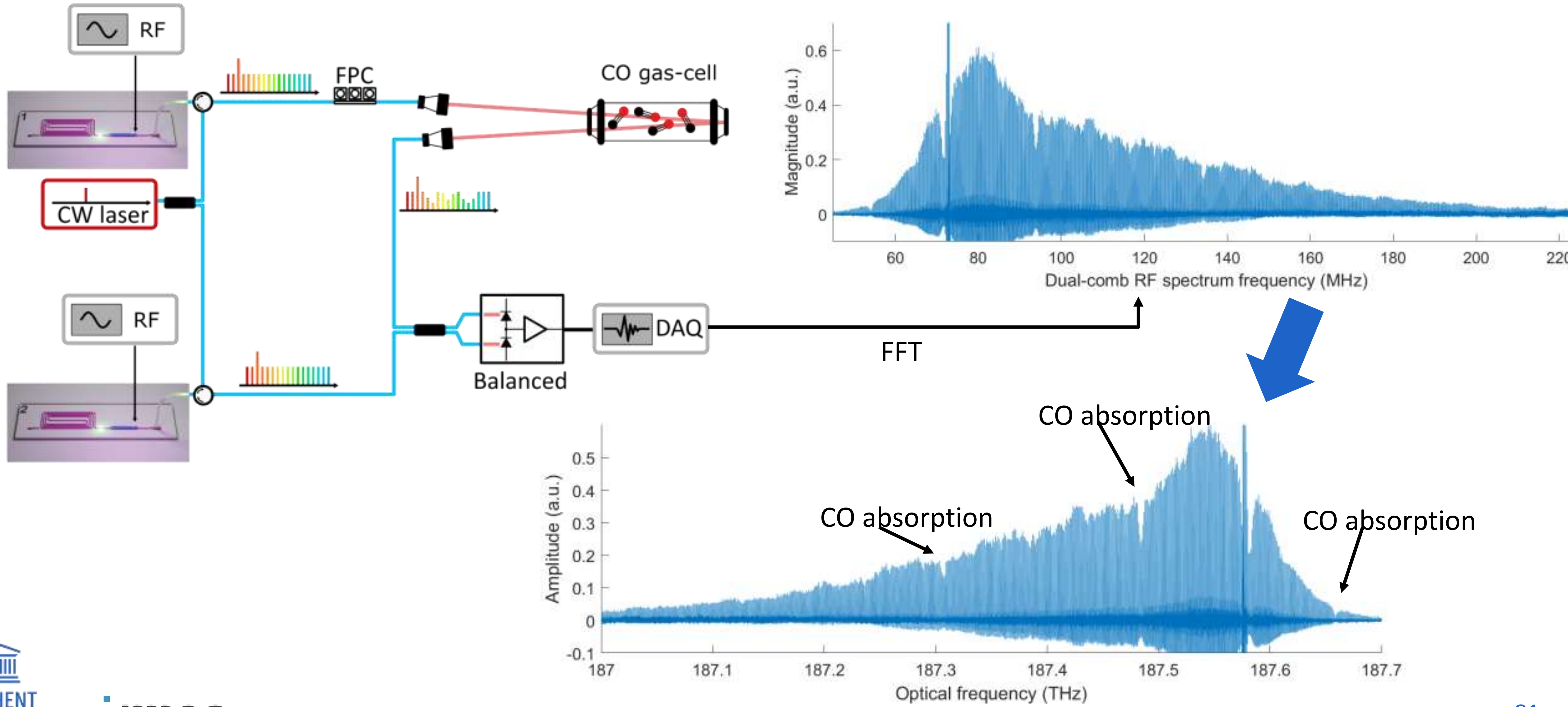




Proof-of-concept demonstration using photoresist as analyte

Vasiliev et al, ACS-Sensors (2017) [*10.1021/acssensors.6b00428*](10.1021/acssensors.6b00428)

DUAL-COMB SPECTROSCOPY OF CO WITH TWO INP-ON-SOI COMB LASERS

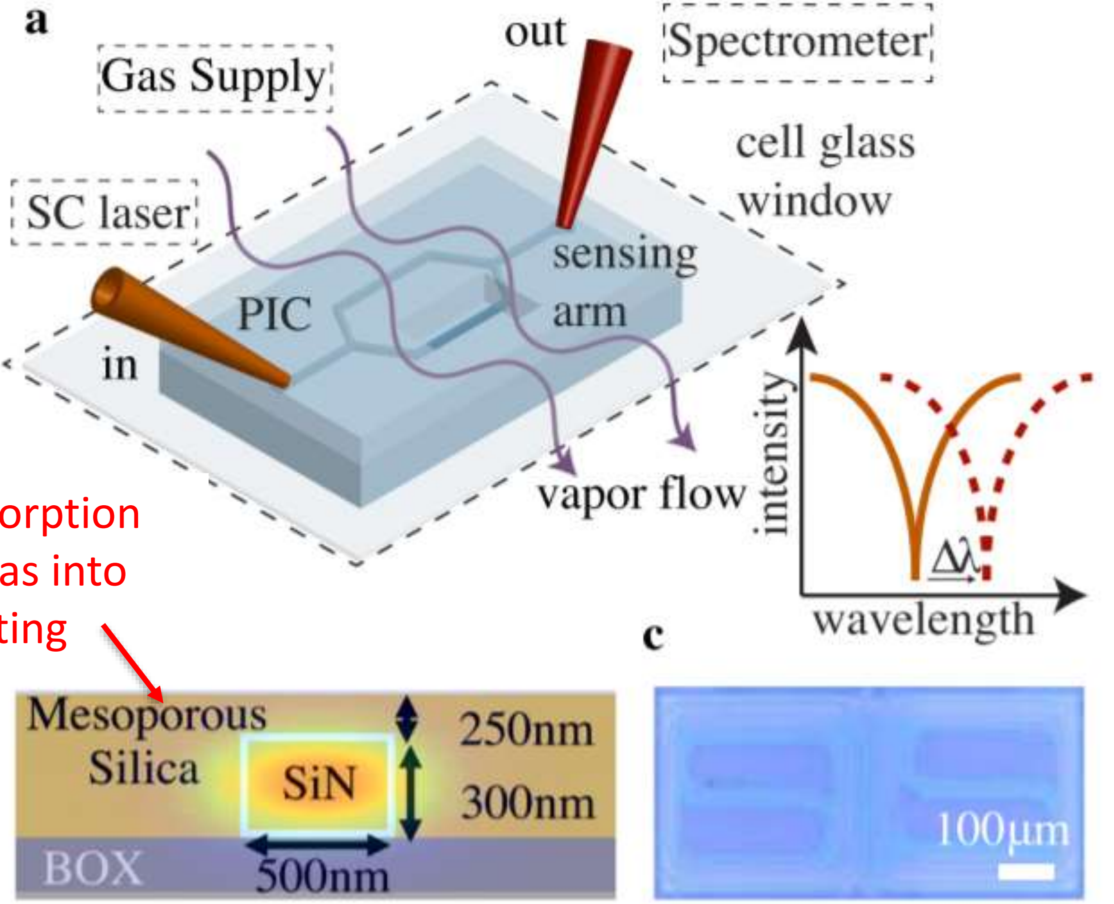


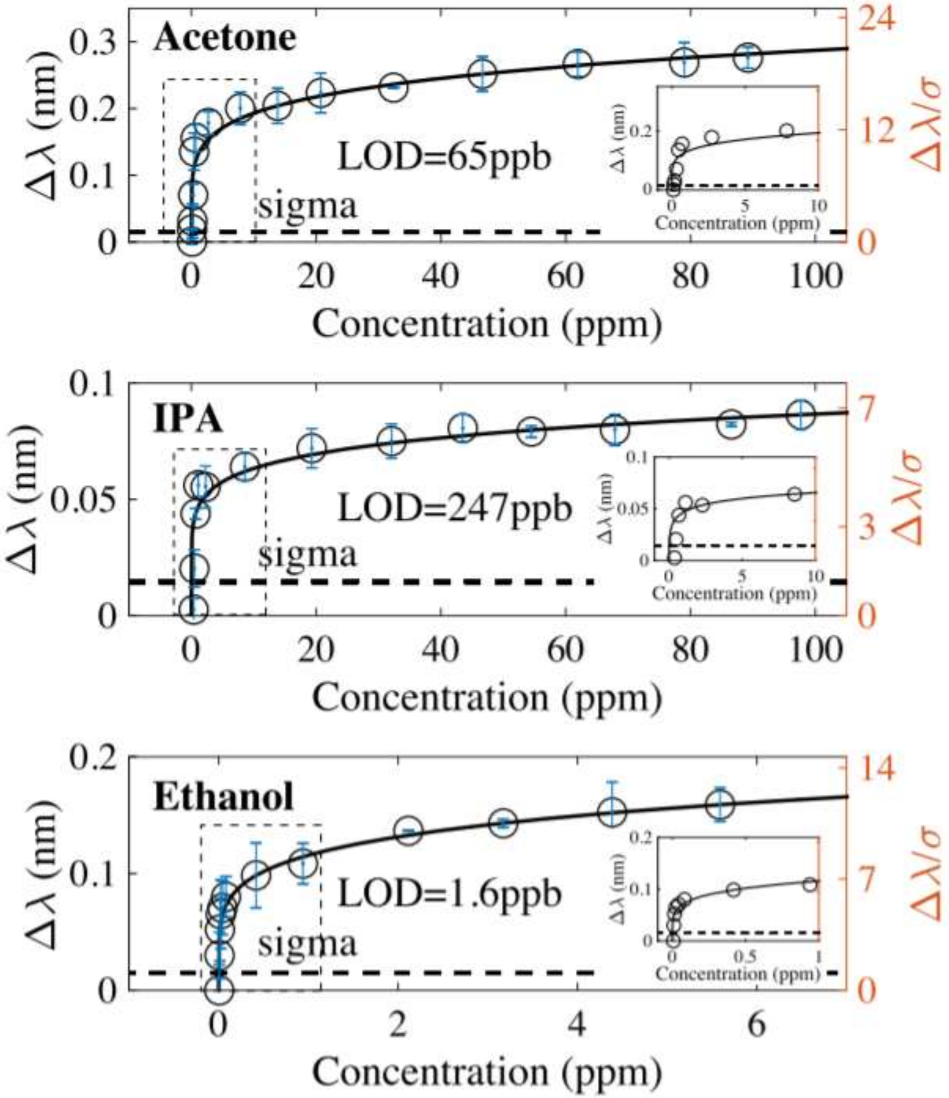
K. Van Gasse et al, CLEO (2021)

ULTRASENSITIVE GAS SENSING WITH REFRACTIVE INDEX SENSORS

Medical application: breath analysis

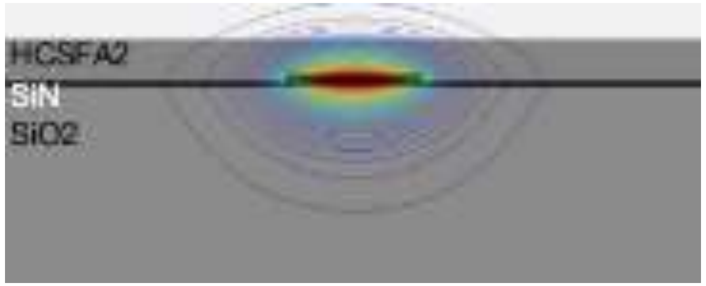
Adsorption of gas into coating



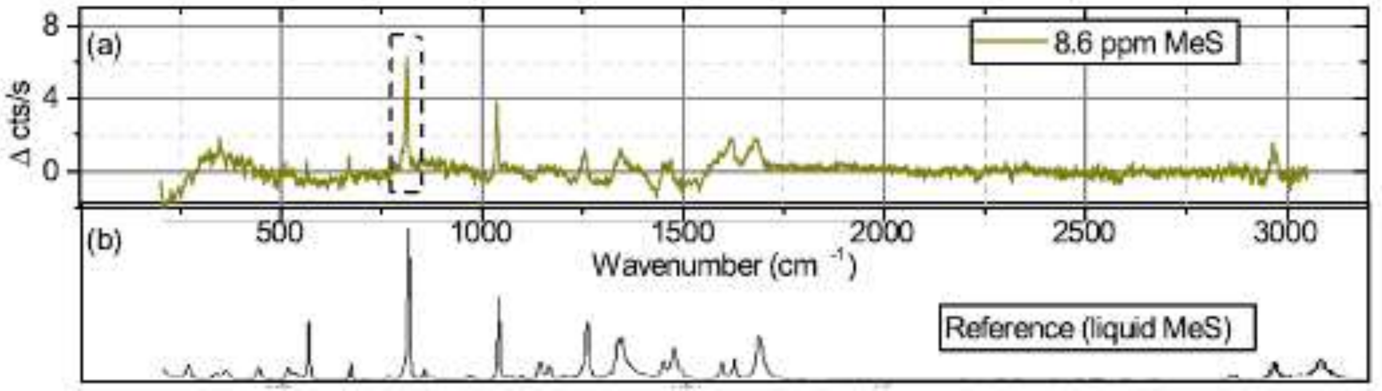


G. Antonacci et al, APL Photonics 2020 [doi:10.1063/5.0013577](https://doi.org/10.1063/5.0013577)

TRACE GAS SENSING WITH ON-CHIP RAMAN SPECTROSCOPY



Hypersorbent polymer (HCSFA2)
coating on SiN waveguides.
Partition coefficient ~ 10^8



Raman spectrum of gaseous MeS
(methyl salicylate, a hydrogen-bond basic organic ester)

Detection limit ~100 ppb
Densification ~ 10^8

S. Holmstrom et al. Optica (2016) *https://doi.org/10.1364/OPTICA.3.000891*

OUTLINE

Brief introduction to silicon and silicon nitride PICs

Spectroscopic sensing modalities

On-chip spectrometers

On-chip tunable lasers

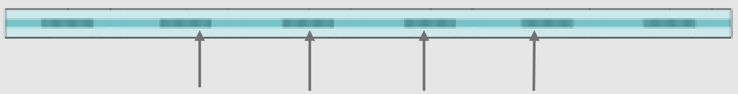
On-chip Raman spectroscopy

Application cases

- Glucose monitoring
- Biosensing
- Gas sensing
- ➡ Fiber Bragg Grating readout
- Water pollutant monitoring

SENTEA FBG INTERROGATOR

FIBER SENSOR

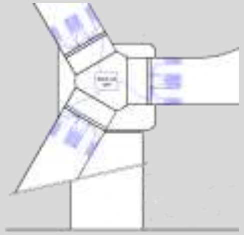

Multiple distributed sensing points

Resistant to harsh environments

Strain Temperature Vibration

EASY INSTALL
PACKAGED OR EMBEDDED SENSORS


Fiber sensors mounted on bridges

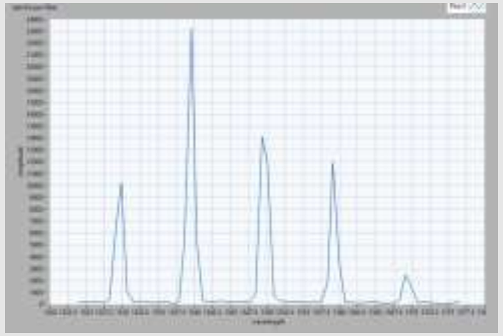

Fiber sensors embedded in wind turbine blades


Fiber sensors for industrial temperature sensing

Fiber sensors embedded in bearings & gearboxes

COST-EFFECTIVE FIBER SENSING
THROUGH SILICON PHOTONICS

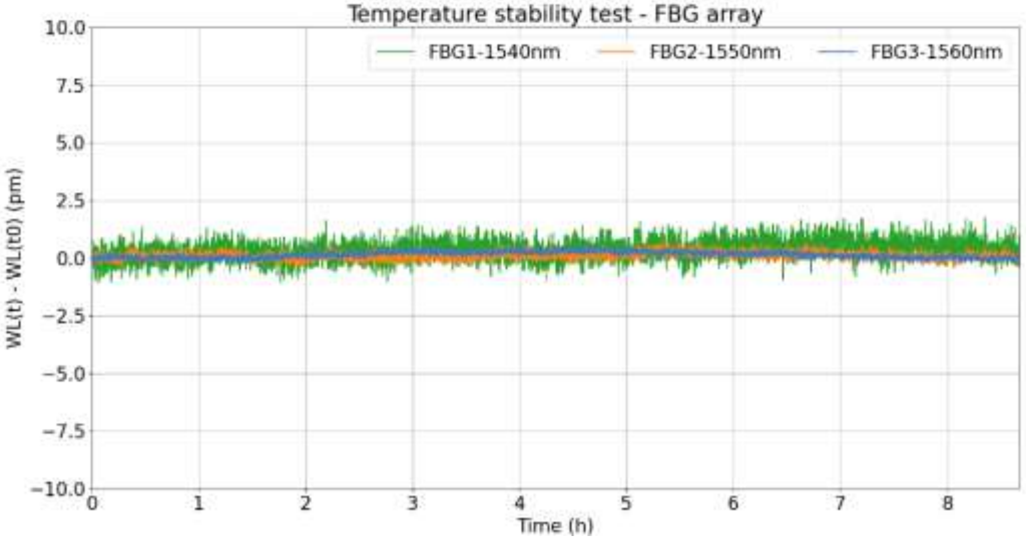
On-chip polarization independent spectrometer with sub-pm resolution



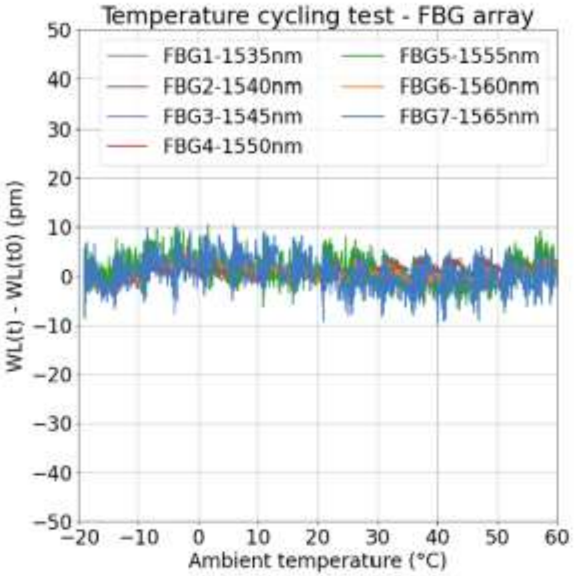
PERFORMANCE DM-4120

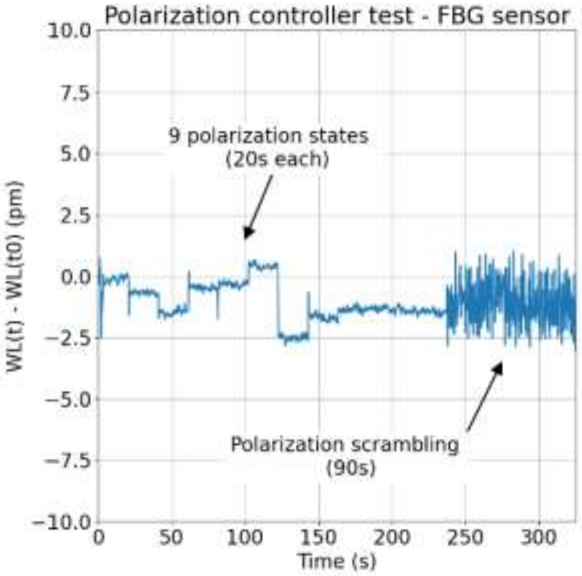
DM-4120^{TM} FBG fiber interrogator

STABILITY AT ROOM TEMPERATURE



STABILITY AGAINST TEMPERATURE & POLARIZATION VARIATIONS





OUTLINE

Brief introduction to silicon and silicon nitride PICs

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On-chip Raman spectroscopy

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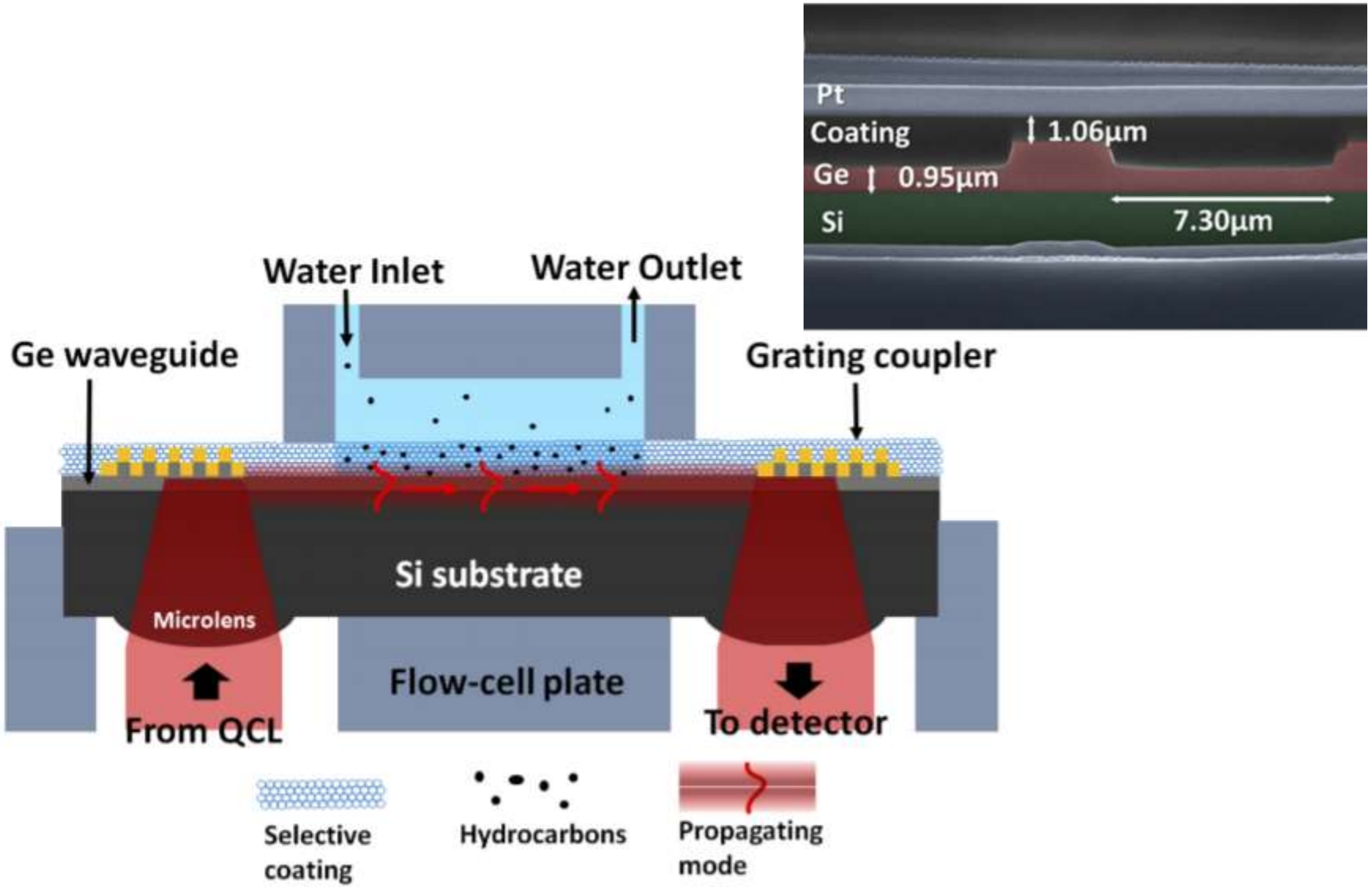
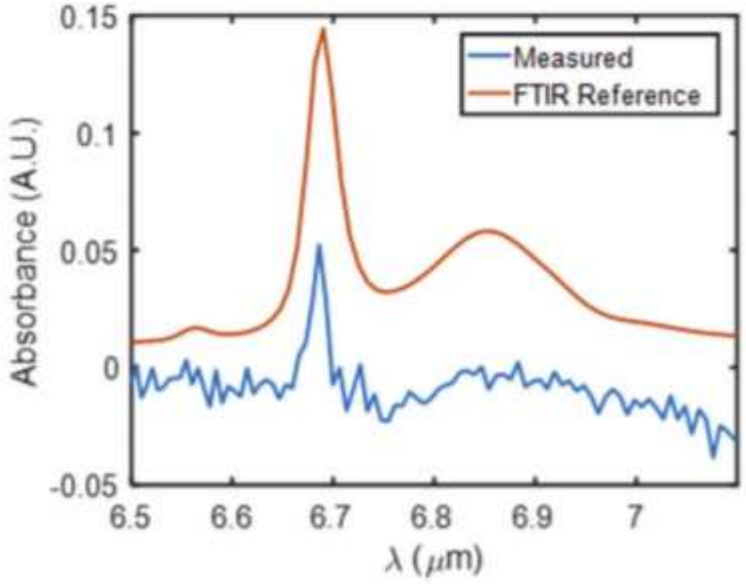
MID-IR ABSORPTION SPECTROSCOPY OF TOLUENE IN WATER



Ge-on-Si (GOS) waveguide with mesoporous coating, probed with external tunable QCL (6.5-7.5 µm)

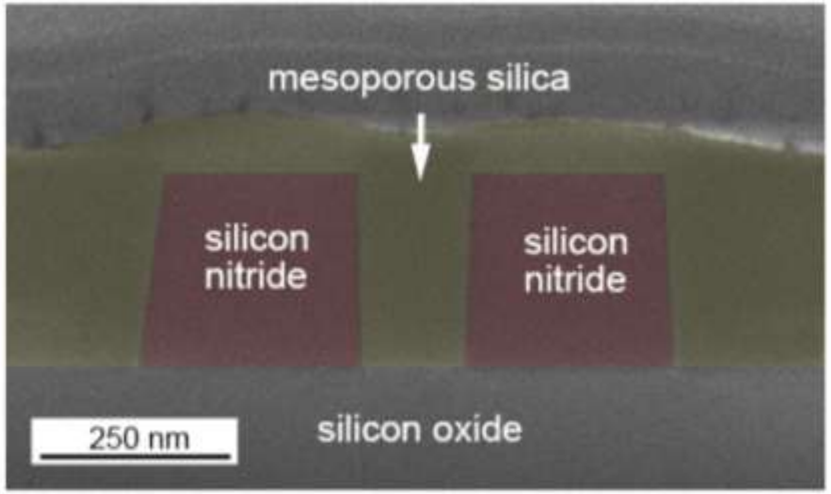


Absorption spectrum

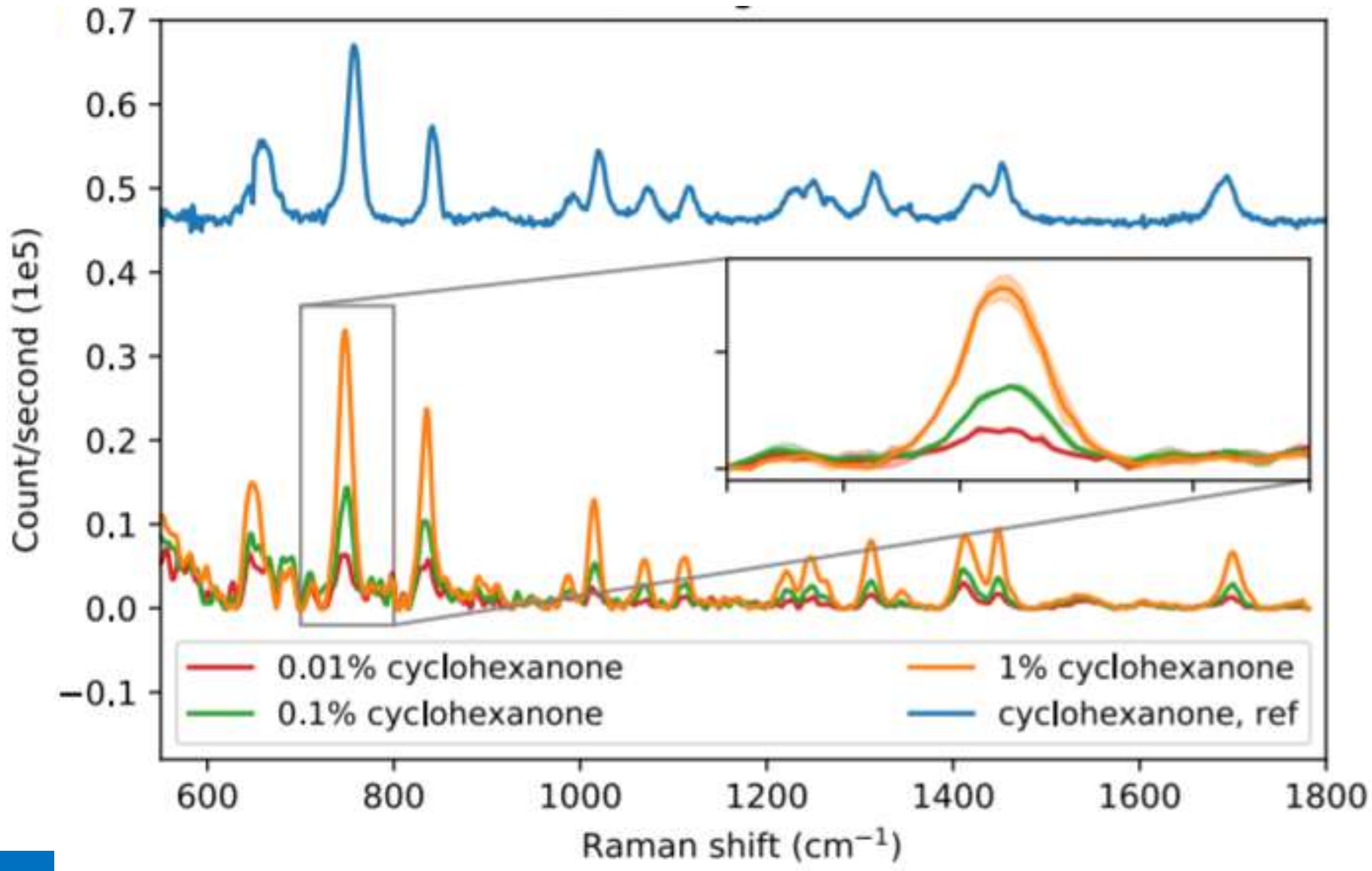
Limit of detection ~ 7 ppm
Density enrichment ~ 760-860x

N. Teigell Benetez et al, Optics Express (2020) [10.1364/OE.399646](https://doi.org/10.1364/OE.399646)

ON-CHIP RAMAN SPECTROSCOPY OF CYCLOHEXANONE IN WATER



Silicon nitride slot waveguide
covered with mesoporous silica



Detection of Cyclohexanone in water
(pump wavelength: 785 nm)

Detection down to 100 ppm demonstrated
Density enrichment by mesoporous coating ~ 600x

Z. Liu et al, Optics Letters (2021) doi:10.1364/OL.416464

SUMMARY

Silicon PICs (SOI, SiN, GOS)

- compact
- low cost

Enabling many spectroscopic sensing modalities

- absorption spectroscopy (in all its many variants)
- Raman spectroscopy
- readout of spectral filters (RI-sensing, FBG…)

Emerging industrial take-up

- personal health care
- monitoring of critical functions (infrastructure, water quality, safety, industrial sensing…)