OSA

Nanophotonics Technical Group

About the OSA Nanophotonics Technical Group

Mission statement

OSA Nanophotonics Technical Group focuses on the study and design of optics and optical devices that interact with light on the nanometer scale.

About the OSA Nanophotonics Technical Group

Group Chair

Cheng Zhang

Professor, Huazhong University of Science and Technology (HUST), China

cheng.zhang@hust.edu.cn

Group Chair-Elect

Sejeong Kim

Assistant Professor, University of Technology Sydney, Australia

sejeong.kim@unimelb.edu.au

Social Media Officer

Sachin Kumar Srivastava

Assistant Professor, Indian Institute of Technology Roorkee, India

sachin.srivastava@ph.iitr.ac.in

Member

Jinghui Yang

Post-doctoral Researcher, National Institute of Standards and Technology, USA

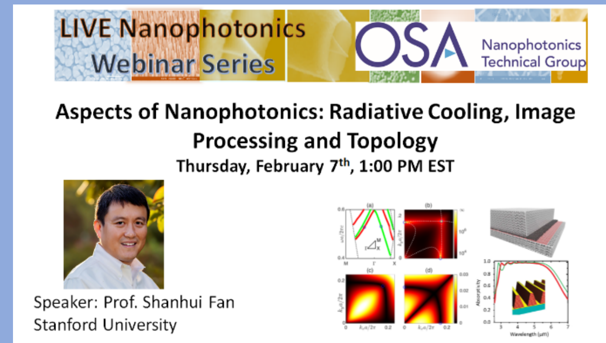
jinghui.yang@nist.gov

Member

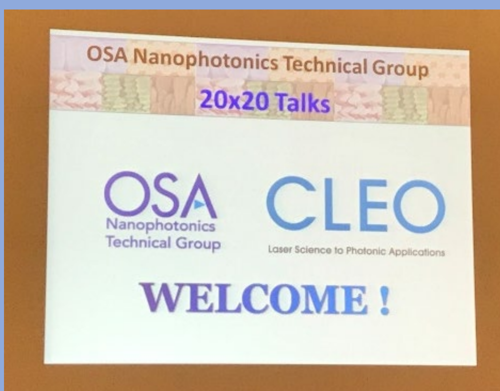
Sajid Muhaimin Choudhury, Assistant Professor, Bangladesh University of Engineering and Technology, Bangladesh

sajid@eee.buet.ac.bd

Create a community for nanophotonic researchers



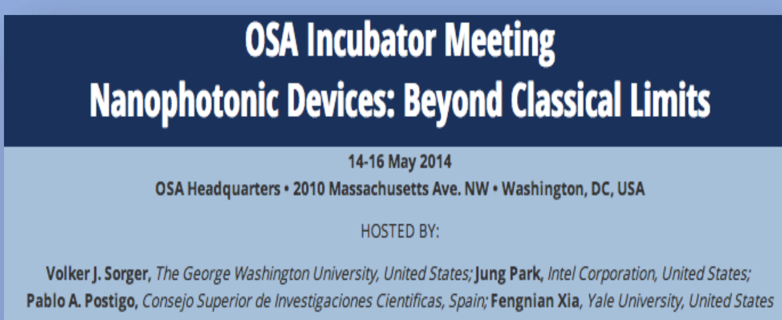
Webinars



20 x 20 Talks at CLEO

Personalized mentoring at FiO

Special events at OSA conferences



Incubator meetings

Where to find us ?

Home / Get Involved / Technical Groups / Optical Interaction Science

Nanophotonics (ON)

Get Involved

- Virtual Engagement
- Diversity, Equity & Inclusion
- Public Policy
- Chapters and Sections Map
- Technical Groups –
  - Bio-Medical Optics
  - Fabrication, Design & Instrumentation
  - Information Acquisition, Processing & Display
  - Optical Interaction Science –
    - Fundamental Laser Sciences (OF)
    - Nanophotonics (ON)
    - Nonlinear Optics (OL)
    - Optical Cooling and Trapping (OT)
    - Optical Material Studies (OM)
    - Optical Metrology (OR)

Nanophotonics

This group focuses on the study and design of optics and optical devices that interact with light on the nanometer scale. This new field is enabled by newly developed capabilities to fabricate optical components and devices on a nano-scale.

On-Demand Nanophotonics Webinars

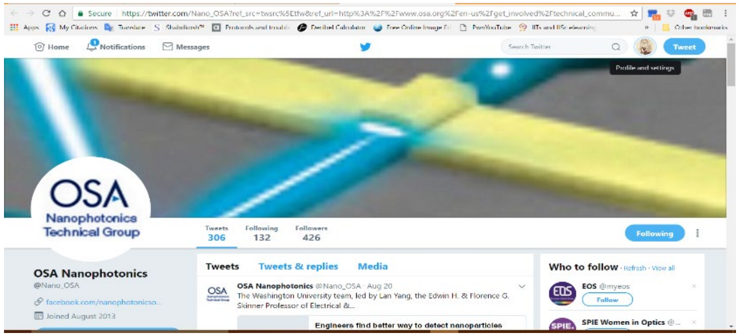
You can watch any of the following webinar presentations, which were hosted by the OSA Nanophotonics Technical Group, on-demand.

- Plasmonic Nanolasers: Physics, Applications, and Challenges
- Aspects of Nanophotonics: Radiative Cooling, Image Processing and Topology
- Enabling Chip-Scale Trace-Gas Sensing Systems with Silicon Photonics
- Photonic Skin-Depth Engineering and Universal Spin-Momentum Locking of Light

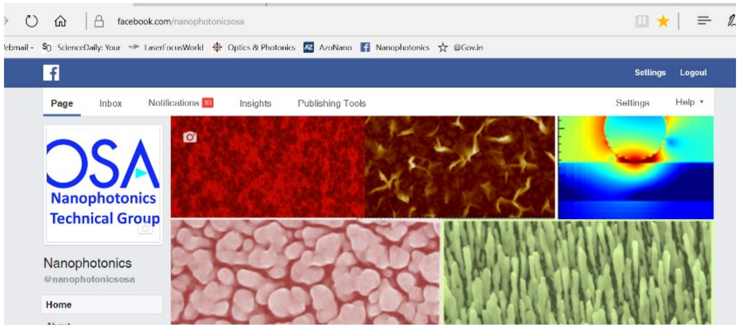
Website: www.osa.org/NanophotonicsTG

Email: osananophotonics@gmail.com

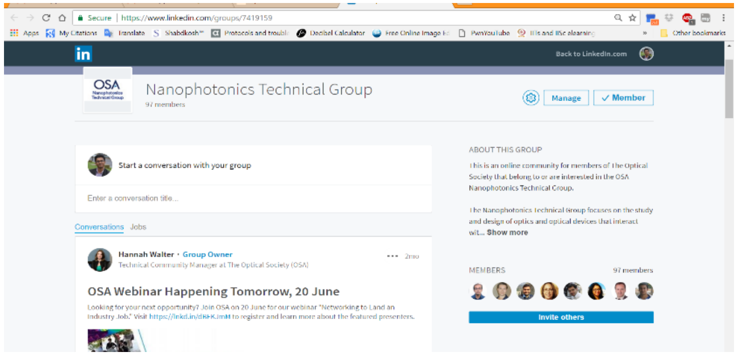
Where to find us ?



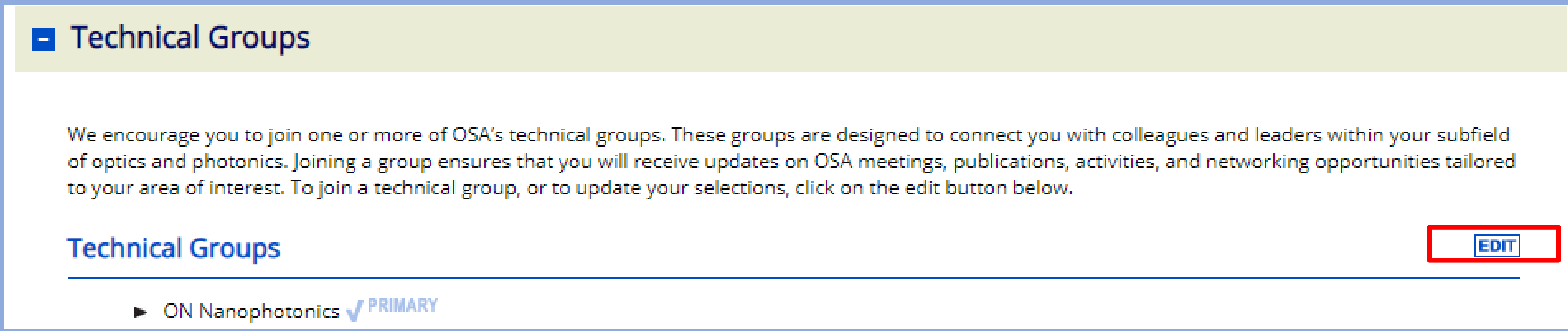
@Nano_OSA



facebook.com/nanophotonicsosa



How to join ON Nanophotonics group's email list?



Materials and Designs for Wavelength Selective Infrared Devices

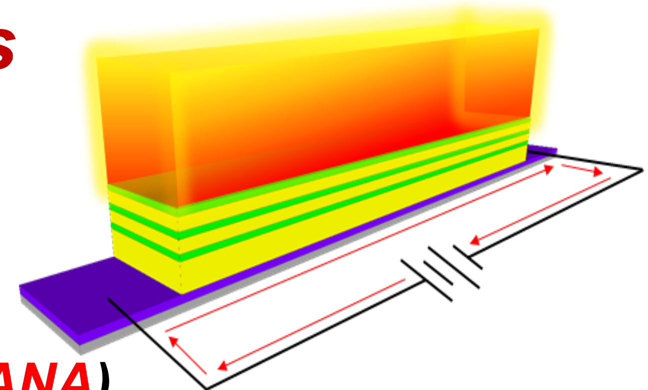
Prof. Tadaaki Nagao

National Institute for Materials Science
& Hokkaido University

OSA Webinar, May 19, 2021

Nano Revolution for the Future

Materials and Devices for Wavelength-Selective Infrared Devices



Tadaaki NAGAO[1,2]

Photonics Nano-Engineering Group,

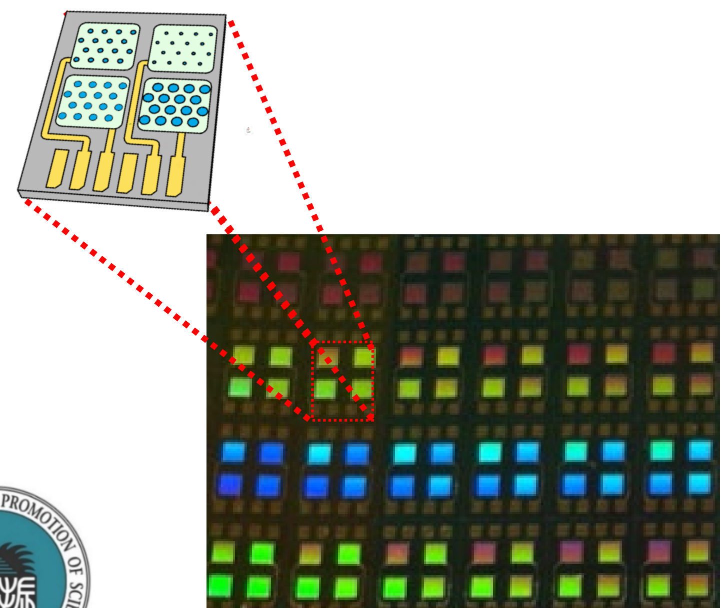
[1]Center for MAterials NanoArchitechtonics (MANA)

National Institute for Materials Science (NIMS),

Tsukuba, JAPAN

[2]Department of Condensed Matter Physics

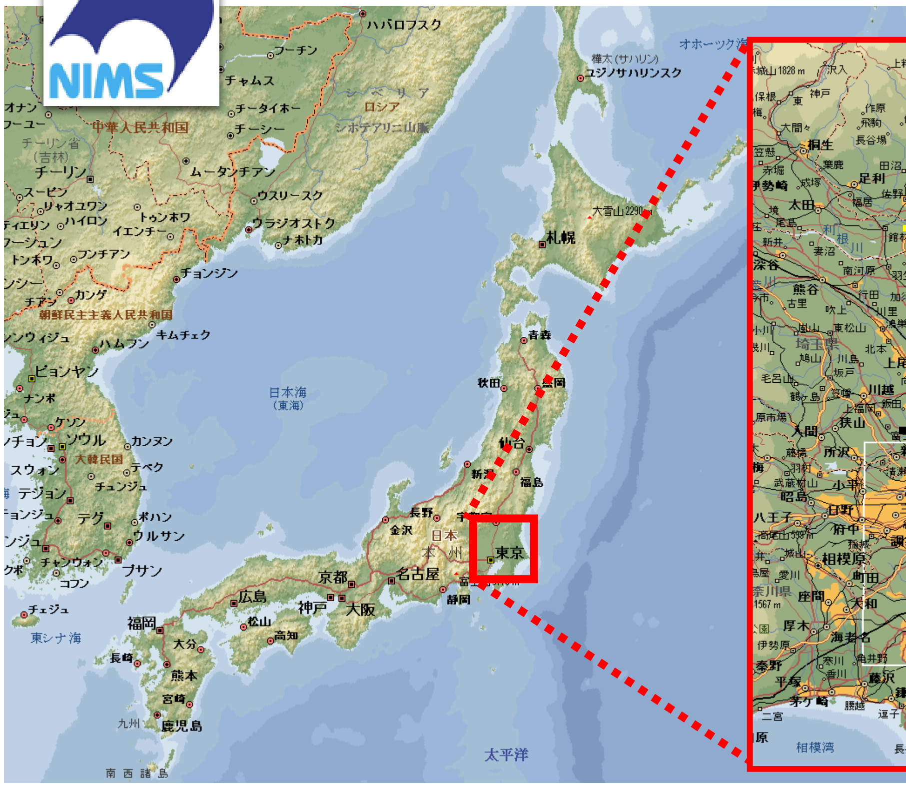
Hokkaido University, Sapporo, JAPAN

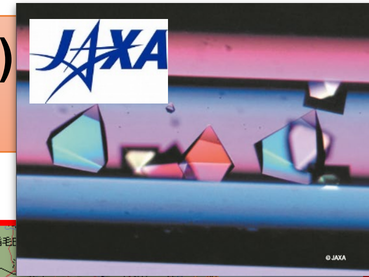


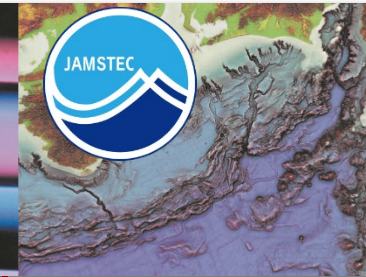
In collaborations with: T.D. Dao, A.T. Doan, S. Ishii, D.T. Ngo, H.D. Ngo, A. Ohi, T. Nabatame, R.P. Sugavaneshwar

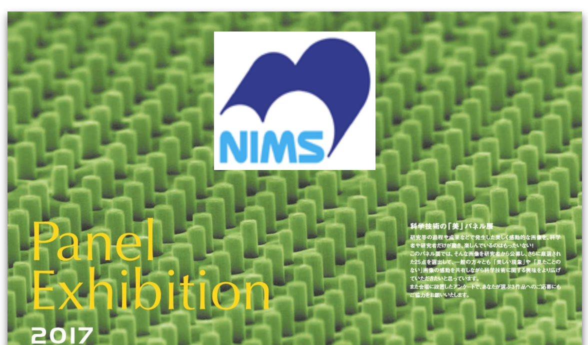
NIMS wpi 北海道大学 HOKKAIDO UNIVERSITY

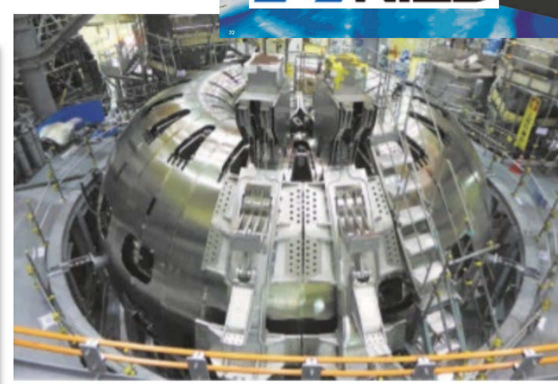
National Institute for Materials Science (NIMS)
特別国立研究開発法人　物質･材料研究機構





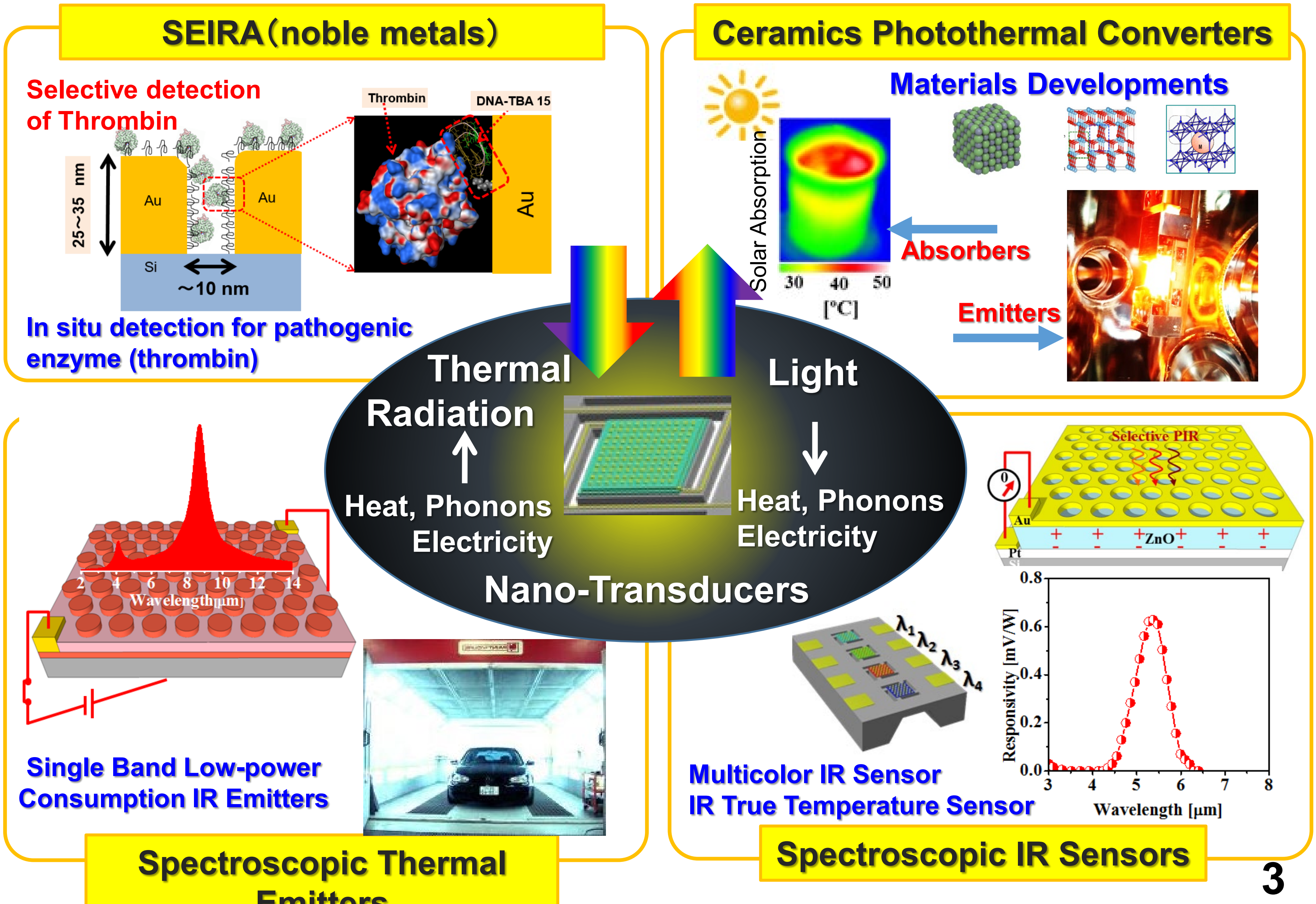






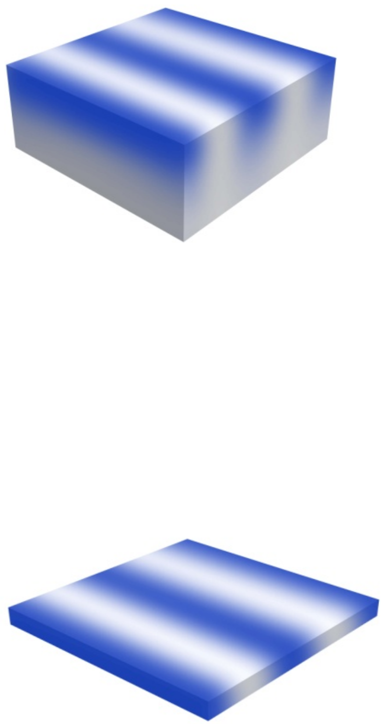
Nanomaterials for Light/Signal (Heat) Transduction

NIMS
Photonics Nano-Engineering G



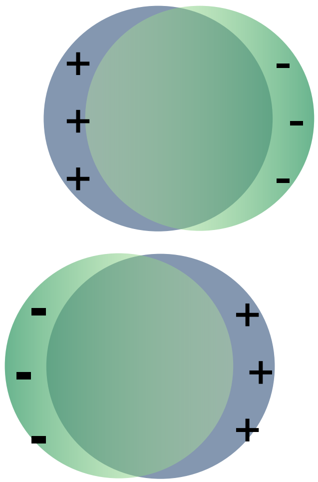
Confined electromagnetic waves in tiny nano-objects

Flat surface



Surface Plasmons, Surface Polaritons

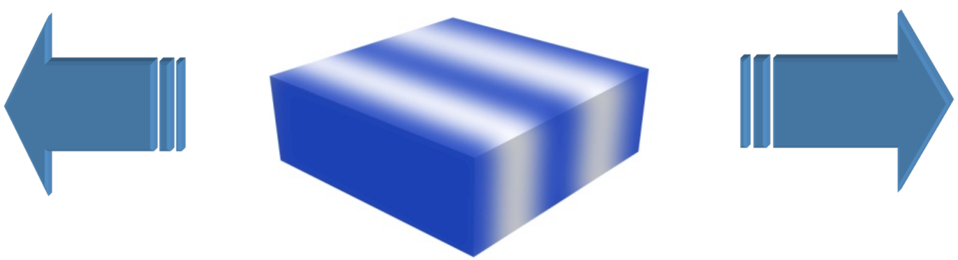
Finite-size

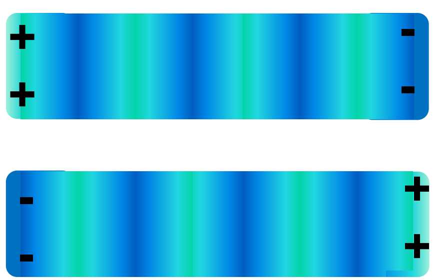


3D volume

Open structure

Closed structure





2D sheet

Propagating-modes

Confined-modes

Standing Waves, Resonators

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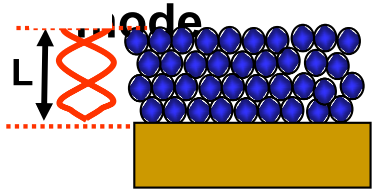
Acoustic Waves

MACRO **NANO SCALE**

Organ pipe phonon mode



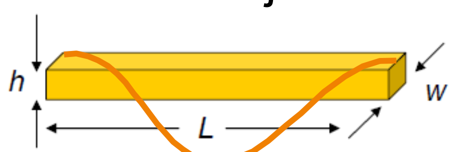
Nλ= 4L N: Odd Number, L: Size

EM Waves

MACRO SCALE

NANO SCALE

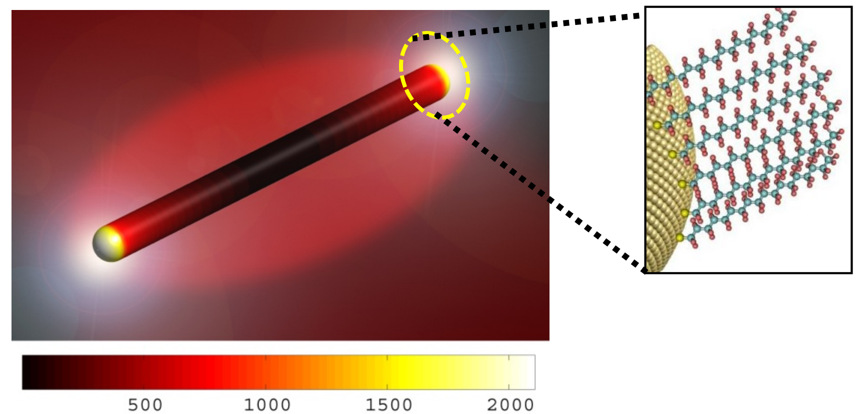
Antenna Resonance of Nano-objects



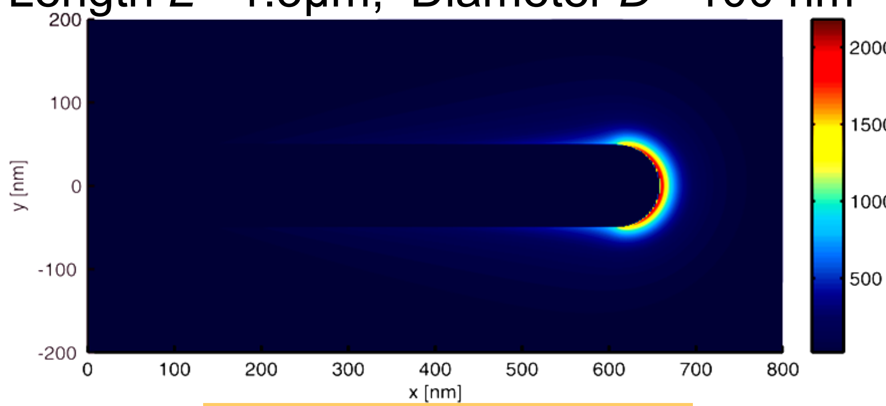
Nλ/n* = 2L N: Integer L: Size

Metal Nanorods: Nano-resonators

Enhanced (E_{loc}/E_0) nearfield at the two ends of the resonator



Length L= 1.3μm, Diameter D =100 nm



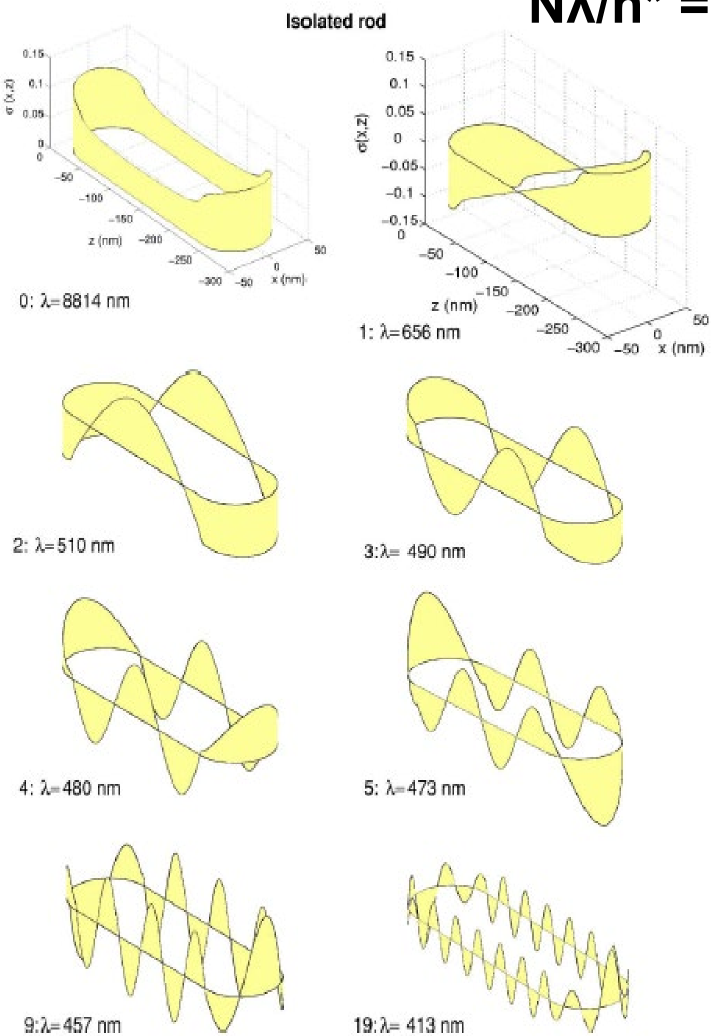
$(E_{loc}/E_0)^2$ >> 2000

Calculation by J. Aizpurua, Donostia, Spain

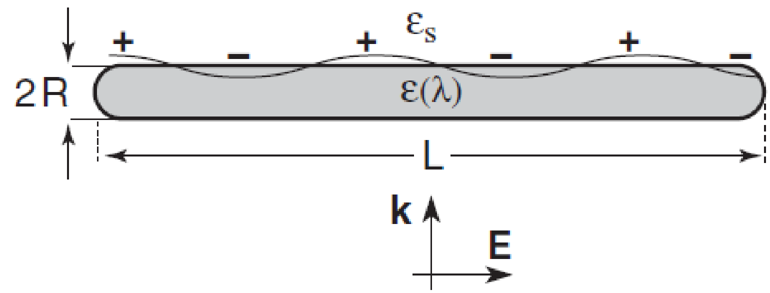
Micron-sized optical antenna (for IR spectroscopy)

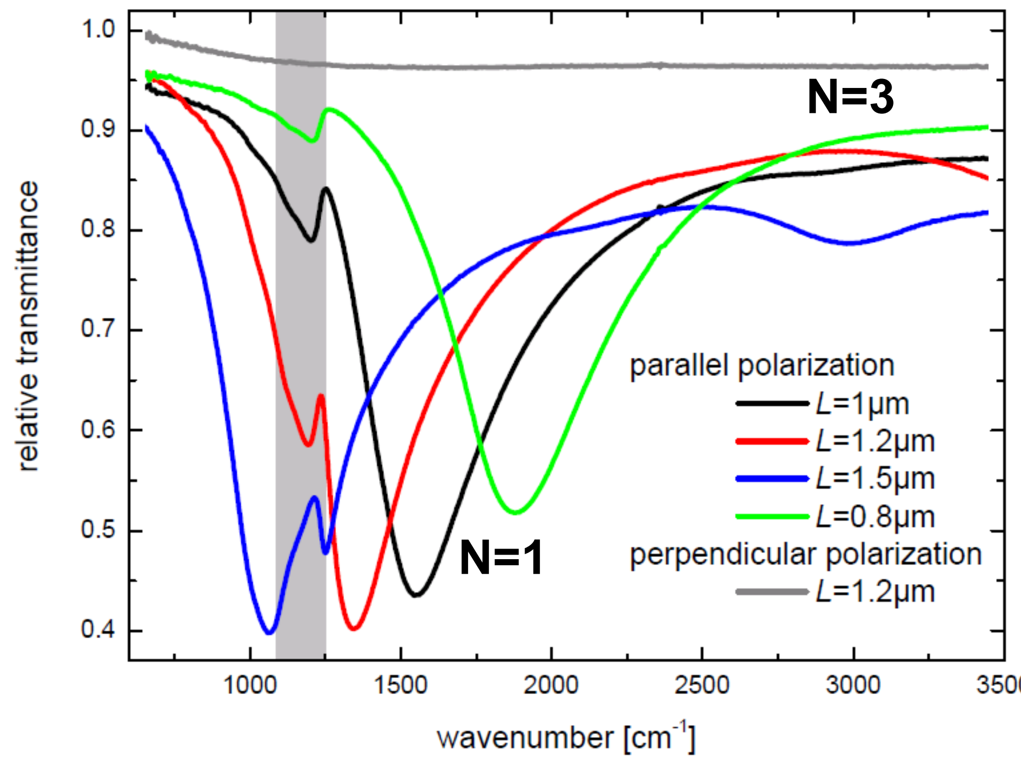
Tuning of antenna resonance by rod length: by e-beam lithography

$N\lambda/n^* = 2L$, N: integer number L: rod length, n*: constant



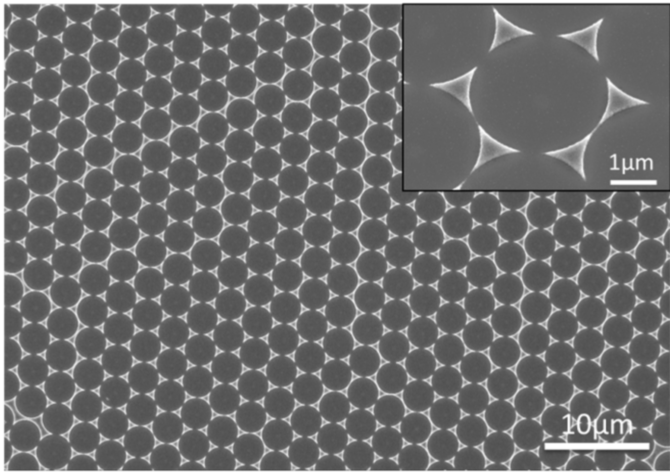
Induced surface charge with light irradiation

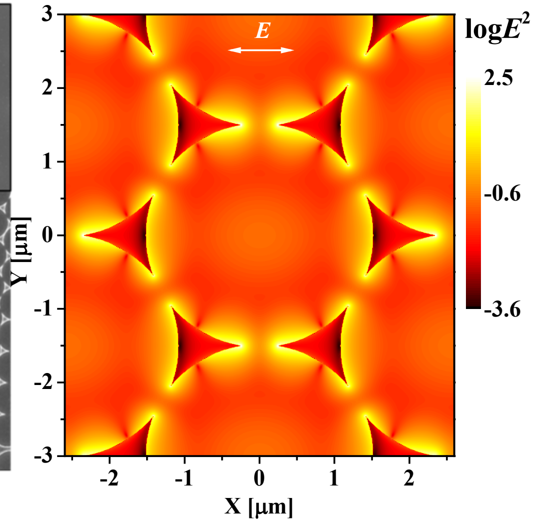




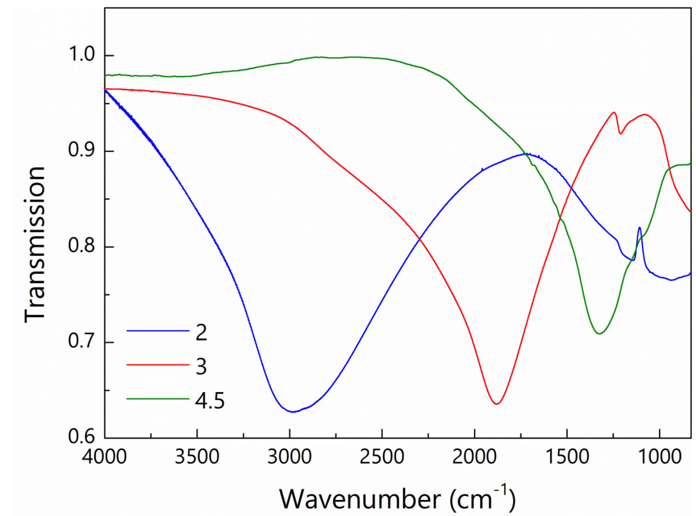
F. Neubrech, et al., J. Phys. Chem. C**114** (2010) 7229-7301

Tunable Infrared Absorbers for SEIRA

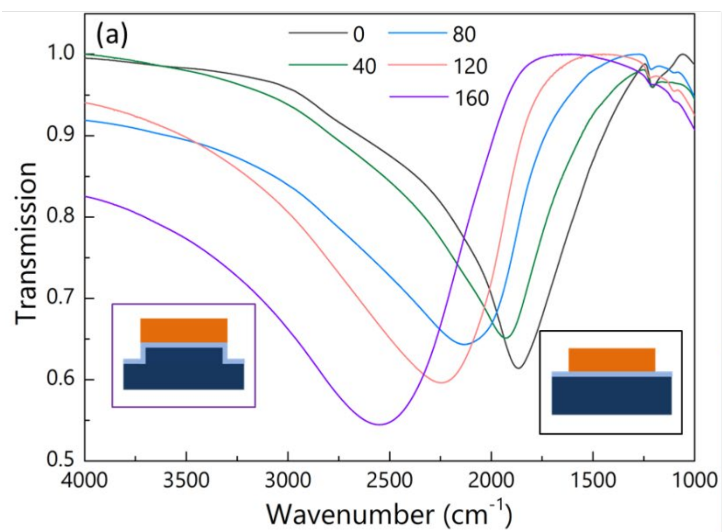


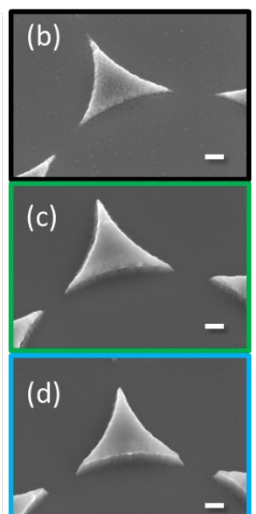


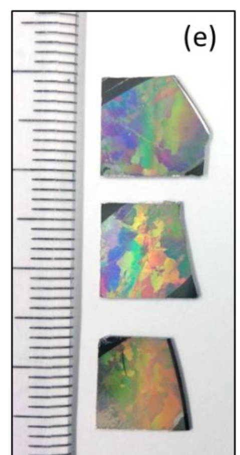
change sphere size



Controllable fine tuning of the resonance by CF_4 dry etching







- Tune the plasmon resonance
- Increase the sensing volume

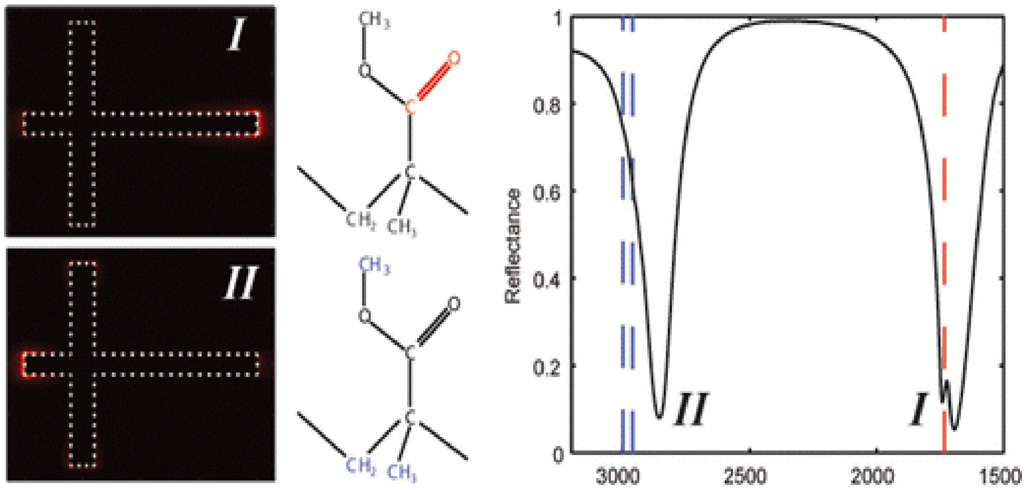
$$\omega_{particle}^{drude} = \sqrt{\frac{1}{3}\frac{Ne^2}{m\varepsilon_0}}$$

K. Chen, *Sci. Rep.*, 7, 44069, 2017

Perfect Absorbers: Spectroscopic Light-heat transducer

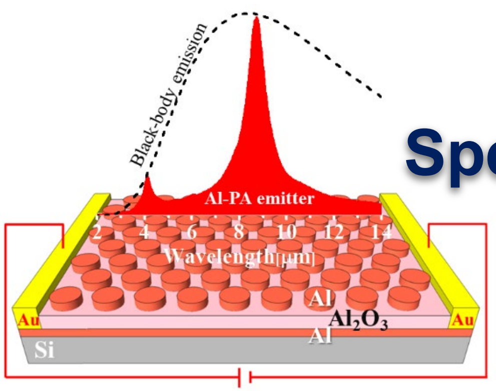
- **Perfect absorbers**: Near unity absorptivity at desired wavelengths
- **2D lithographic patterning:** Controllability of transmission, reflection and absorption of light by sub-wavelength patterning.

<u>**Applications**</u>**:** Thermal emitters and thermophotovoltaics, radiative cooling of solar absorbers, NDIR and SEIRA for gas and molecular sensing, pyrometer…

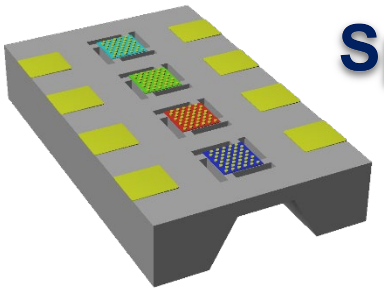


K. Chen *et al.*, ACS Nano **6** , 7998 (2012)

X. Liu et al., *Phys. Rev. Let.* **107**, 045901 (2011)



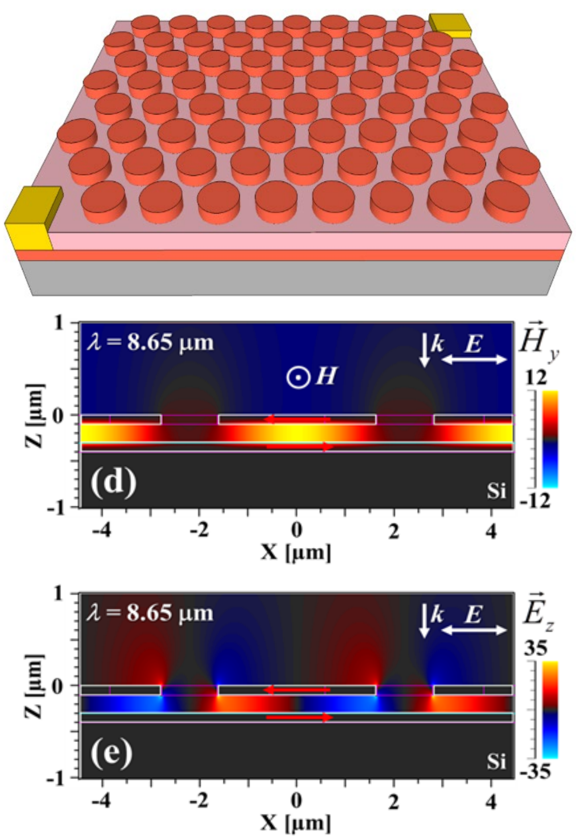
Spectroscopic IR emitter



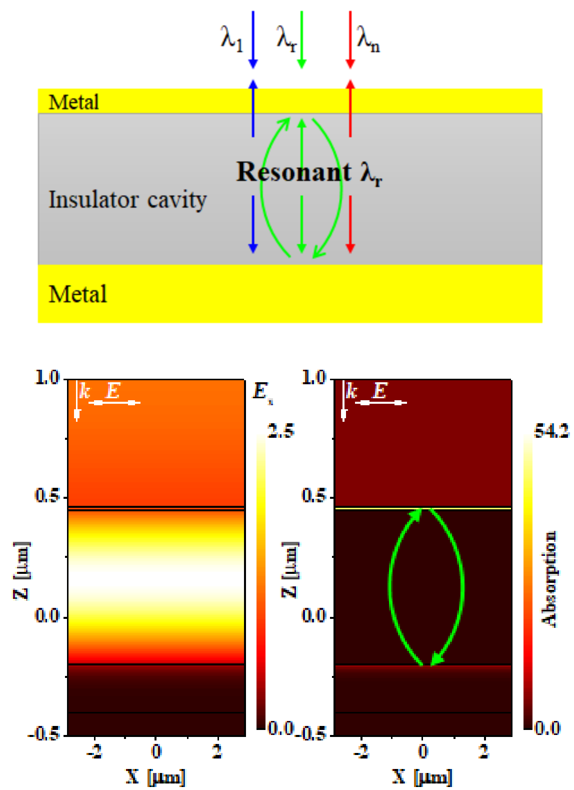
Spectroscopic IR detector

Different Designs for Spectroscopic Perfect Absorbers

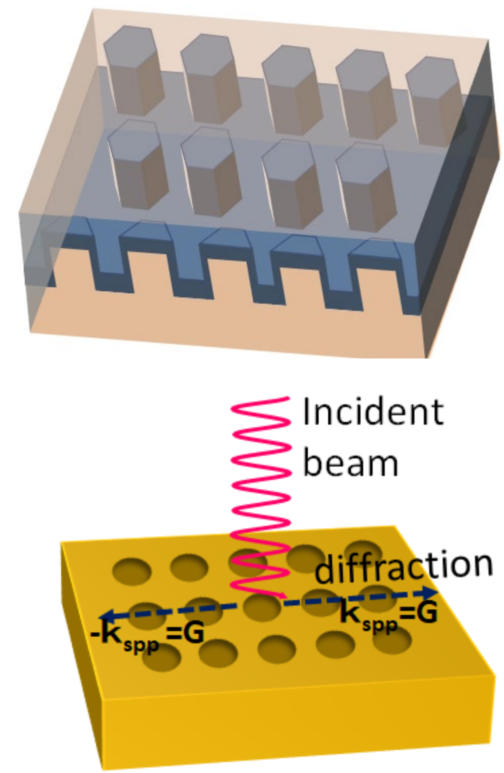
① LSPR + Mirror: Image Dipole, Light Trap



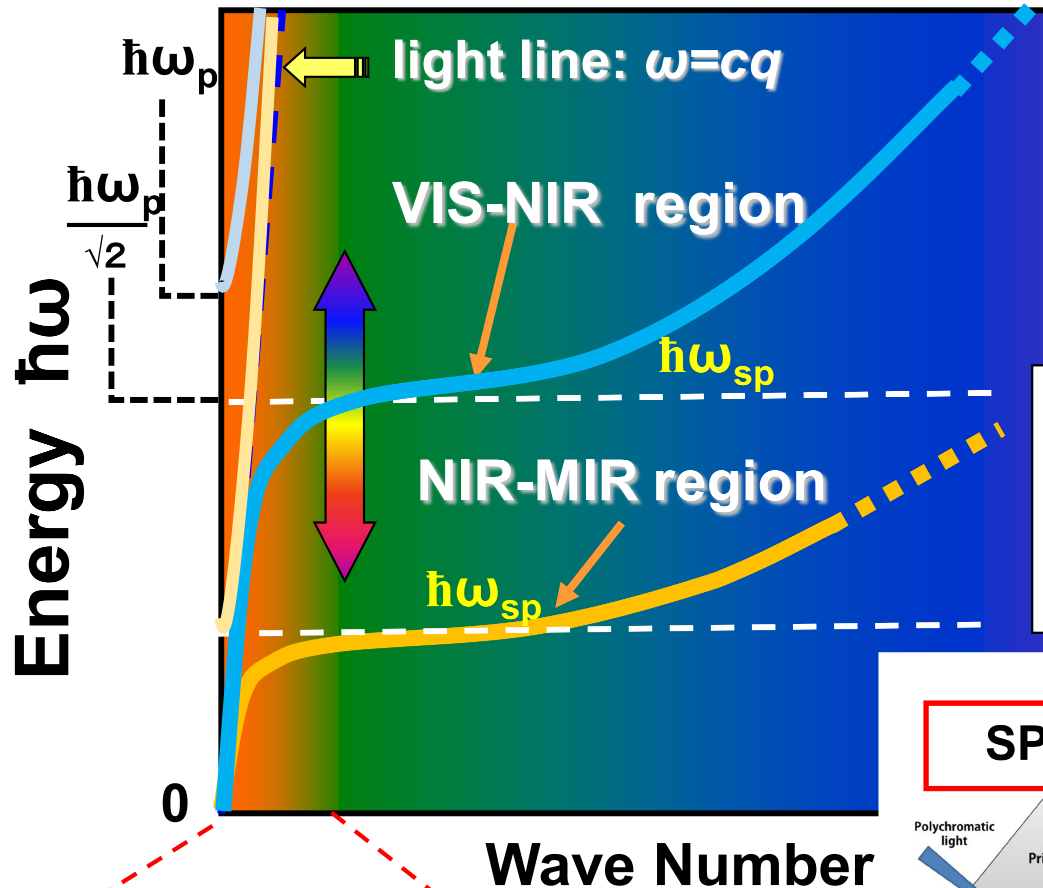
③ 1D Cavity: Multiple Reflection



② Gratings: Surface Wave Resonance



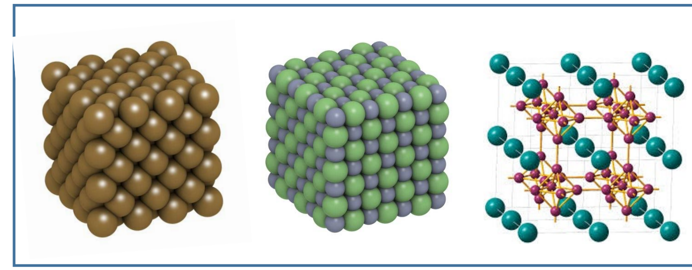
Variety of Plasmonic Materials



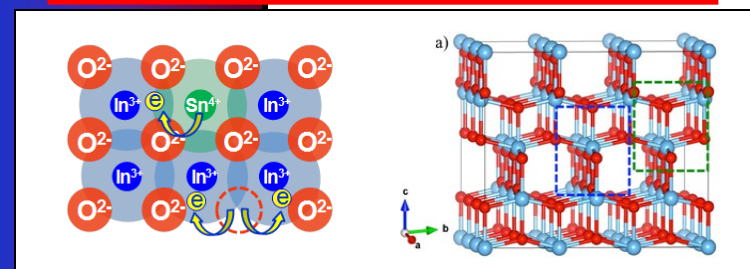
Ⅰ. Photon coupling (polaritonic) region

Ⅱ. Pure plamsm (nanoscopic cha density) regio

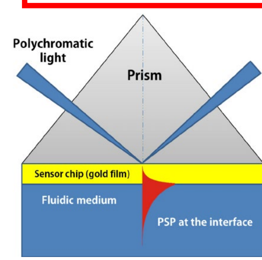
Base Metals, Alloys, Ceramics

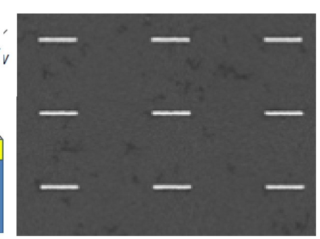


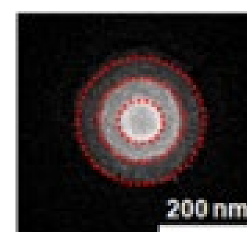
Oxide SPPs: Doping



SPP Engineering: Size, Shape







Outline

- Exploring the Infrared Plasmonic Materials (for SEIRA and Thermal Emitters)

  Al, Mo, ITO, TiN, doped TiO_2, etc

- Wavelength-selective (Spectroscopic) IR Sensors (and Emitters ..)

  Bolometer, Pyroelectric, IR Sensors
  Multiband (sub-100 nm FWHM) IR Sensors

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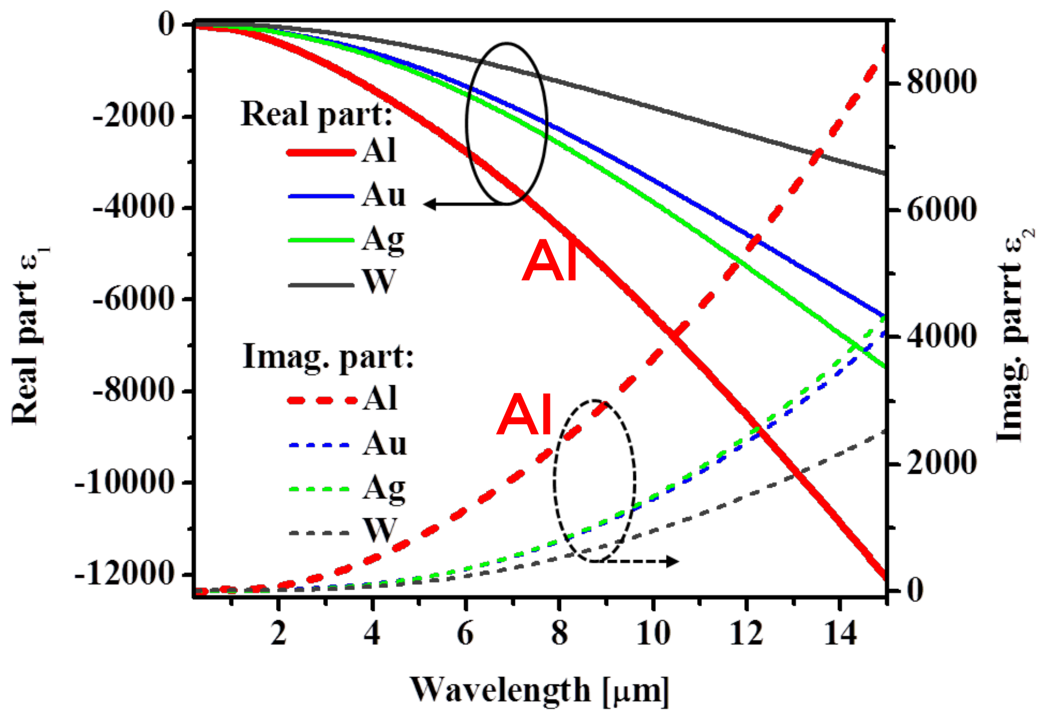
  Bolometer, Pyroelectric, IR Sensors
  Multiband (sub-100 nm FWHM) IR Sensors

Effective Materials Working in The IR Region

$$\varepsilon(\omega) = \varepsilon_1 + i\varepsilon_2$$

Real part ε_1:
Larger negative → Larger optical response

Imaginary part ε_2:
Larger positive → Stronger the dissipation



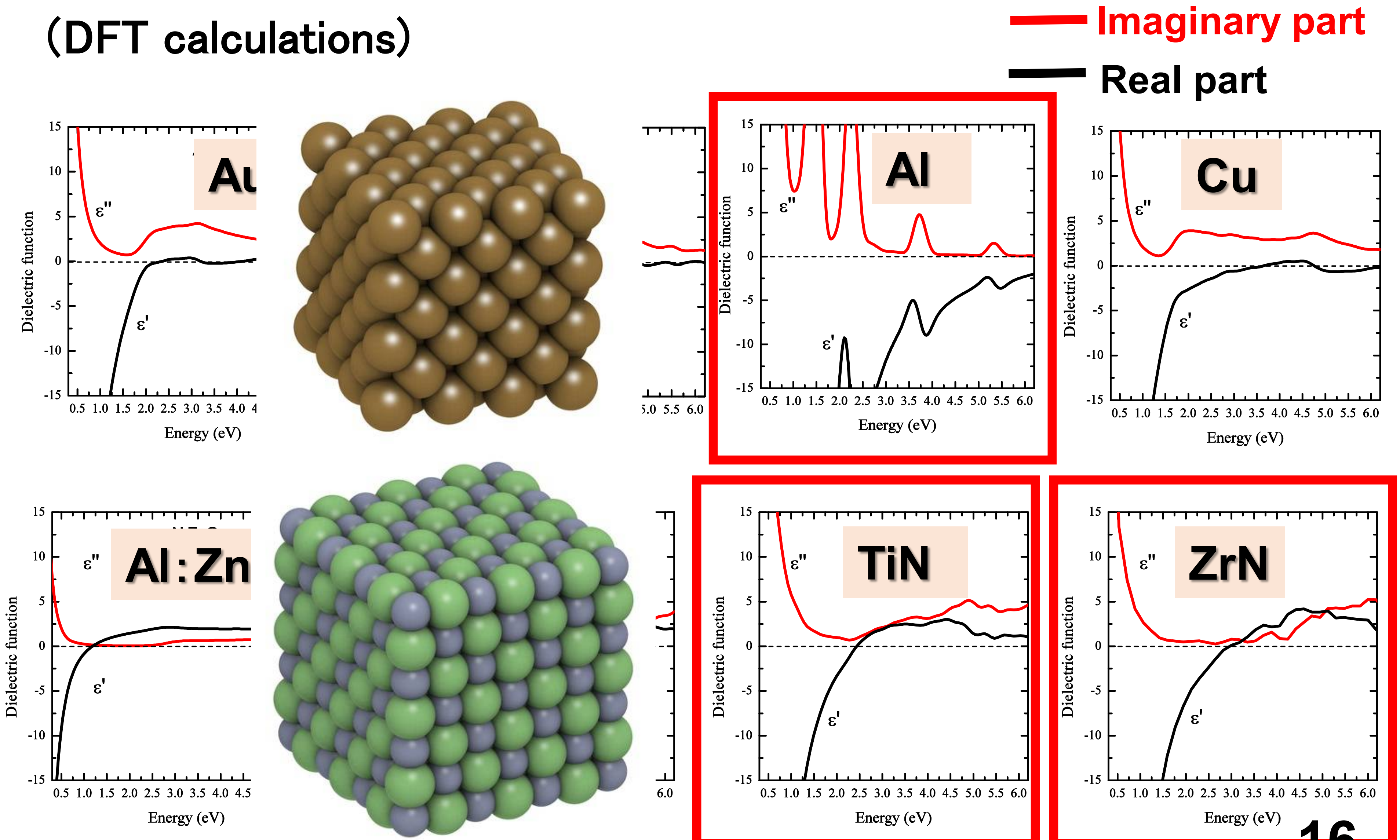
Larger optical response and damping even larger than Au or Ag!

Suitable for IR absorber applications.

A. D. Rakic, *Appl. Opt.*, **37**, 5271 (1998)

Scrutinize the Suitable Material !

Dielectric function of candidate materials: (DFT calculations)

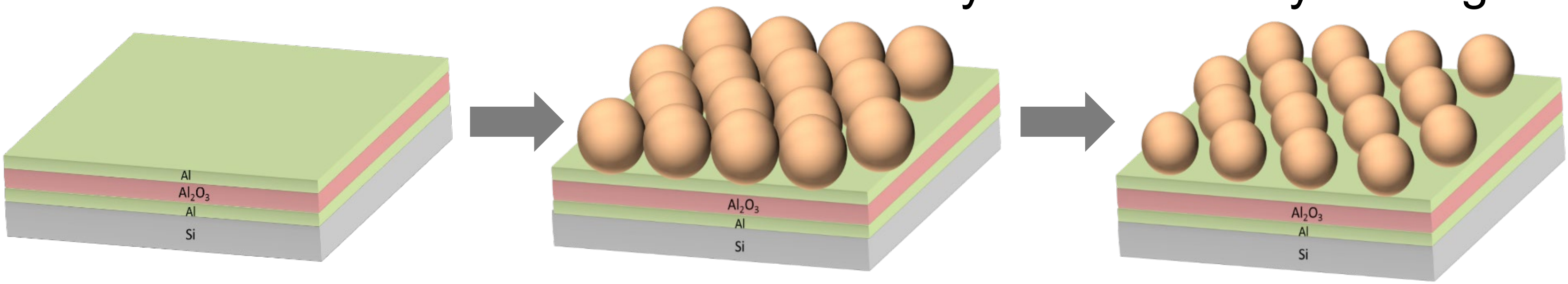


Colloidal Mask Etching

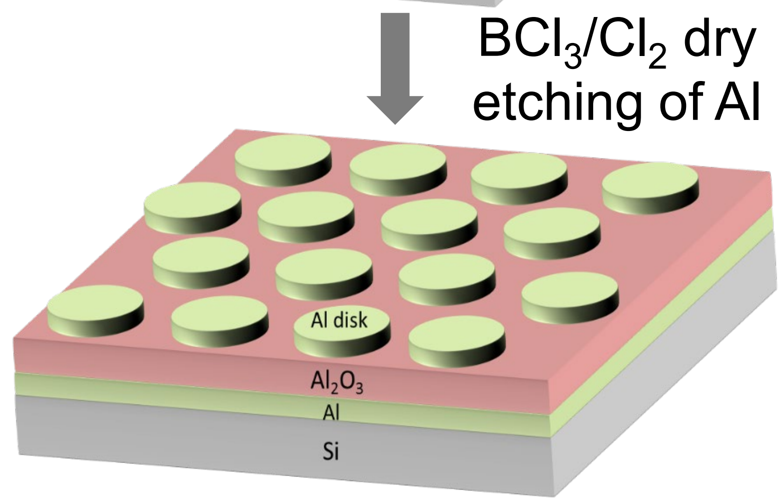
Sputtering deposition

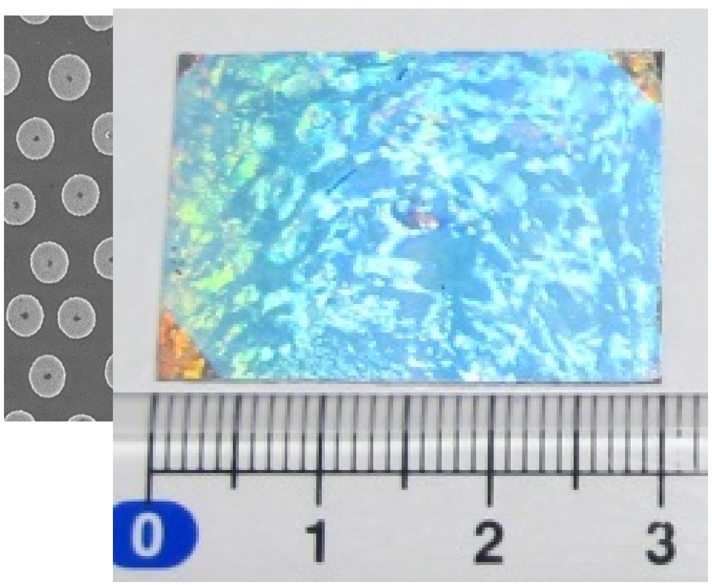
Polystyrene sphere self-assembly

O_2 plasma dry etching



BCl_3/Cl_2 dry etching of Al

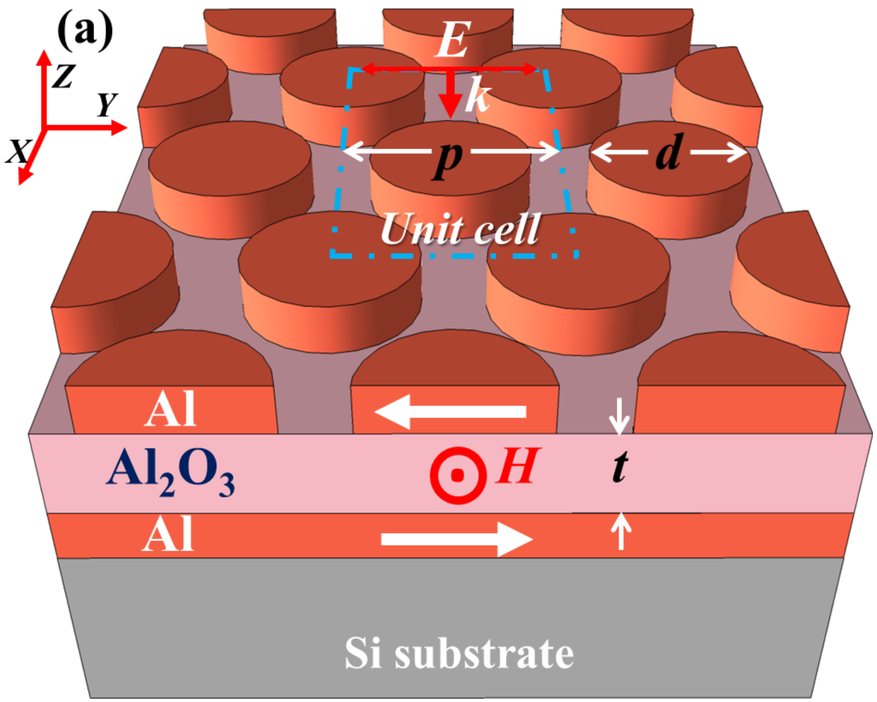


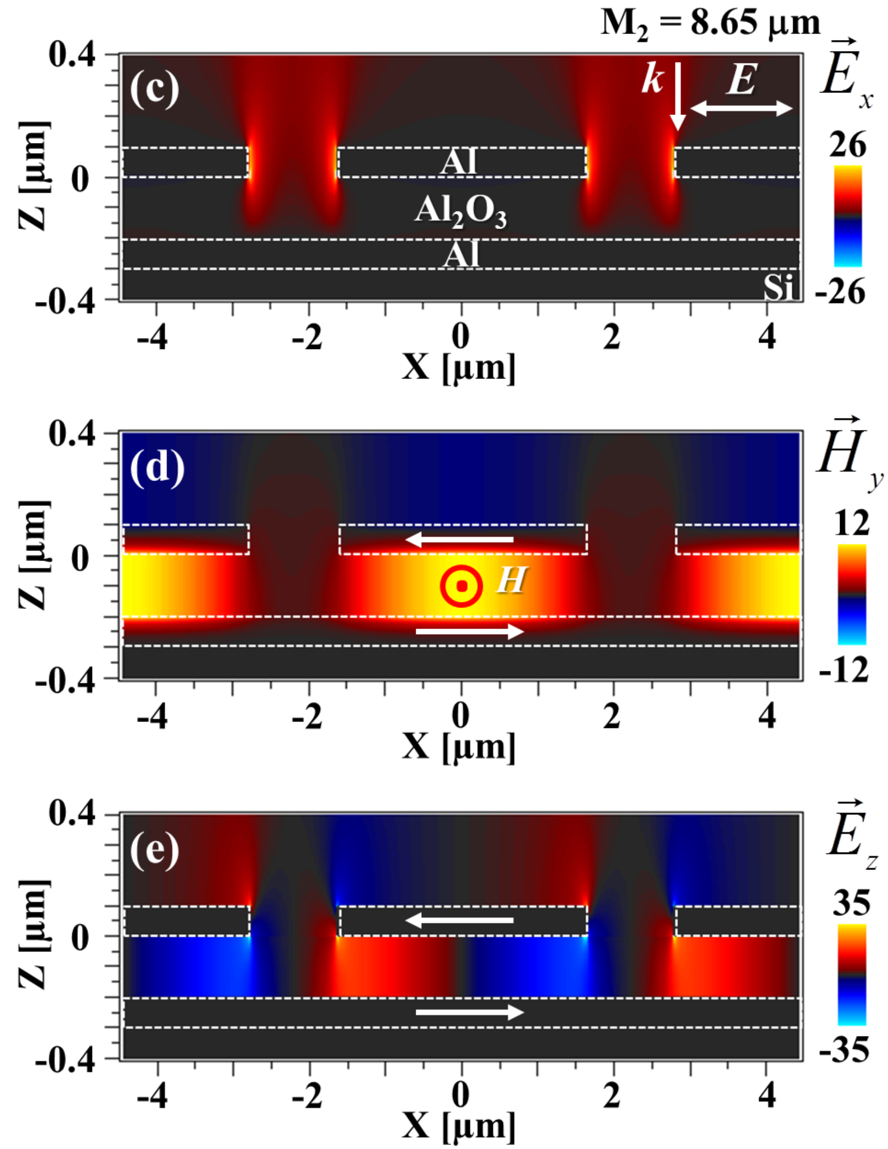


Thang Duy Dao, Kai Chen et al., ACS Photonics 2, 964-970 (2015).

A Device for Efficient Heat-Light Conversion
→Metal-Insulator-Metal perfect absorber (MIM-PA)

- **Aluminum - Aluminum oxide – Aluminum based IR perfect absorber**

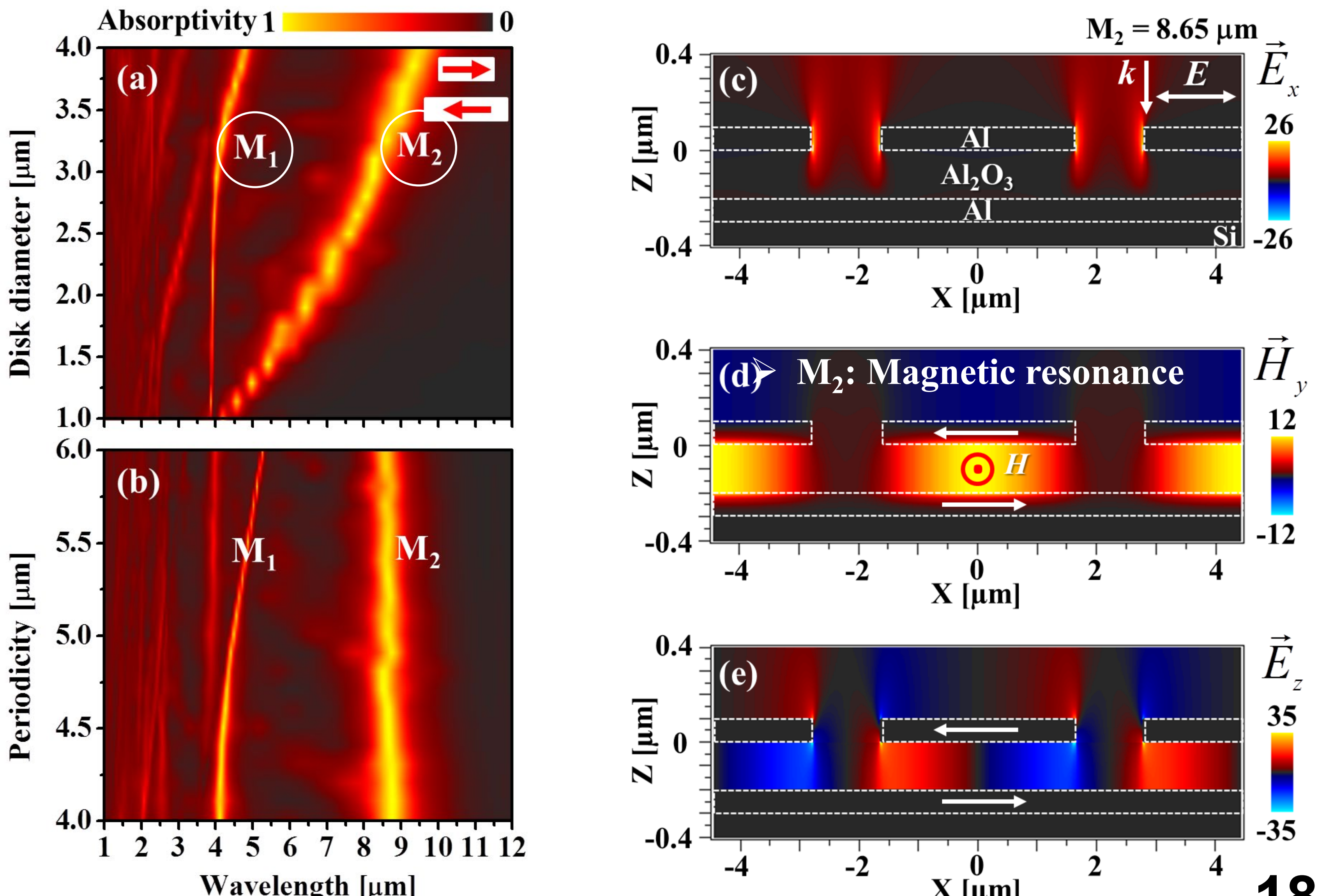




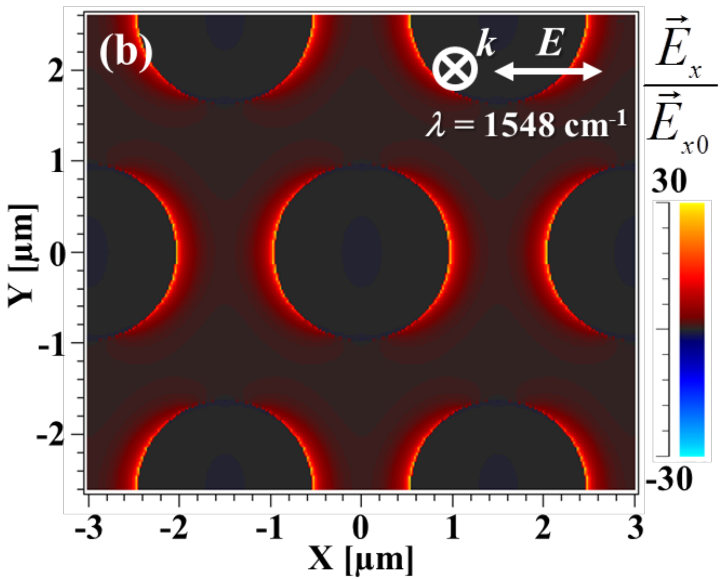
T. D. Dao et al., ACS Photonics, 2, 964 (2015).

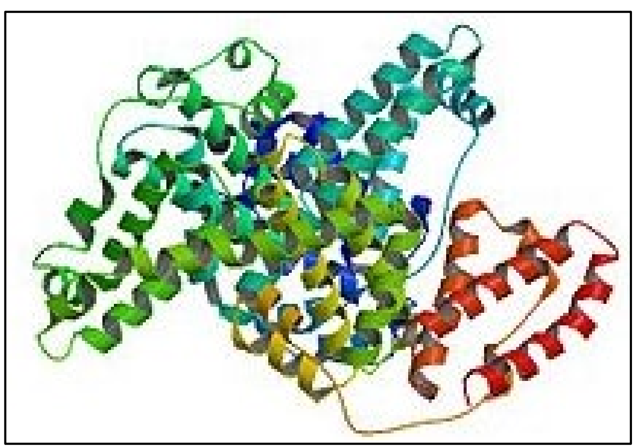
Infrared Perfect Absorbers: Simulations

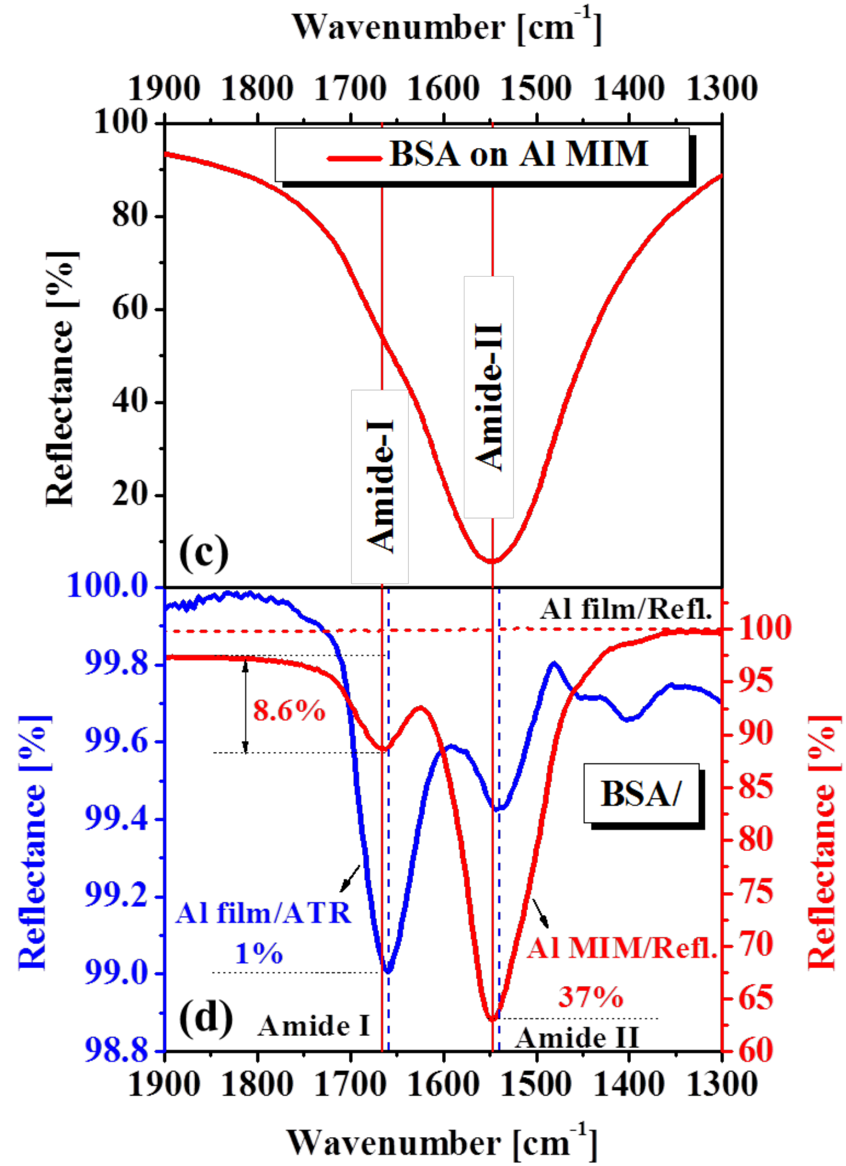
➢ **SP-photonic coupling and magnetic resonances**



Al-PAs based selective IR plasmonic antennas for SEIRA





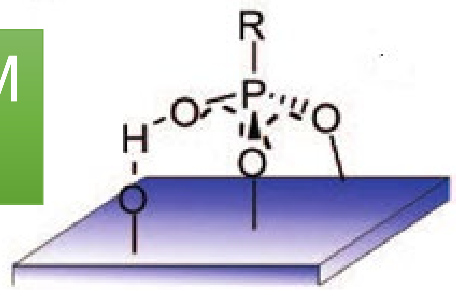


K. Chen, T. Dao, T. Nagao et al., Adv. Func. Mater. **25**, 6637 (2015)

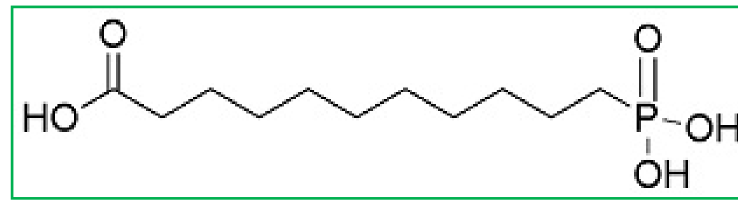
Al_2O_3: Protection & Functionalization: Check by SEIRA

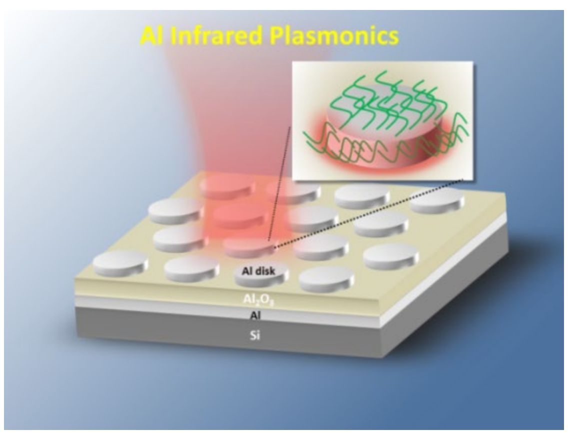
- Thiol-based surface functionalization enables wide applications of Au nanoparticles
- Can we find a similar strategy for Al?

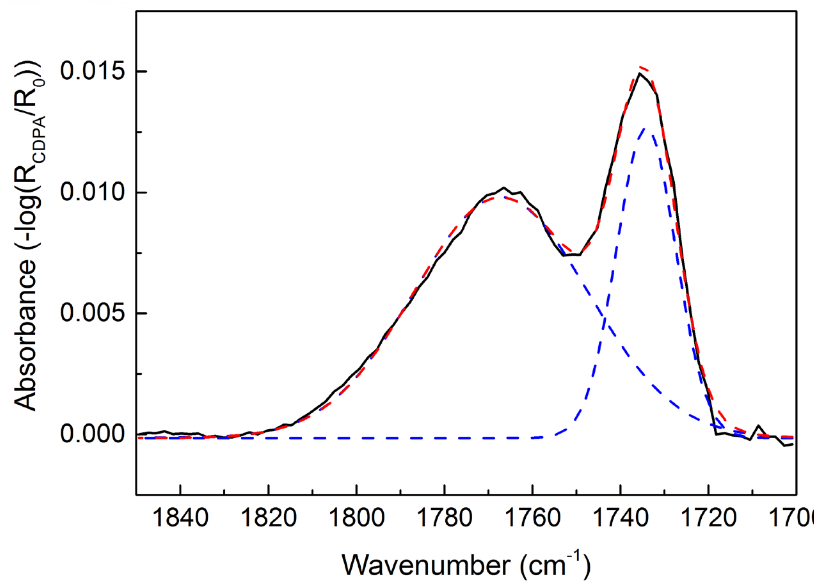
Phosphonic acid SAM on oxide surface



10-carboxydecylphosphonic acid

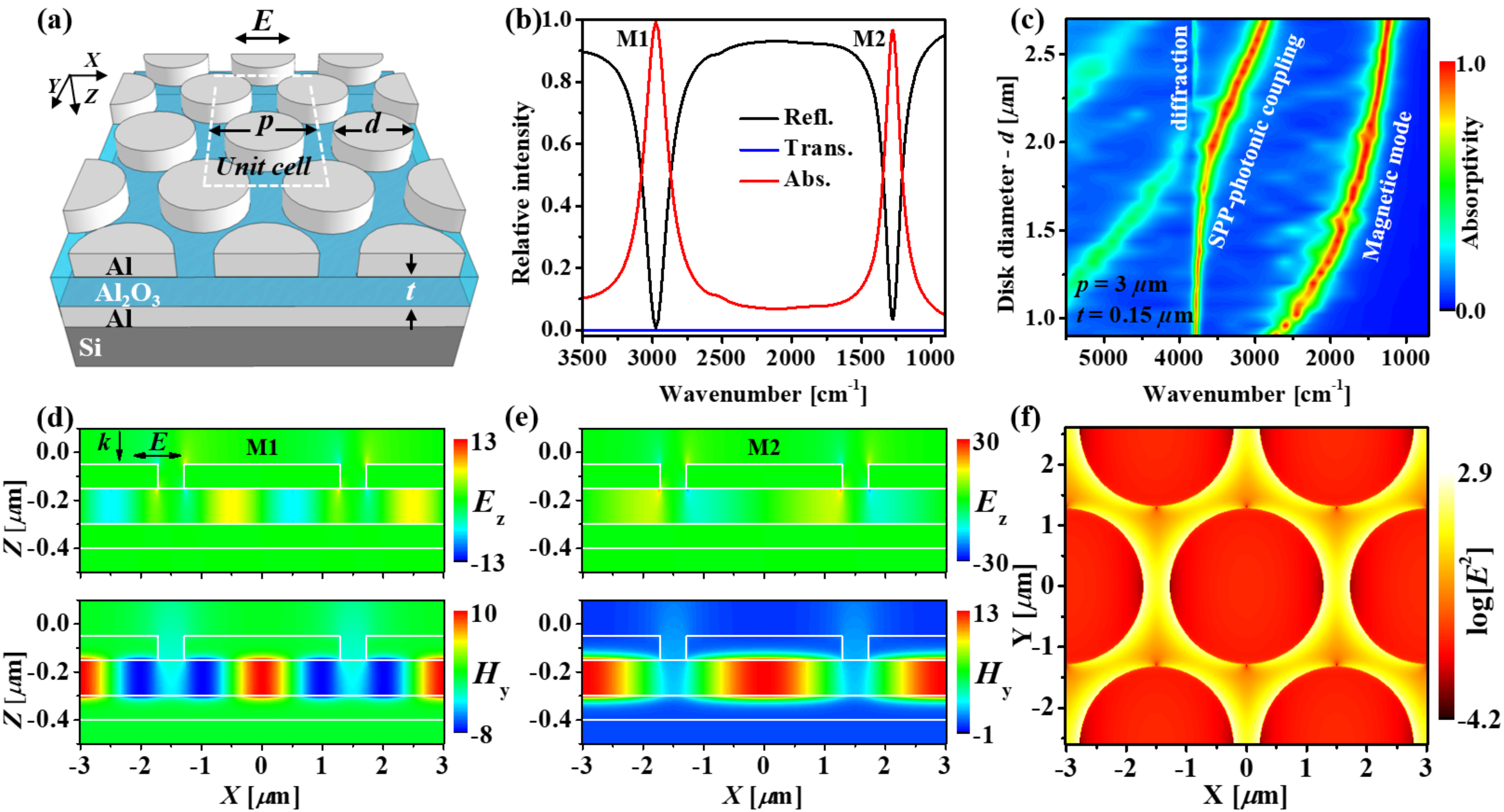






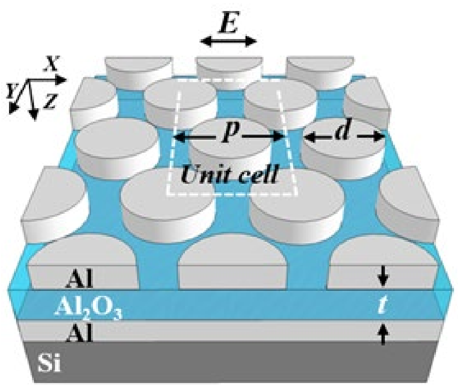
K. Chen, T. D. Dao et al., *Adv. Func. Mat.*, **25**, 6637 (2015).

In situ Dual-band SEIRA Reaction Monitoring

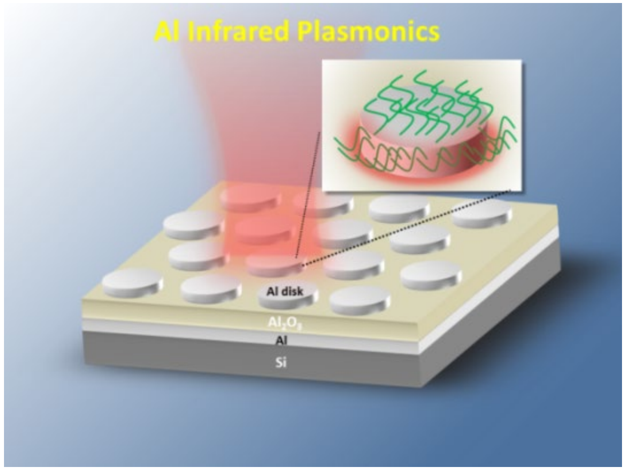


T. D. Dao, K. Chen, T. Nagao., RSC Nanoscale 11, 9508(2019).

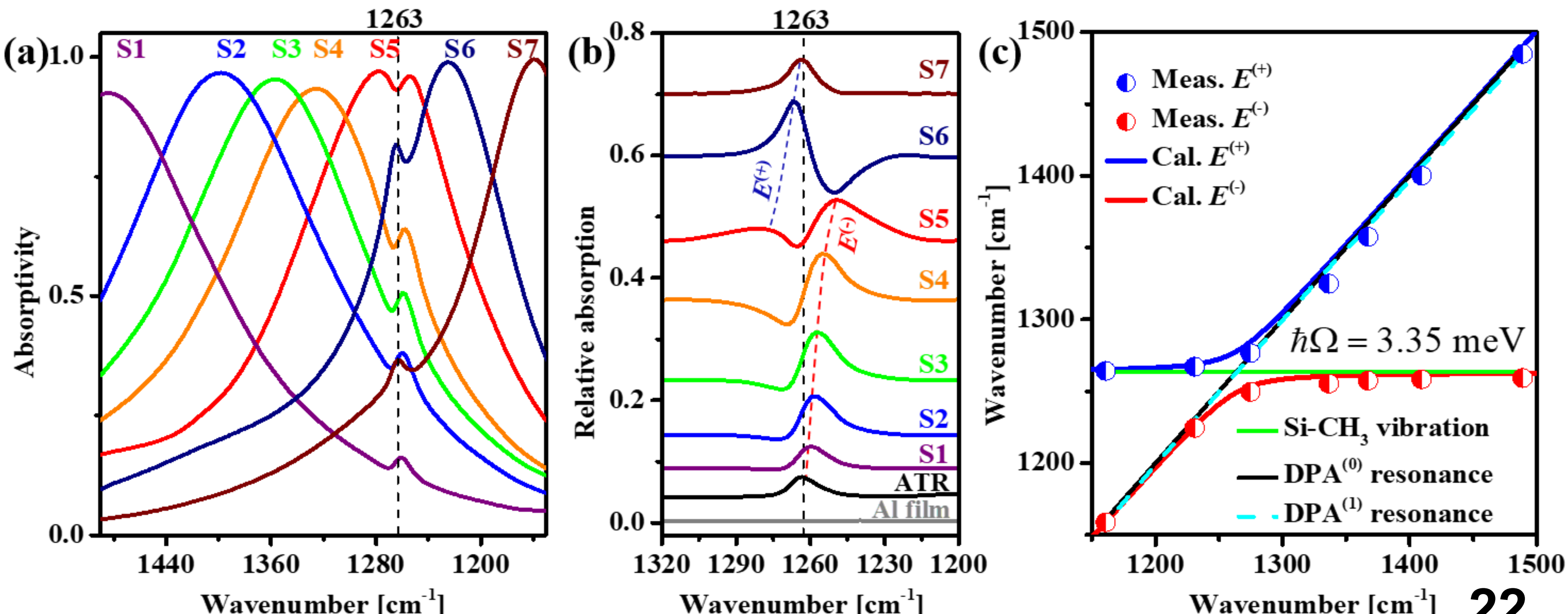
SEIRA devices for Selective detection of molecules



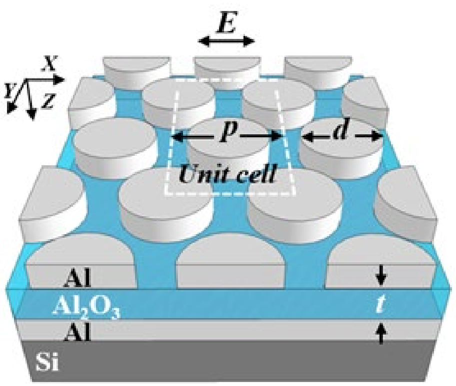
PDMS spin-coated on Al



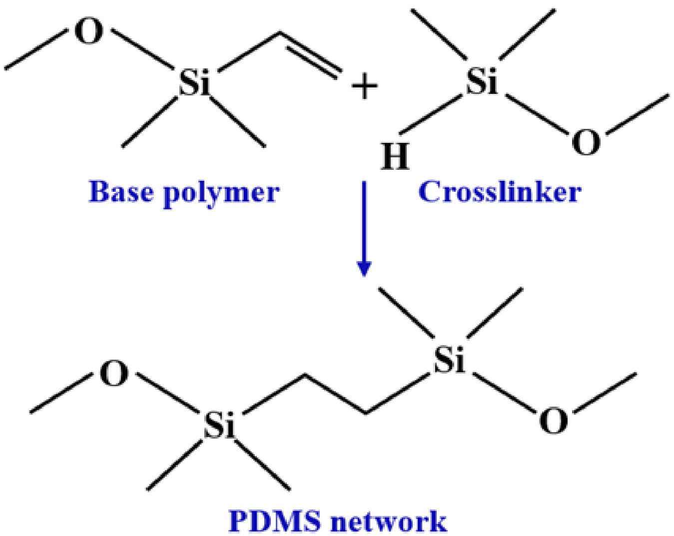
T. D. Dao

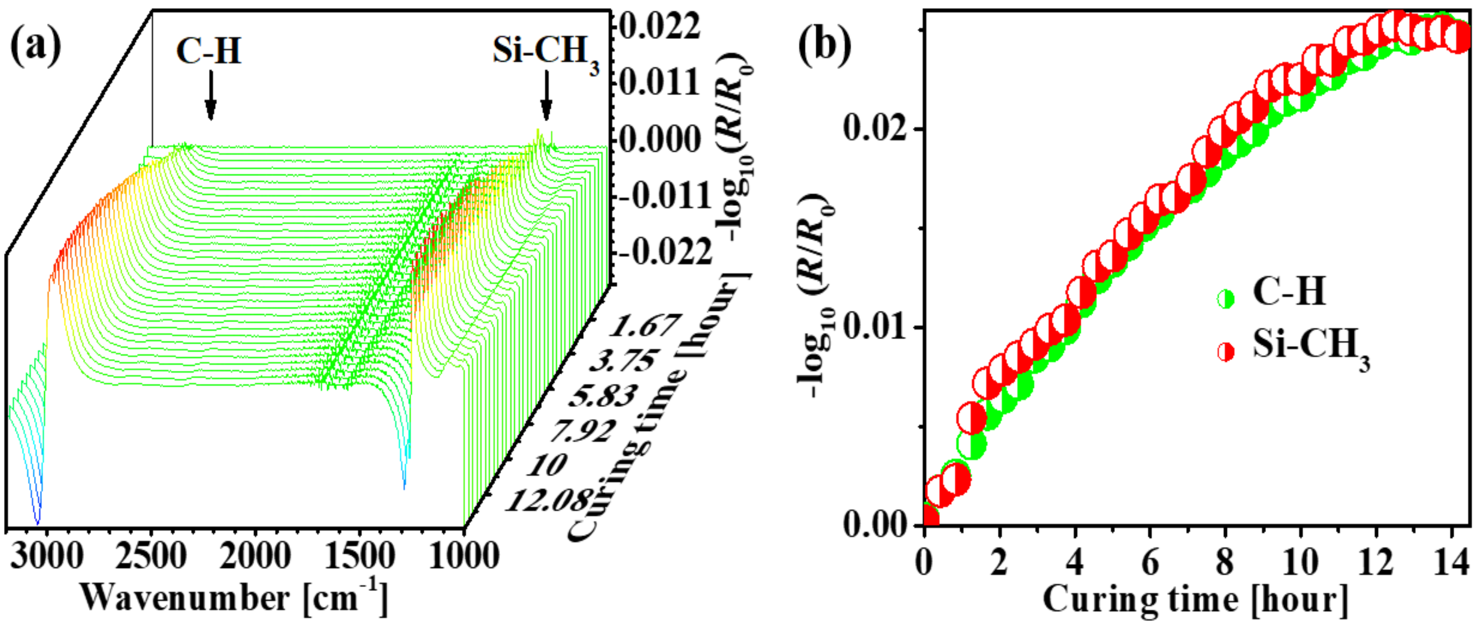


in situ reaction monitoring using dual-band SEIRA



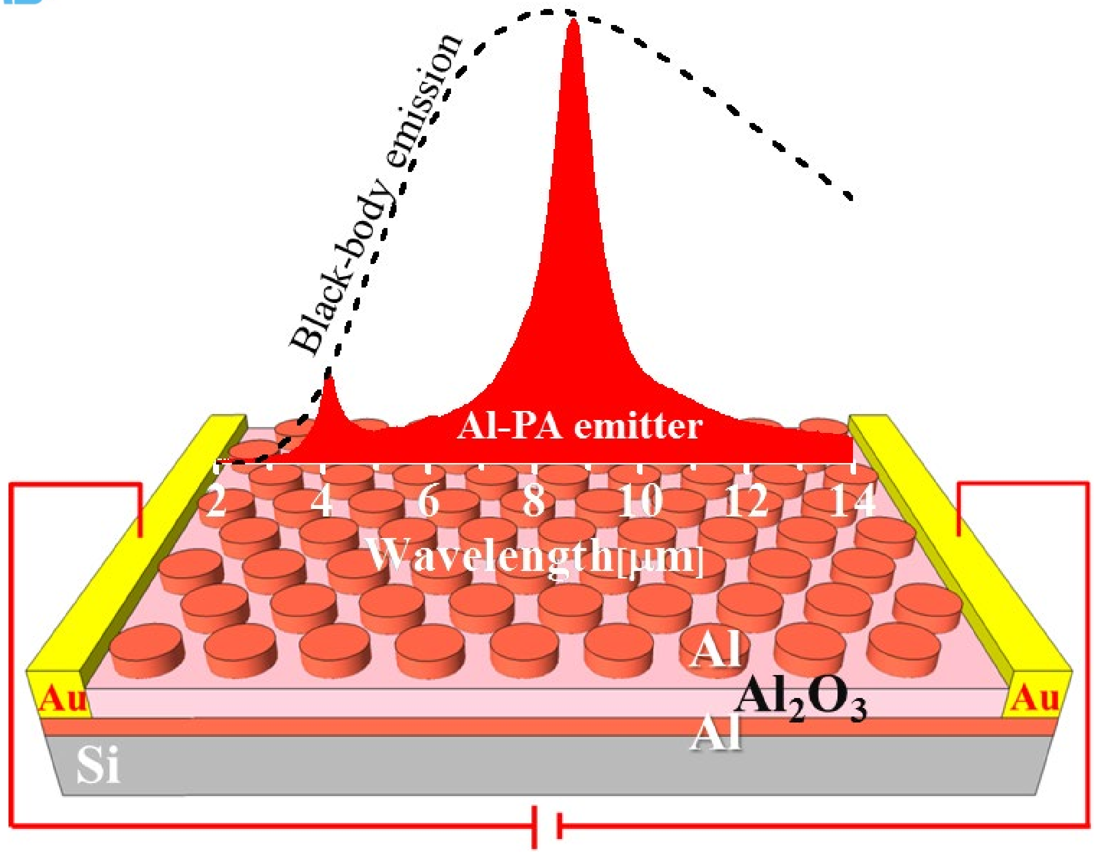
PDMS spin-coated on Al

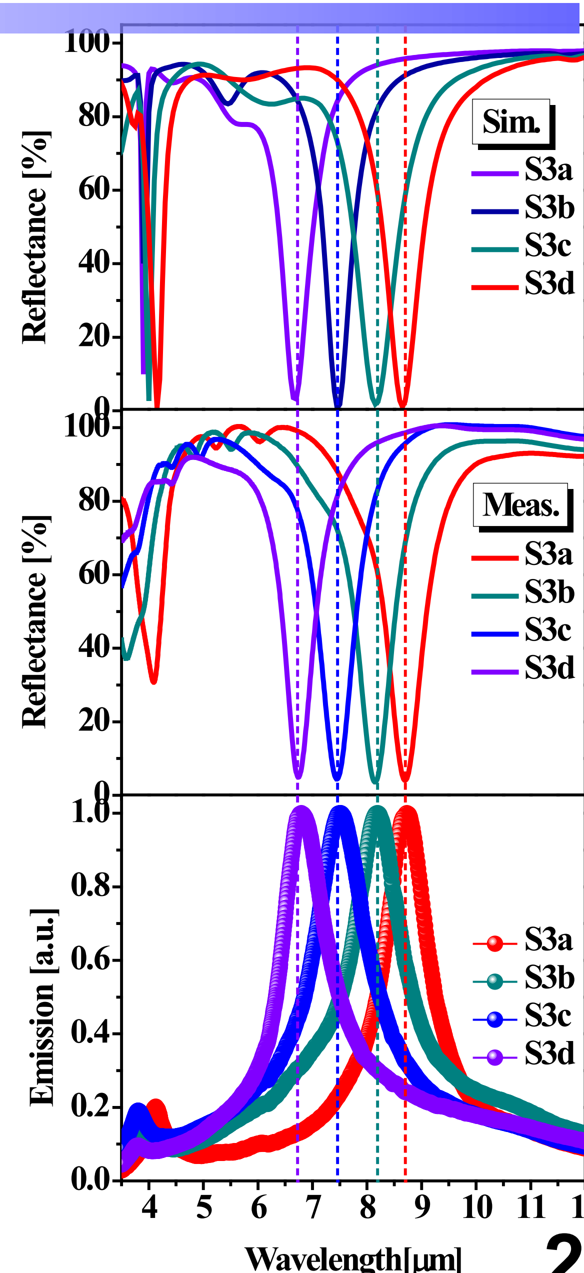




T. D. Dao, K. Chen, T. Nagao., *RSC Nanoscale* 11, 9508-9517(2019).

Al-PAs Based Selective Thermal Emitters





- **Kirchhoff's law in thermal radiation:**

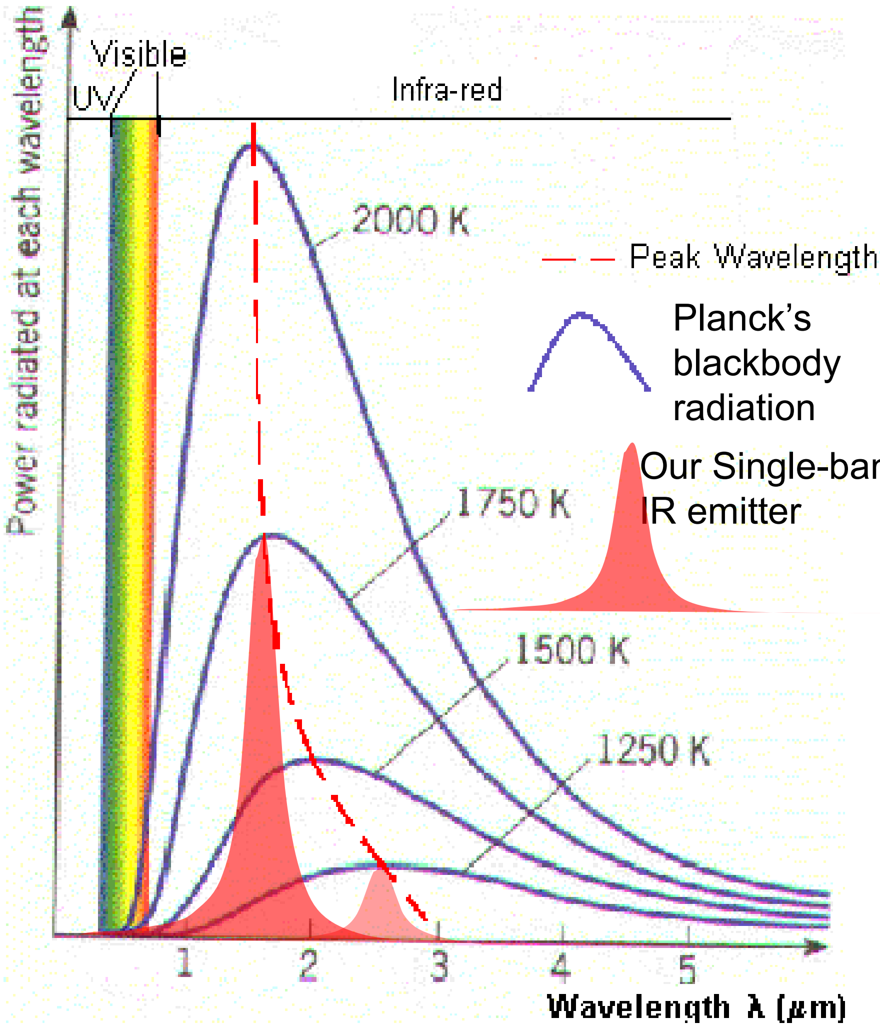
For the condition of thermal equilibrium, the absorptivity is equal to emissivity:

$$\alpha_\lambda = \varepsilon_\lambda \qquad \alpha_\lambda = 1 - R_\lambda$$

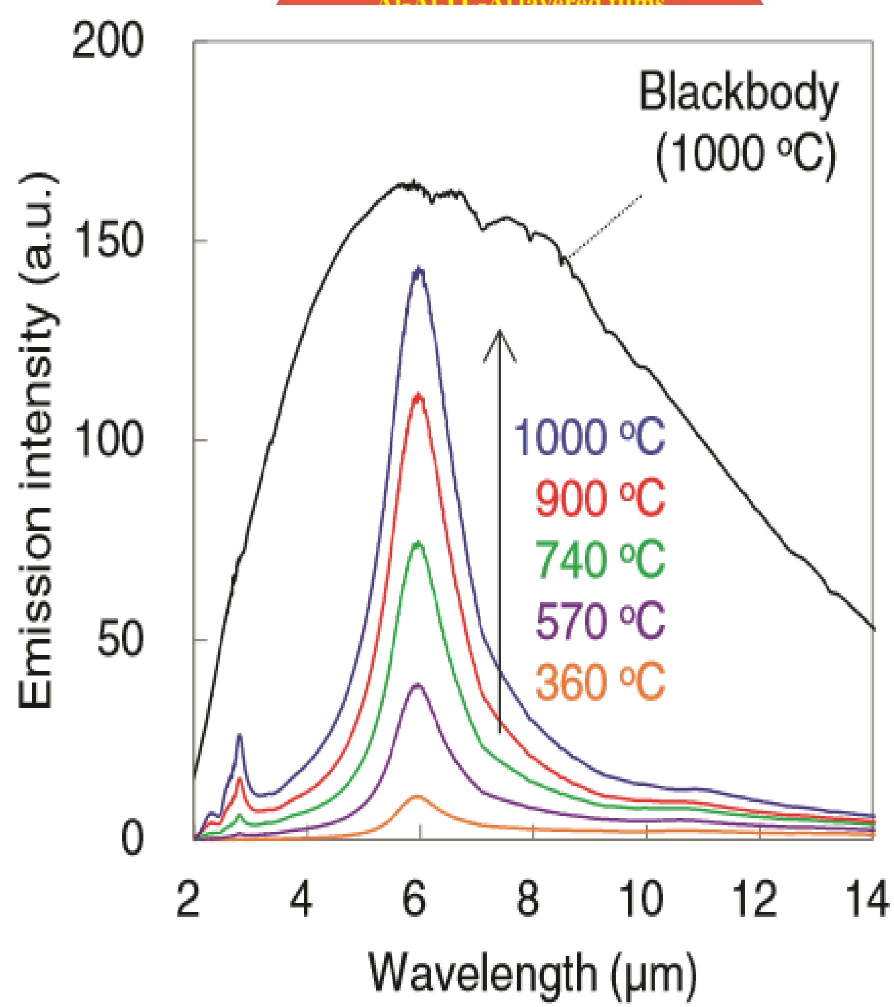
T. Dao et al., ACS Photonics, 2, 964 (2015).

High-temperature Mo Emitter Operative Above 1000 ℃

IR emitter Operative above 1000 ℃



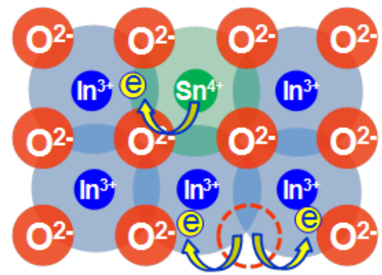
http://voyager.egglescliffe.org.uk/physics/astronomy/blackbody/bbody.html



T. Yokoyama *et al., Adv. Opt. Mat. 4, 1987 (2016).*

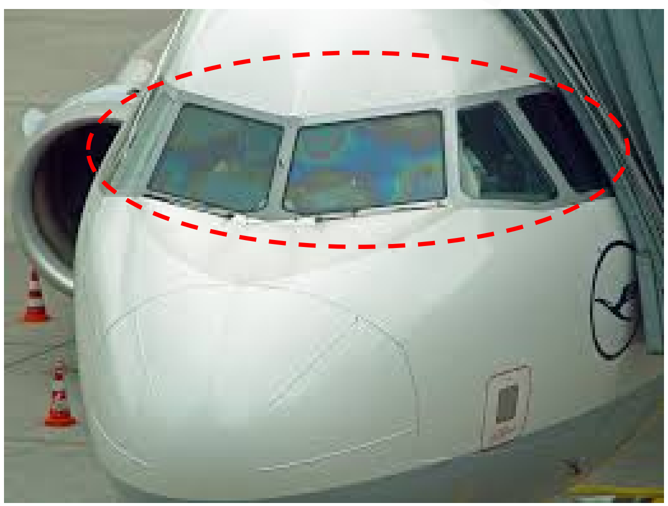
TCO for SEIRA sensors and Thermal Emitters

Indium Tin Oxide (ITO): 74% In, 18% O_2, 8% Sn

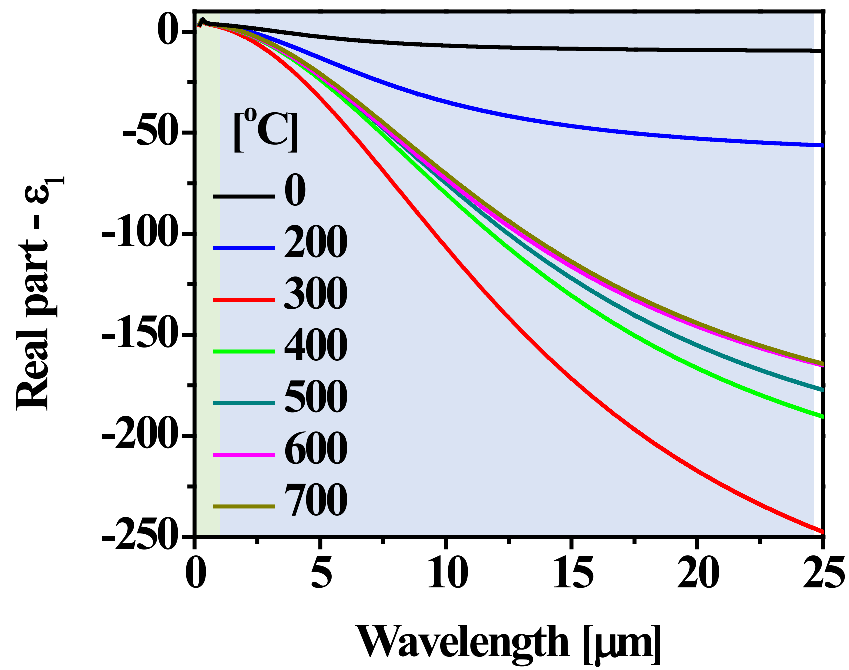


Dielectric in UV-VIS

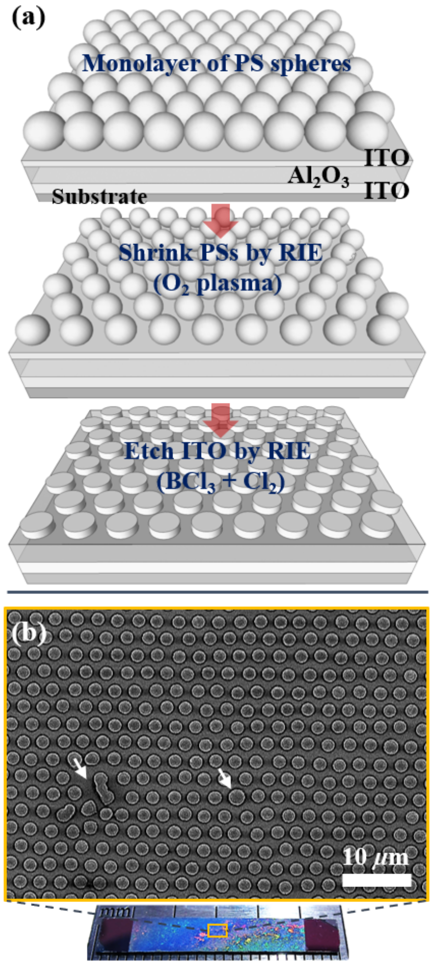
Metallic in NIR-MIR

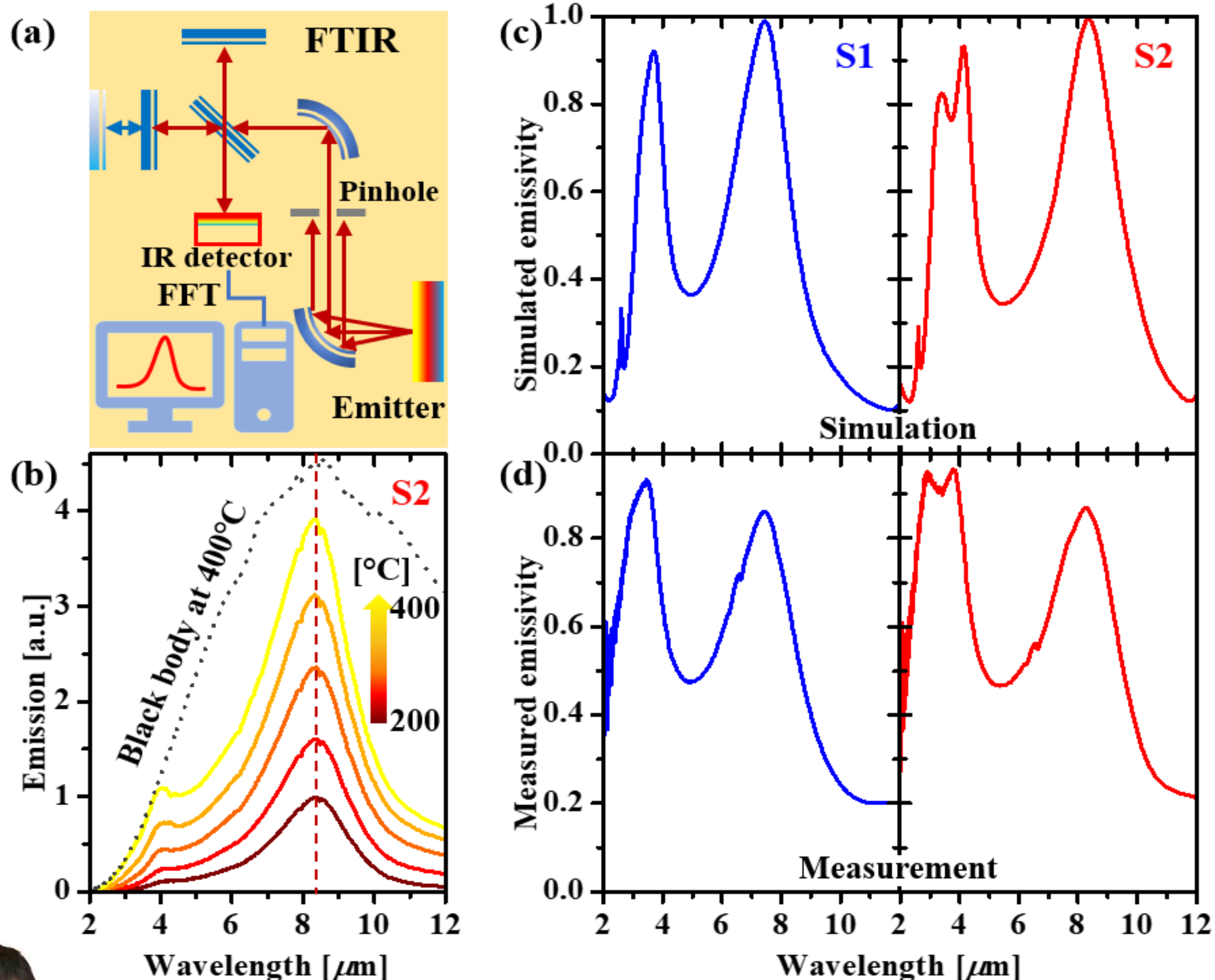


- Defrosting Transparent Heater
- Electromagnetic Shield



High-temperature PAs Operative in Air: ITO

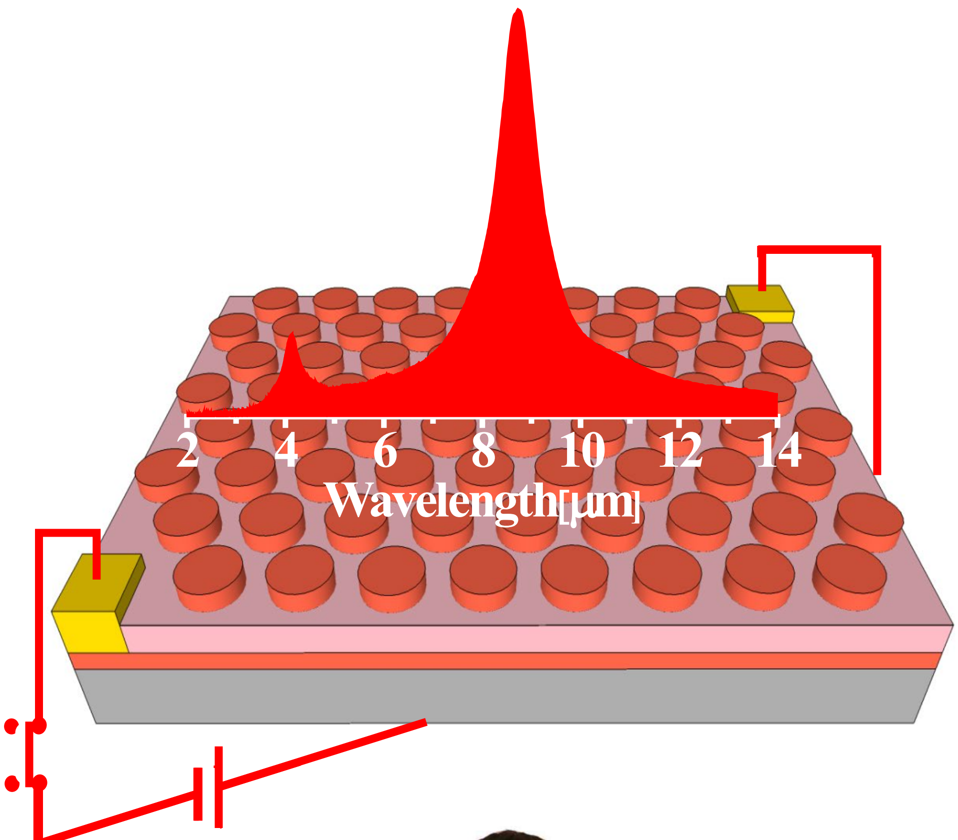


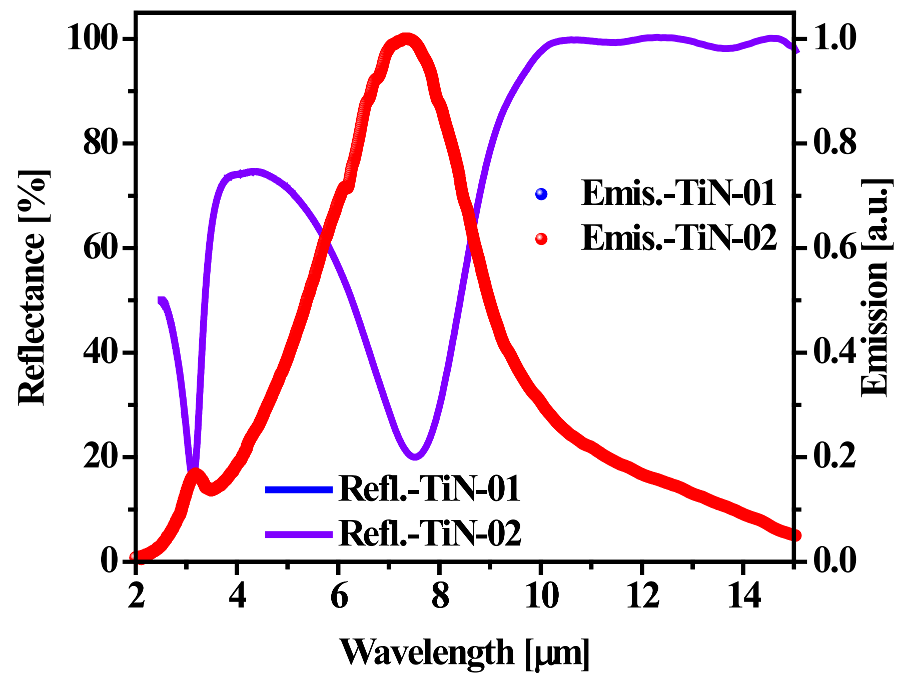


T. D. DAO *et al.*, *Opt. Mat. Exp. 9, 2534 (2019).*

High-temperature PAs Operative in Air: TiN (TiC)

Au, Al, Mo ⇒ **Plasmonic Ceramics TiN (TiC)**





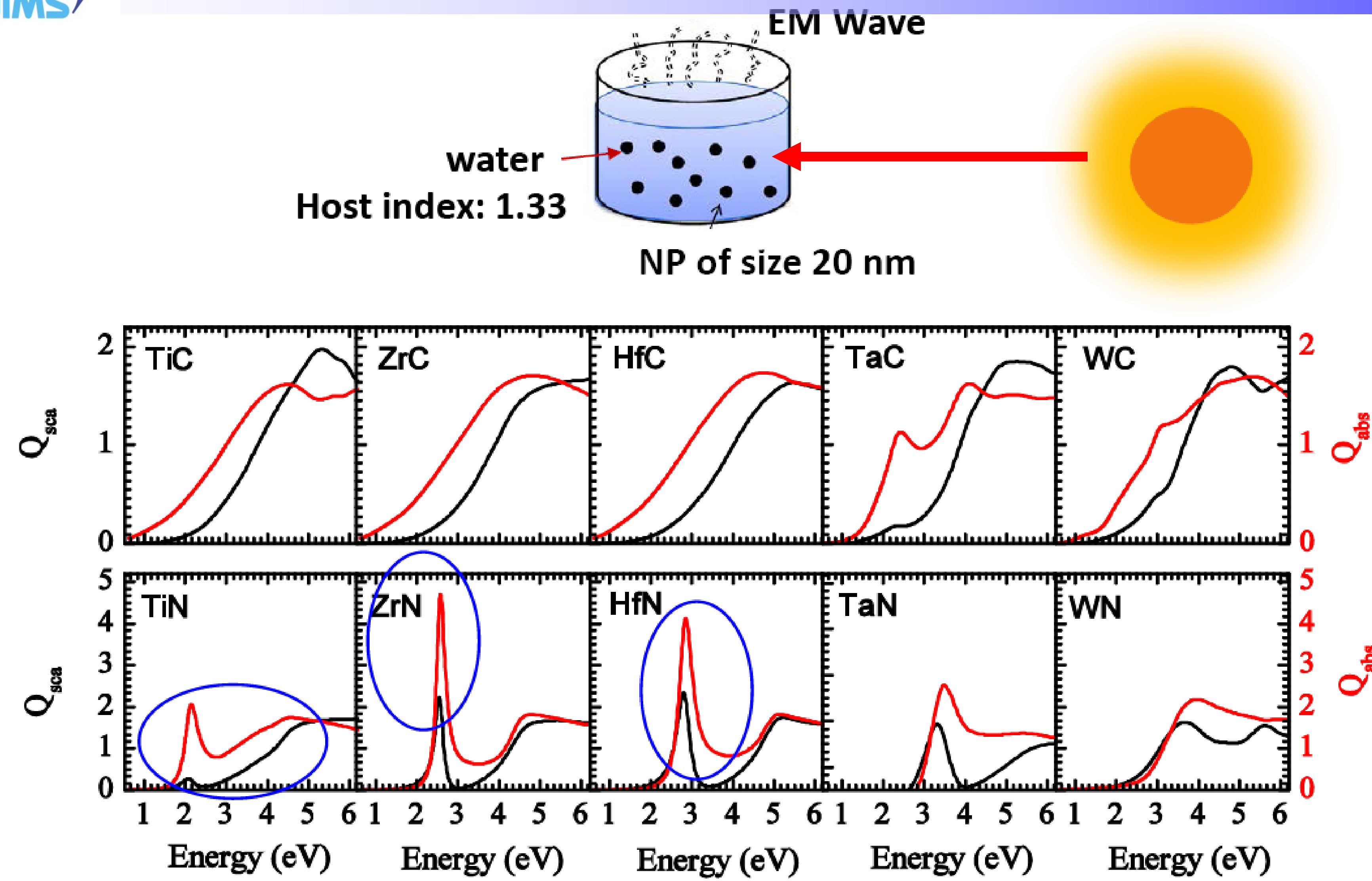
Blue : Absorption

Red : IR emitter

T.D. Dao

- **Kirchhoff's law in thermal emission**

Efficient Light-heat Nano-Tranducer Materials



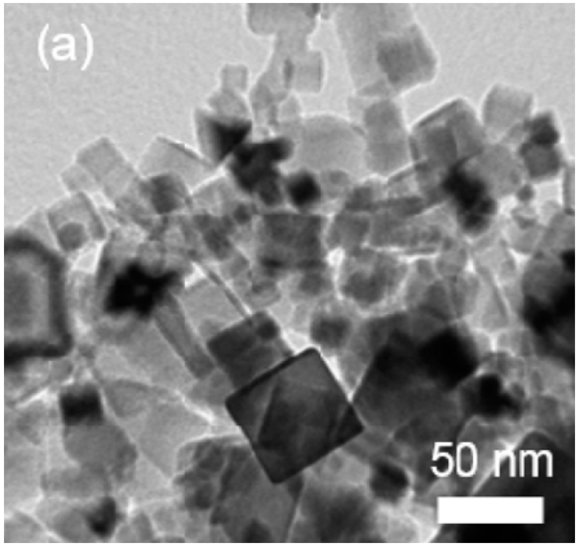
M. Kumar, N Umezawa, S Ishii, T Nagao, ACS Photonics 3 (1), 43-50 (2015).

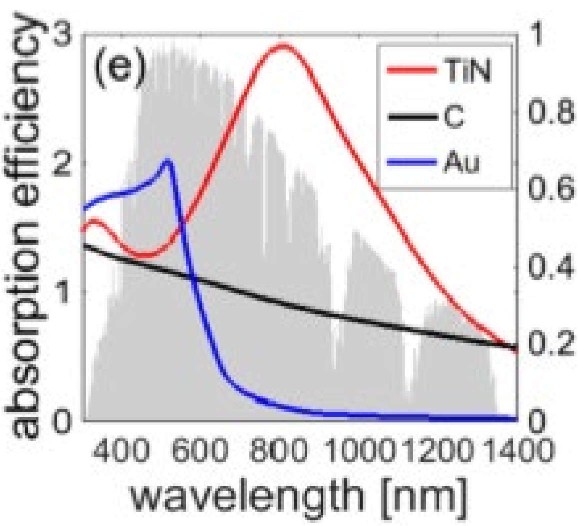
S Ishii, RP Sugavaneshwar, T Nagao, The J. Phys. Chem. C 120 (4), 2343 (2016).

NIMS

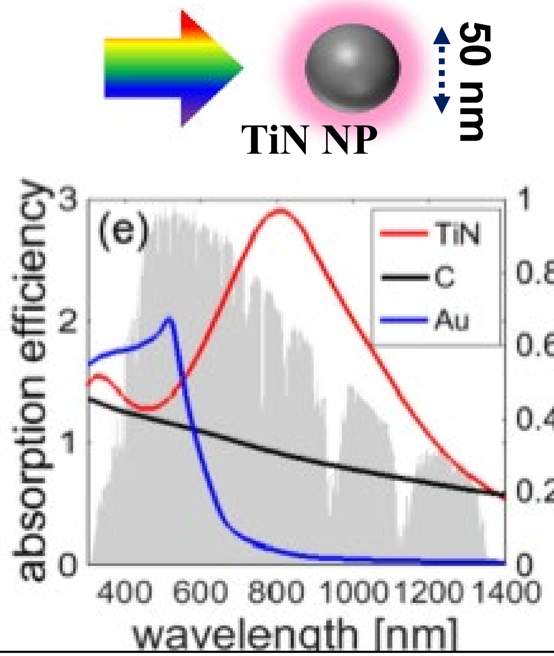
Plasmonic Nitrides, Carbides：TiN

- Nanoparticle Generator (NIMS-Attotec)
- Arc discharge method H_2-Ar (recycled)
- No ligands, clean dry synthesis
- Variety of Materials (alloys, ceramics…)

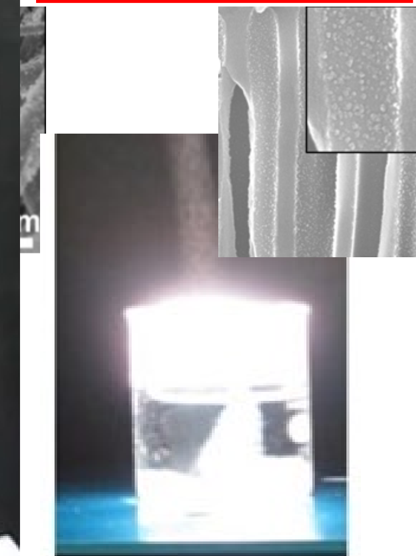




Plasmonic Nitrides, Carbides : TiN



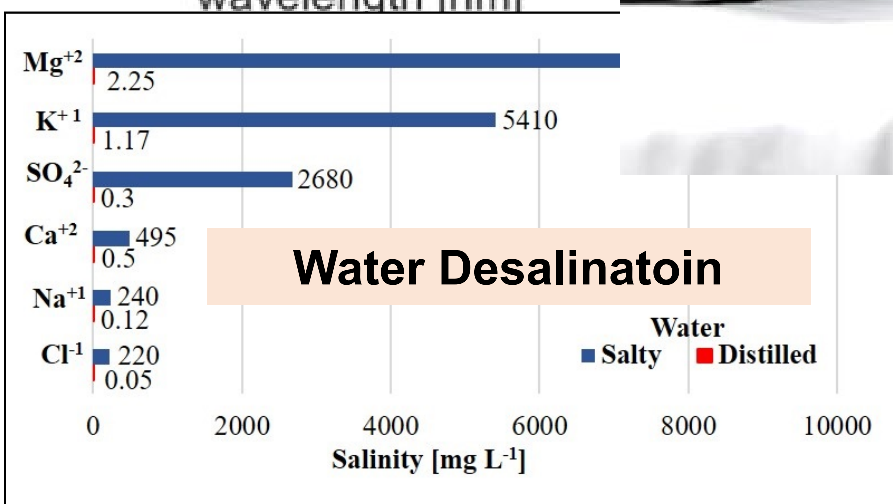
In Nanopores



92%

ions

...ter generation
from 100mW/cm² (1.5AM) solar light



Water Desalinatoin

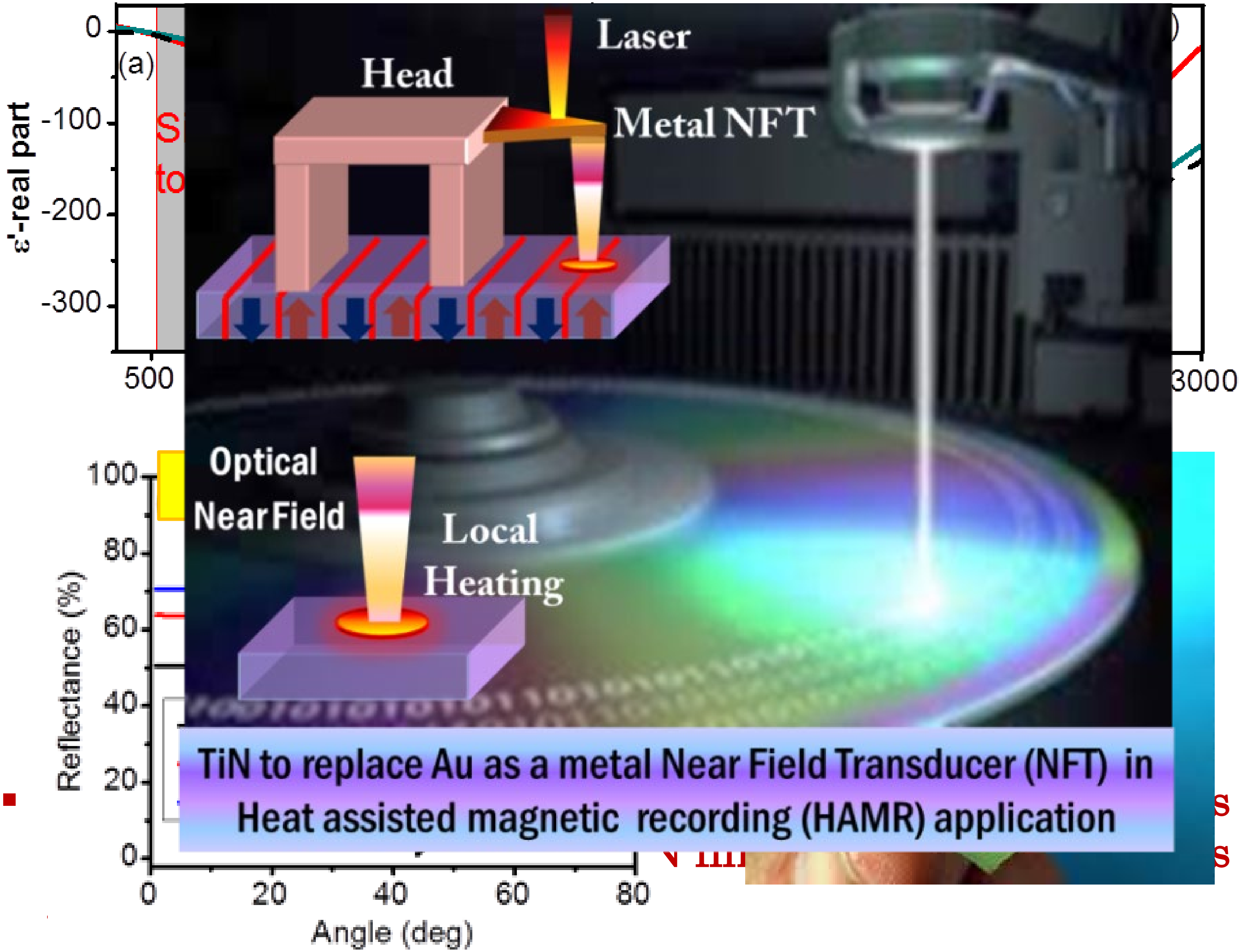
M Kaur, et al, ACS Sustainable Chem. Eng. 5, 8523(2017).

M Kaur, et al., Adv. Sustainable Syst. 3 (2), 1800112 (2018).


S. Ishii


M. Kaur

Plasmonic Ceramic TiN: PLD-grown film

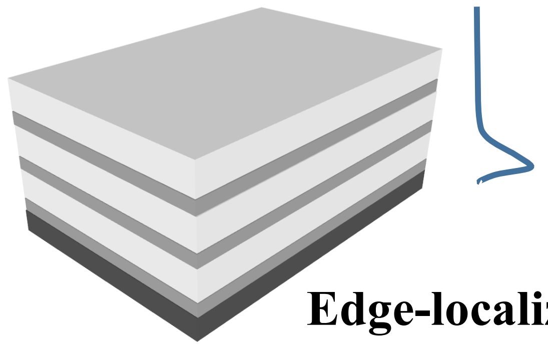


S. Ishii

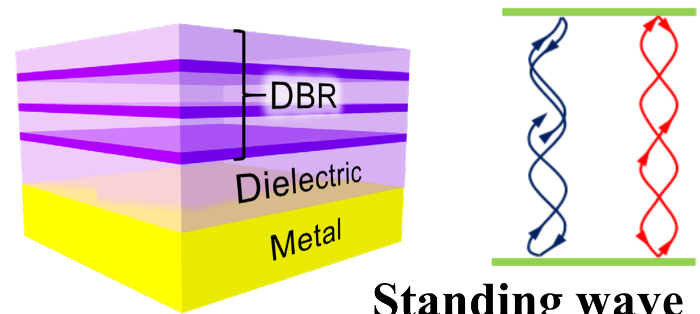
T. Nabatame

R. P. Sugavaneshwar et al ACS Photonics 5, 814-819 (2017).

Tamm Plasmon Polariton vs Gires-Tournois Cavity



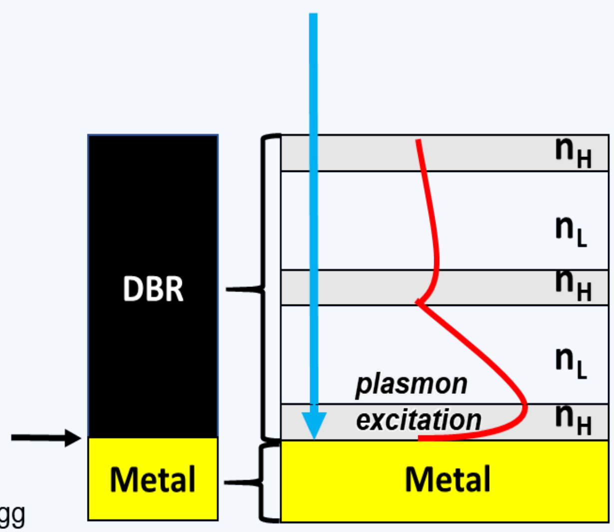
Edge-localized state



Standing wave

TPP structure

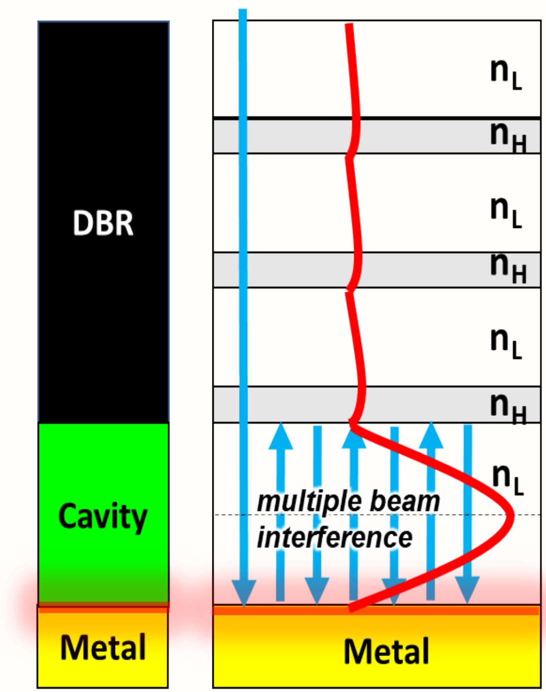
Tamm plasmon polaritons formed at the interface between a metal and a dielectric Bragg reflector



DDM structure

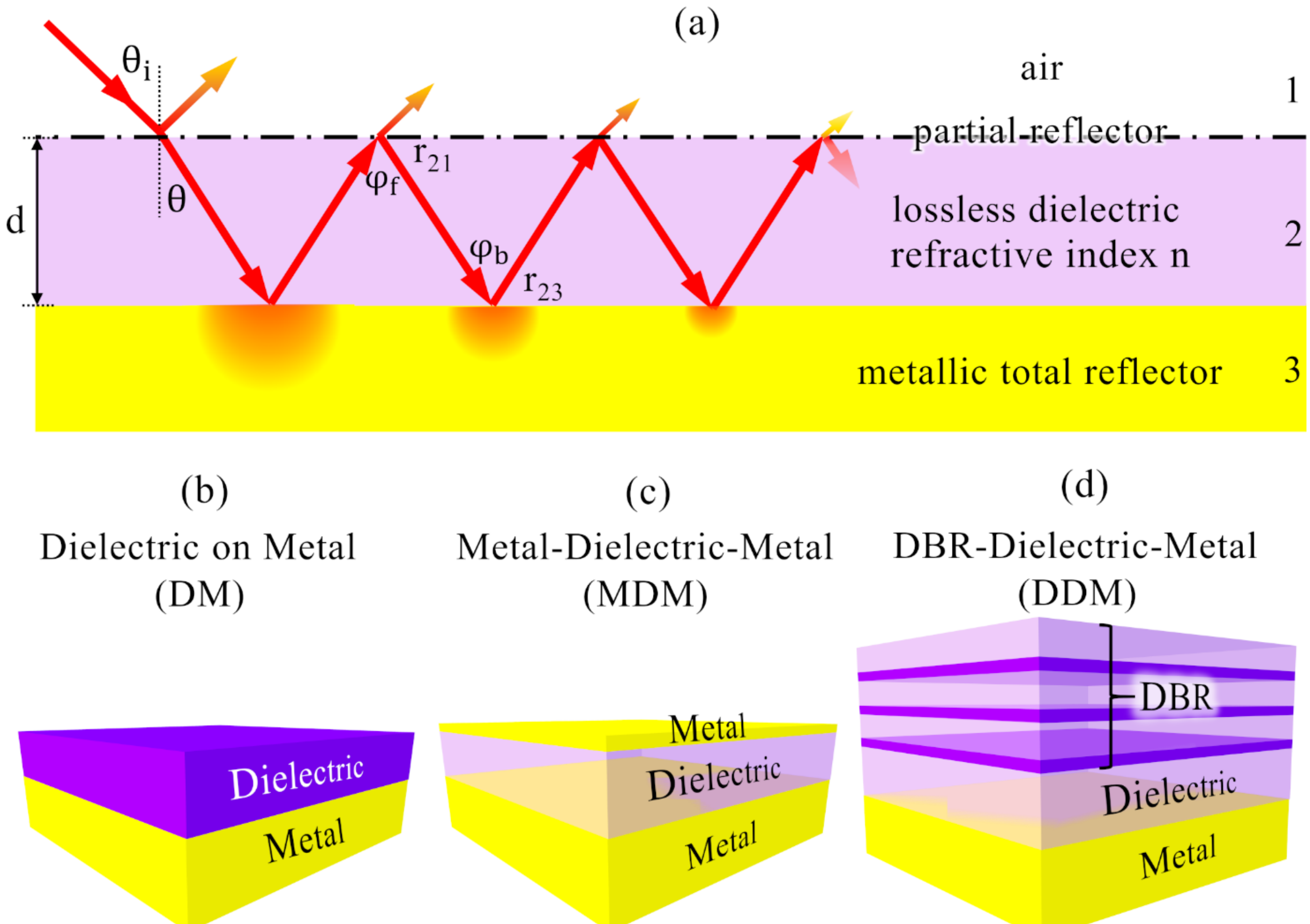
DBR serves as a semi-transparent mirror of the cavity

metallic loss at the back metallic mirror



The GT cavity serves as a spectral filter element to enhance multiple reflection of resonant waves in the cavity

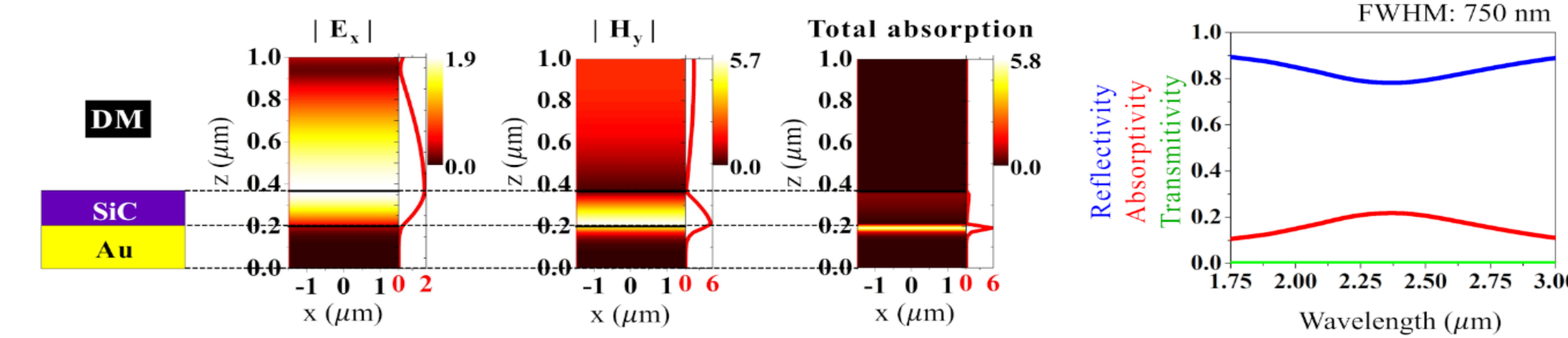
Gires-Tournois Resonator with Metal/Oxide Interfaces



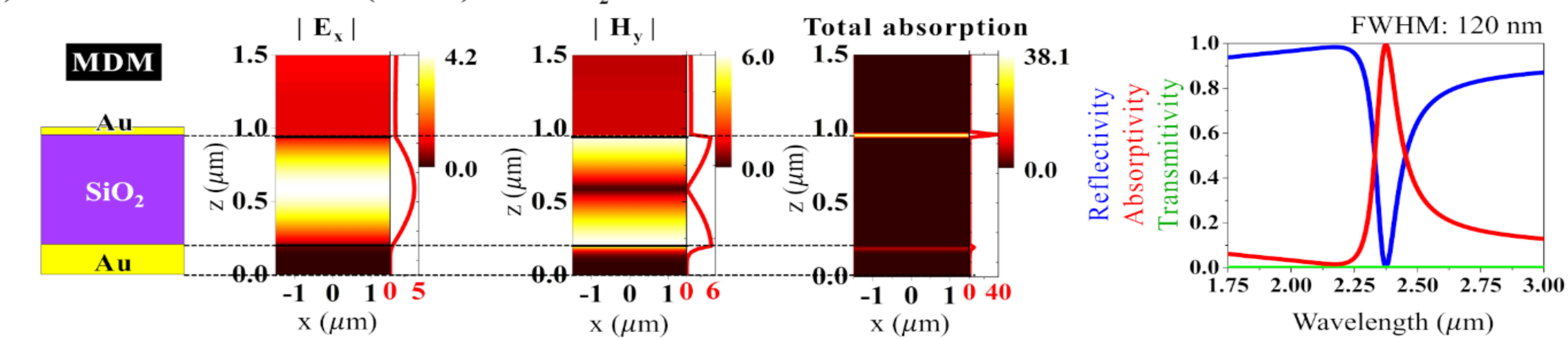
Doan, T. Dao, S. Ishii, and T. Nagao, "Gires-Tournois resonators as ultra-narrowband perfect absorbers for infrared spectroscopic devices," Opt. Express 27, A725-A737 (2019).

Gires-Tournois Resonator with Metal/Oxide Interfaces

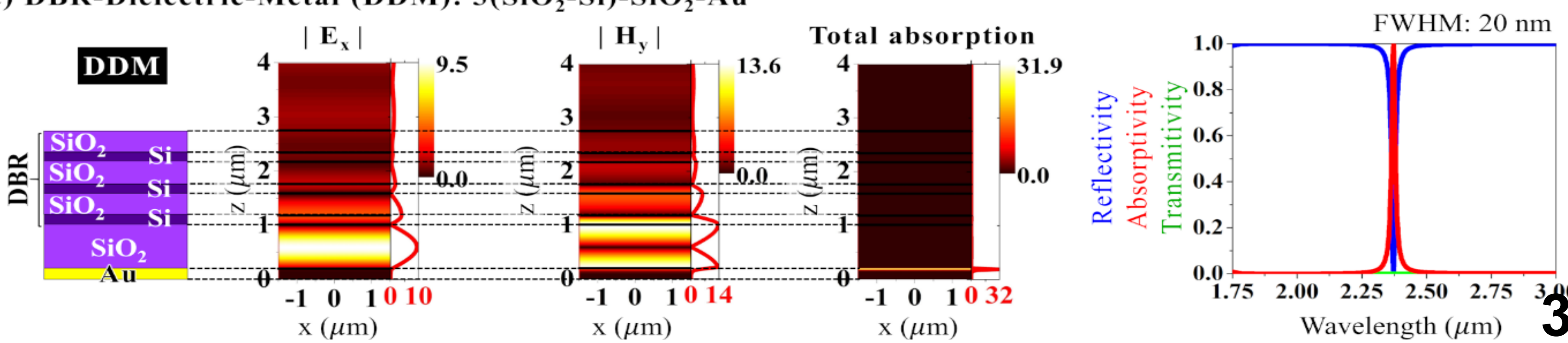
(a) Dielectric Cavity on Metal (DM) : SiC on Au



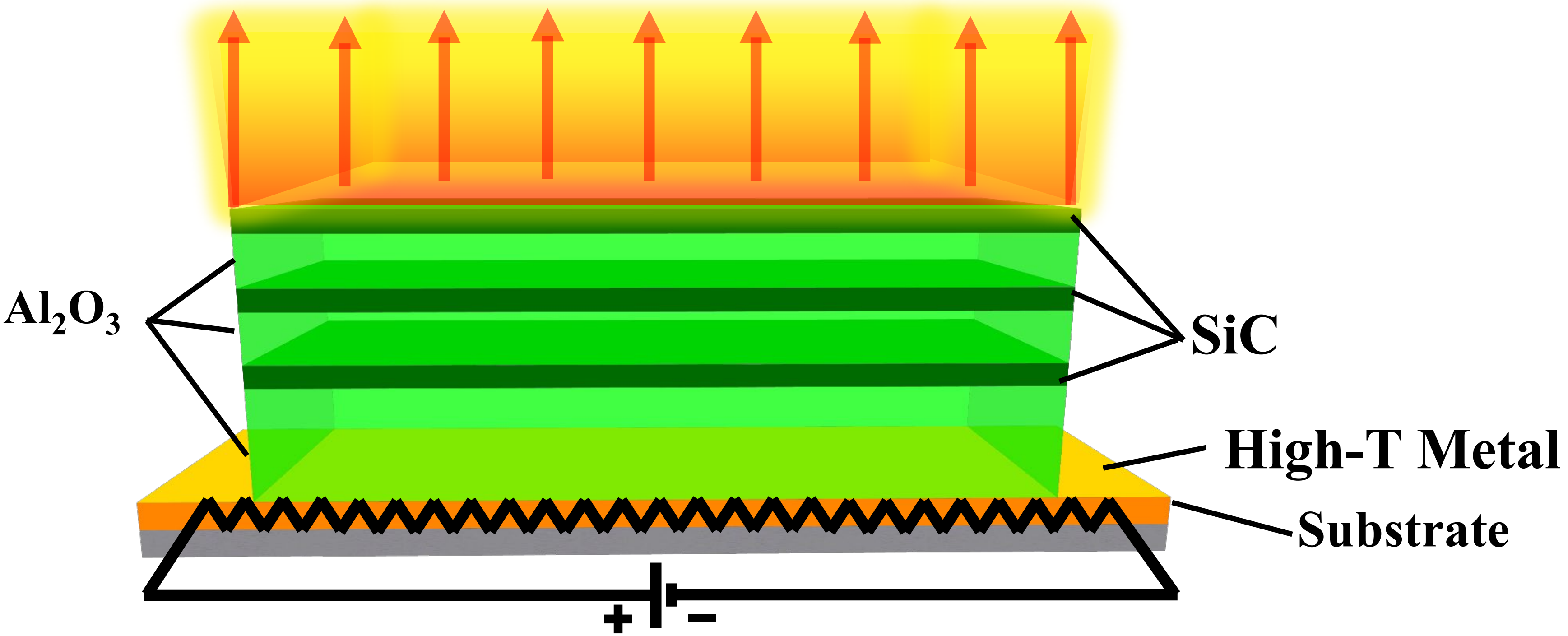
(b) Metal-Dielectric-Metal (MDM): Au-SiO_2-Au



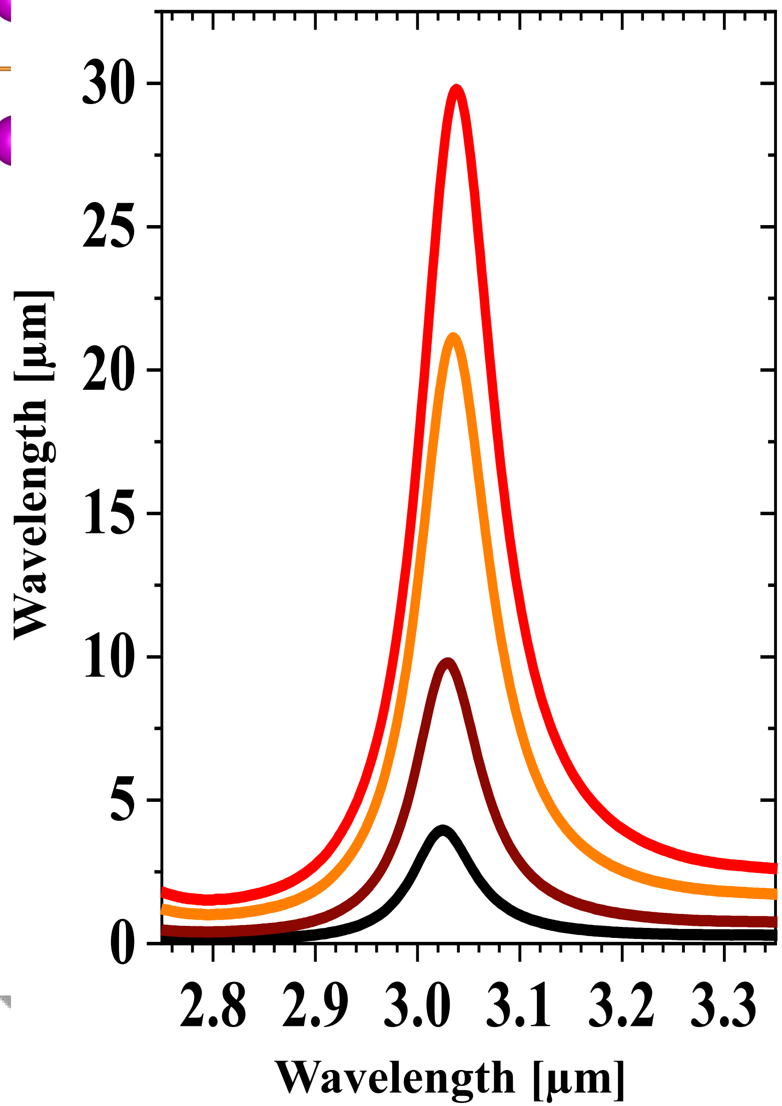
(c) DBR-Dielectric-Metal (DDM): 3(SiO_2-Si)-SiO_2-Au



Gires Tournois cavity-based emitter



Spectroscopic IR Emission by Plasmonic Ceramics

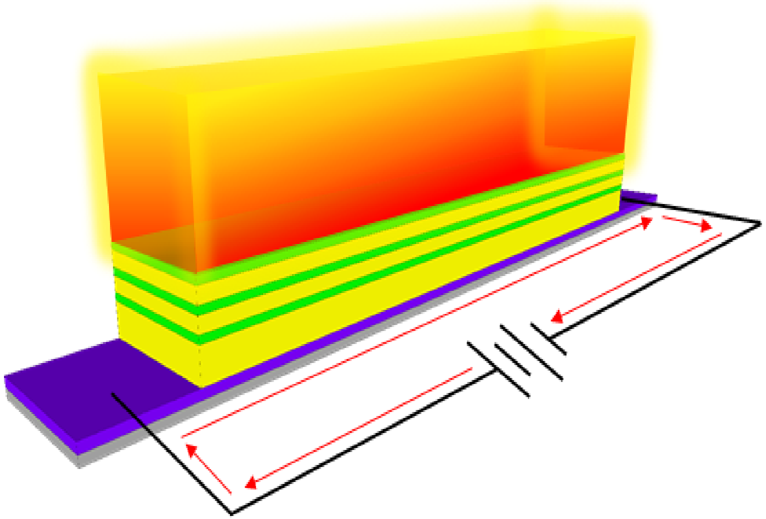


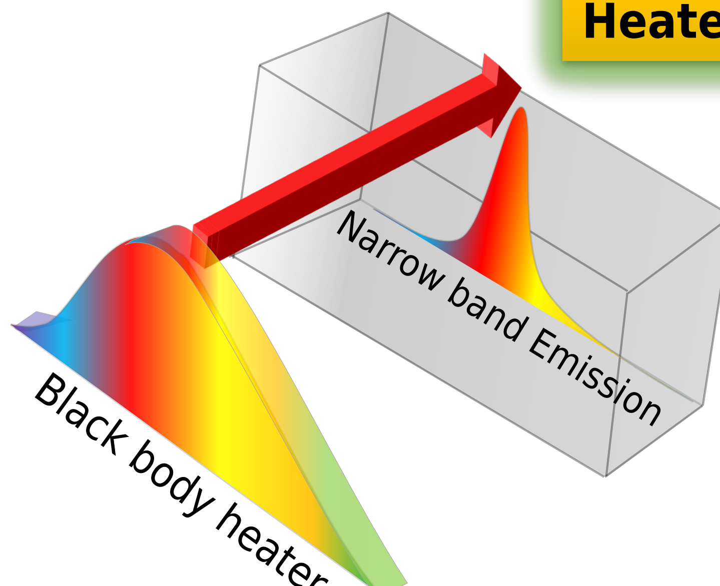
Application for Drying Furnaces

Future Perspective

- Saving Energy by supressing Unnecessary Emission.
- ～70% Reduction of Electricity.
- Avoid Burning/Explosion of Solvents

Spectroscopic Heater





Outline

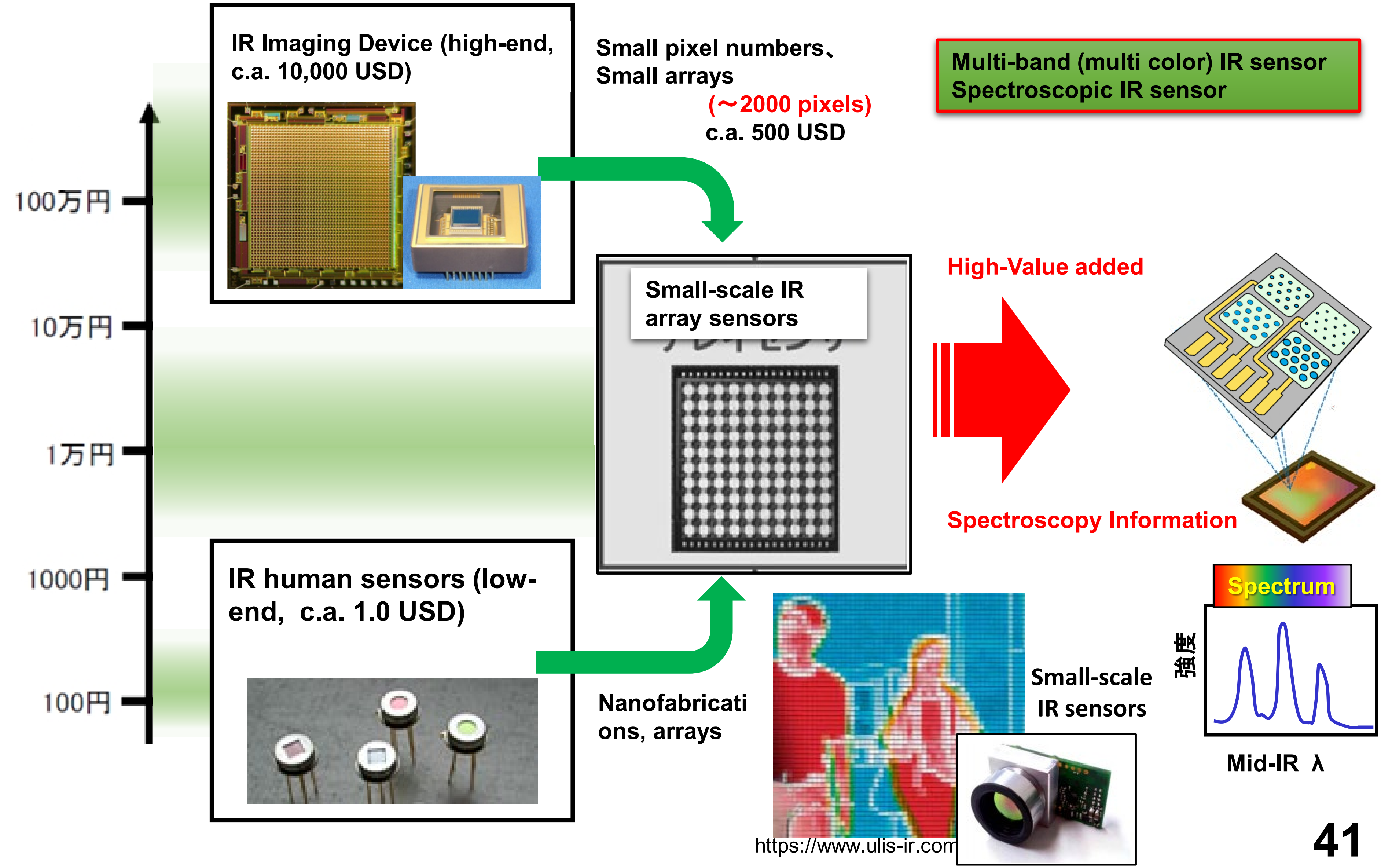
- Exploring the Infrared Plasmonic Materials (for SEIRA and Thermal Emitters)

  Al, Mo, ITO, TiN, doped TiO_2, etc

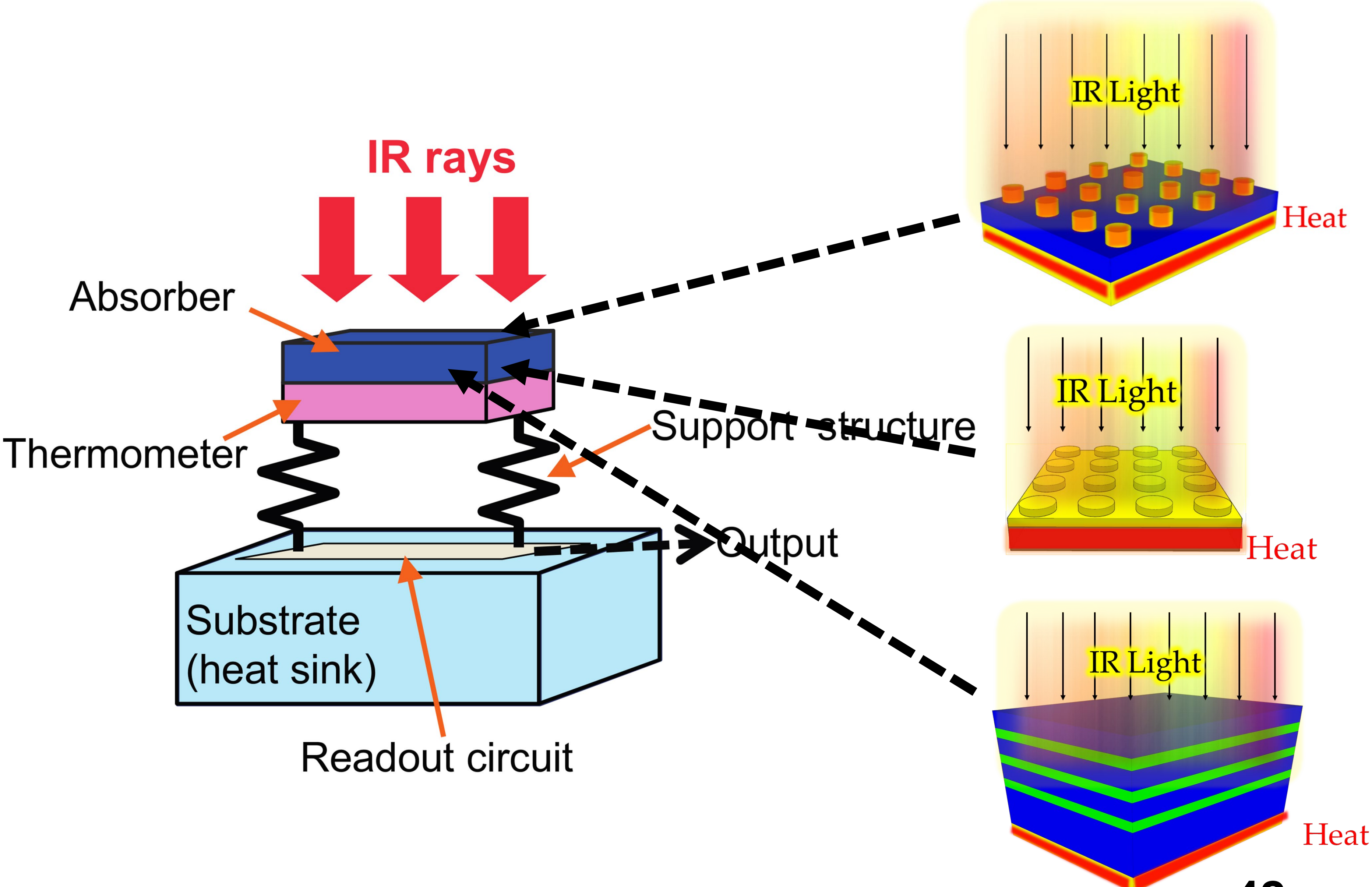
- Wavelength-selective (Spectroscopic) IR Sensors (and Emitters ..)

  Bolometer, Pyroelectric, IR Sensors
  Multiband (sub-100 nm FWHM) IR Sensors

Direction of Our Developments in IR Sensors



Hybrid Infrared Detectors

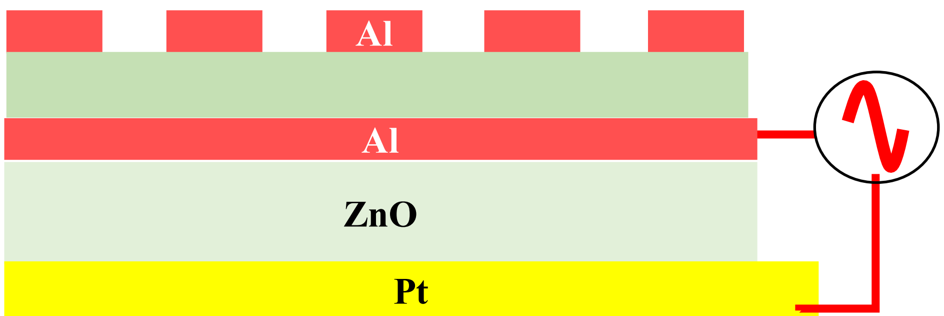


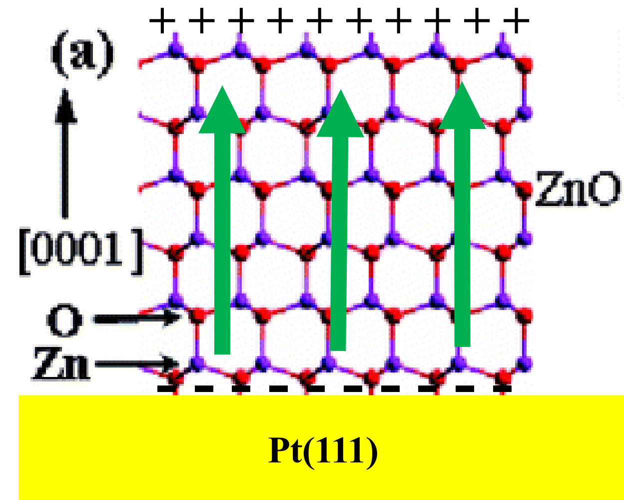
Proof of concept

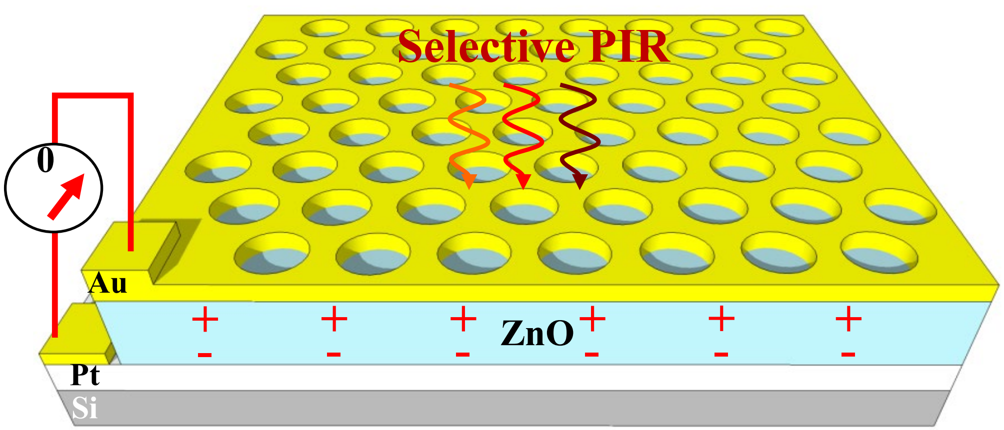
Wavelength Selective Pyroelectric IR Detector

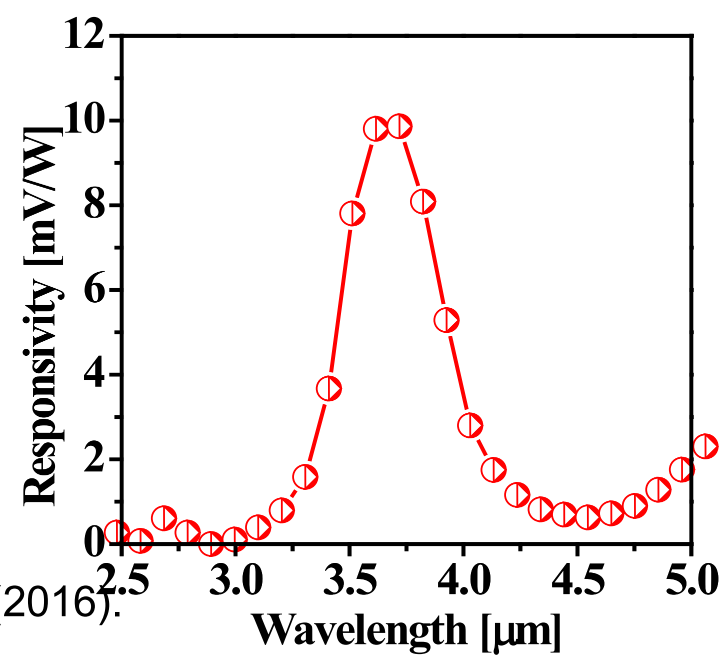
- **Detector + Filter + Amp.**

IR Resonator on Uniaxial ZnO film



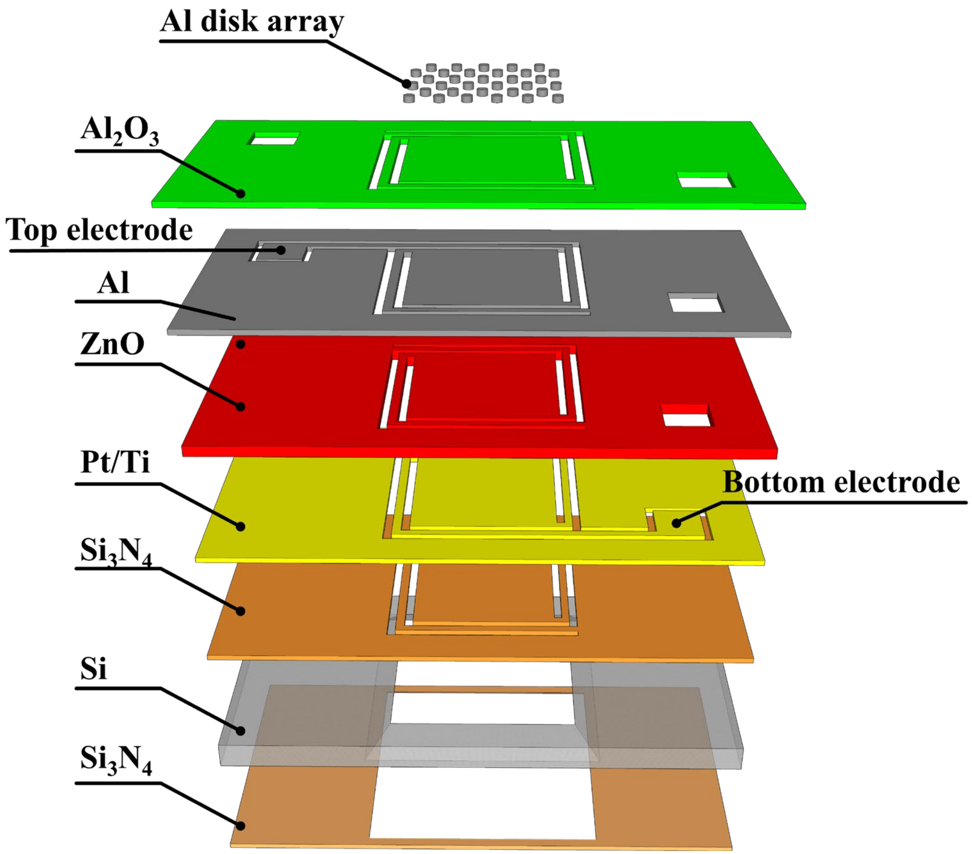


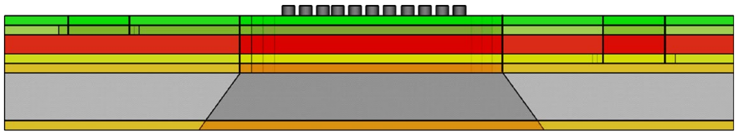




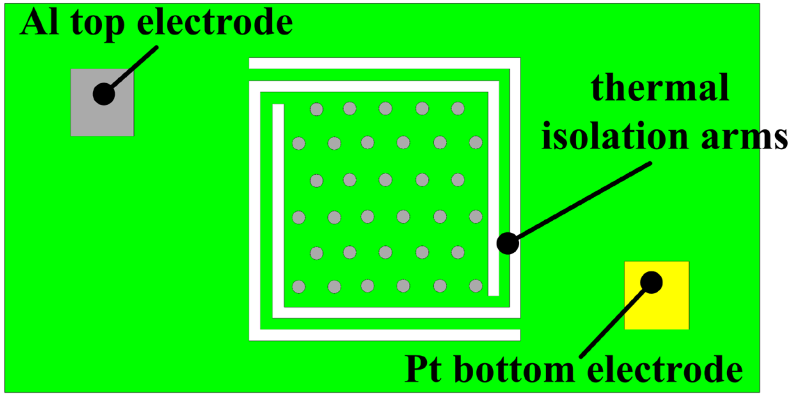
T.D. Dao, et al., ACS Photonics 3 (7), 1271–1278 (2016).

MIM Al Disk Array Pyroelectric Detector

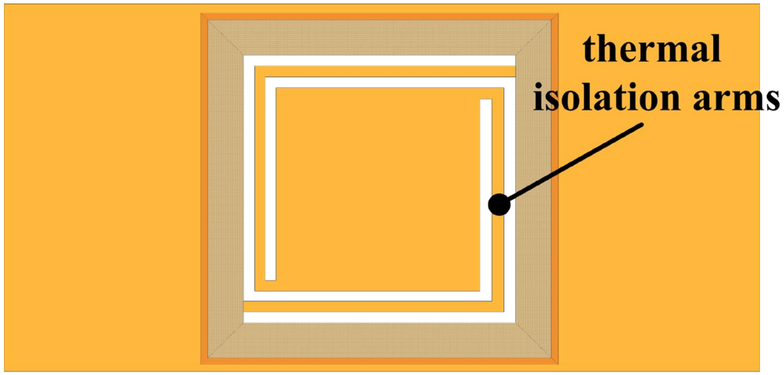




Side view



Top view

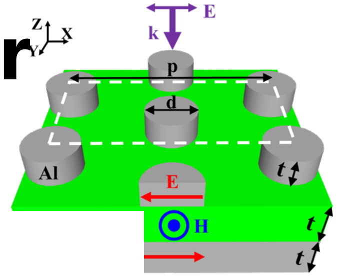


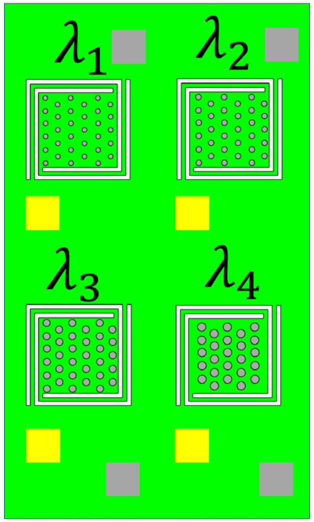
Back view

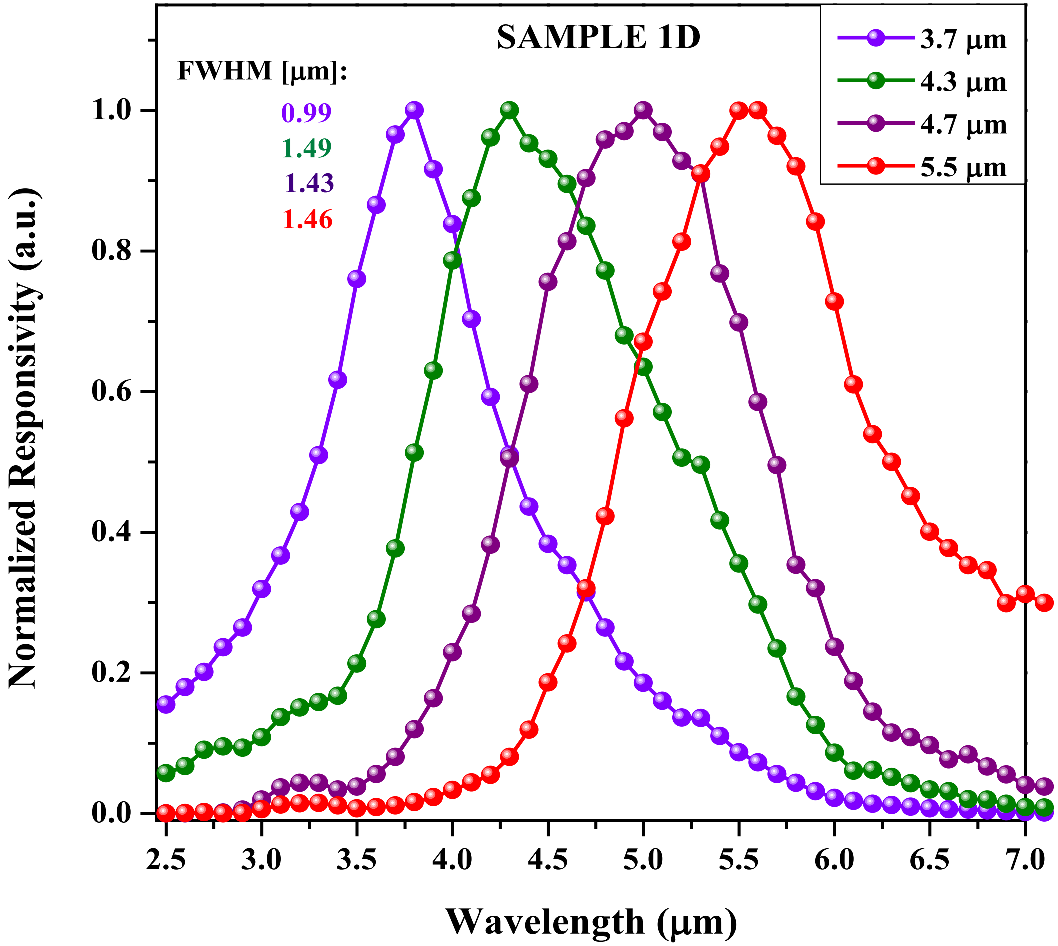
A.T. Doan, et al., "A MEMS-based quad-wavelength hybrid plasmonic-pyroelectric infrared detector",

Micromachines **10** (6), 413(2019).

Multiband Pyroelectric Detector

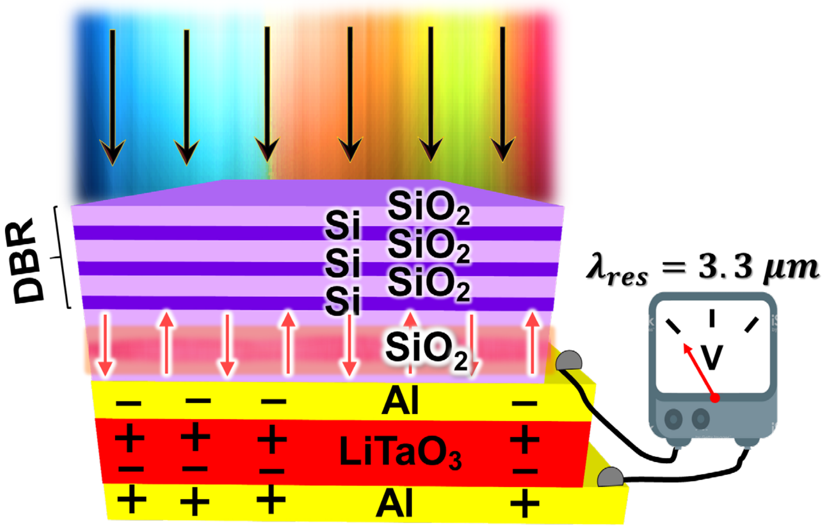


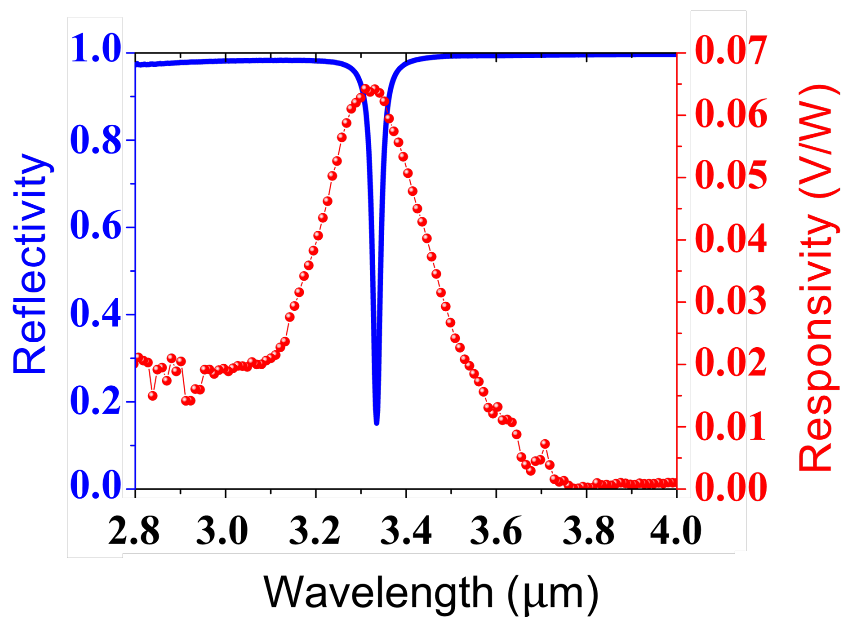


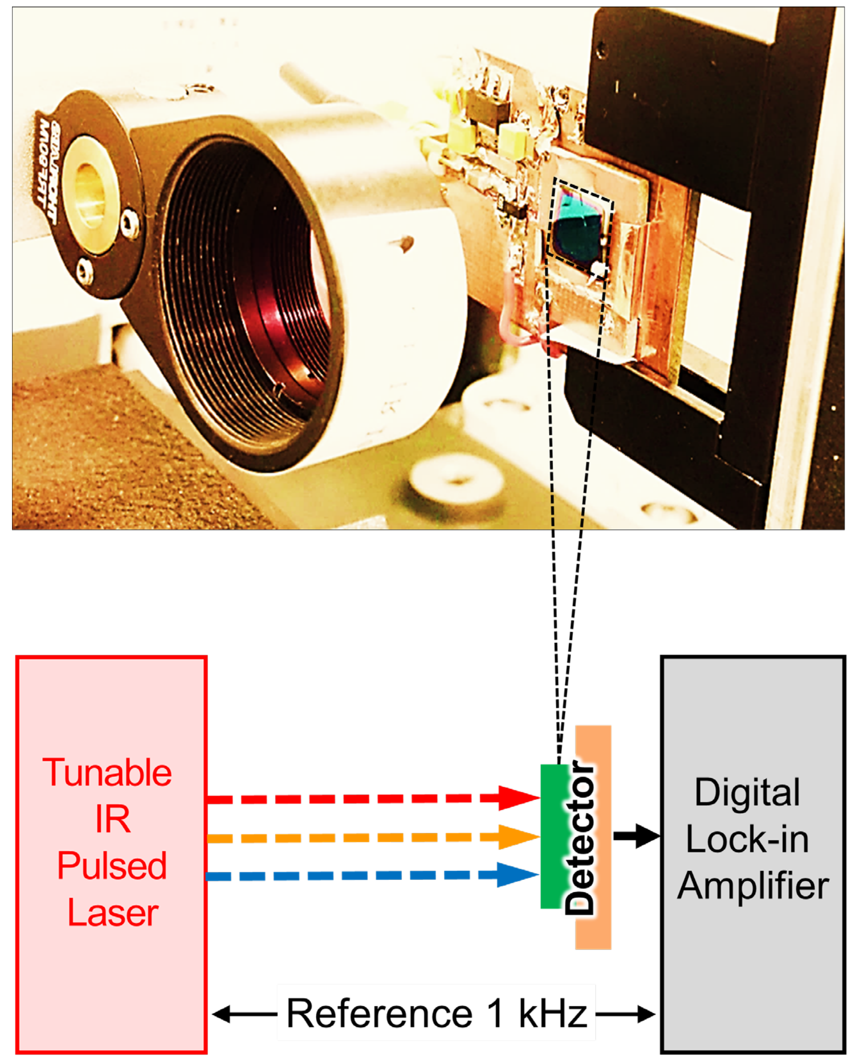


Doan, et al., "A MEMS-based quad-wavelength hybrid plasmonic-pyroelectric infrared detector", Micromachines, Accepted (2019)

Hybrid Pyroelectric Detector

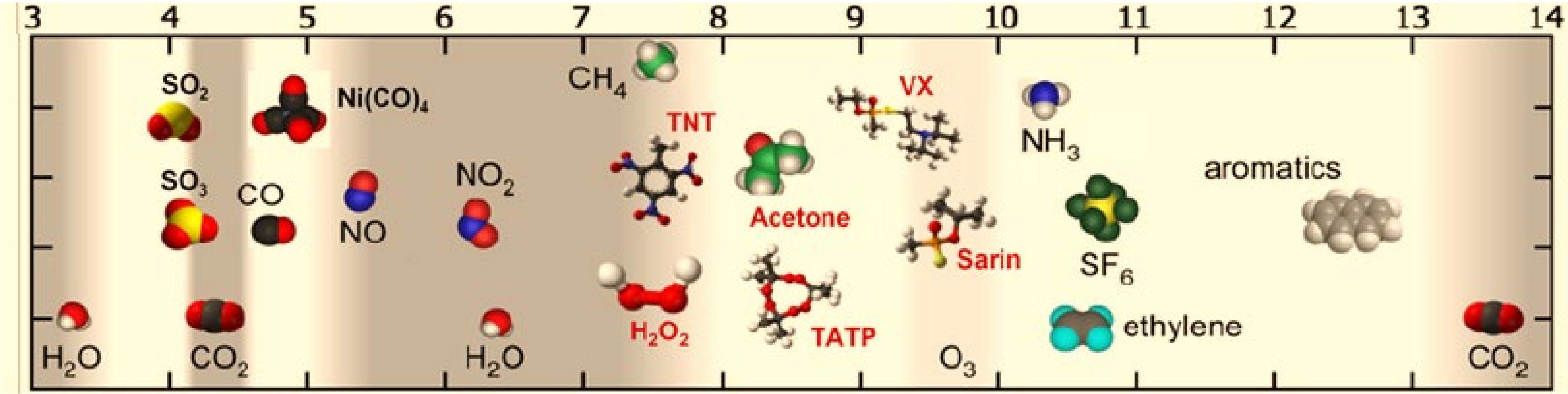




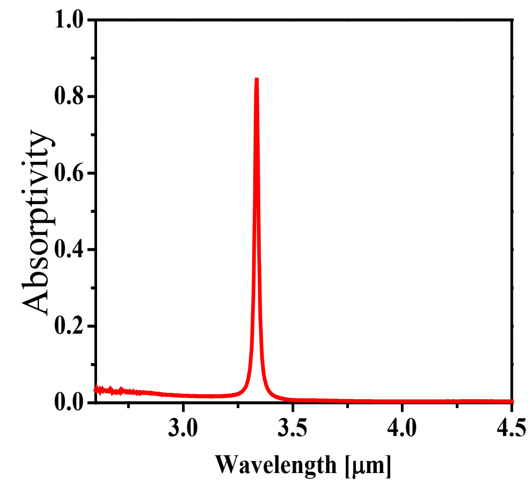


<u>**Doan**</u>, T. Dao, S. Ishii, and T. Nagao, "Gires-Tournois resonators as ultra-narrowband perfect absorbers for infrared spectroscopic devices," Opt. Express 27, A725-A737

Non Dispersive IR (NDIR) for Gas Molecule Detection

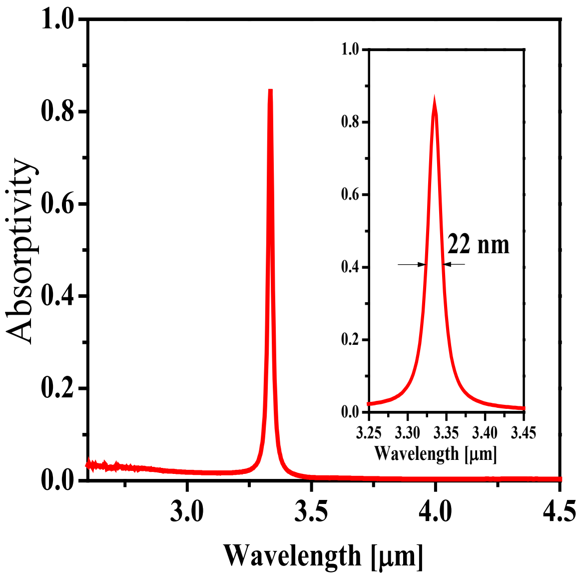


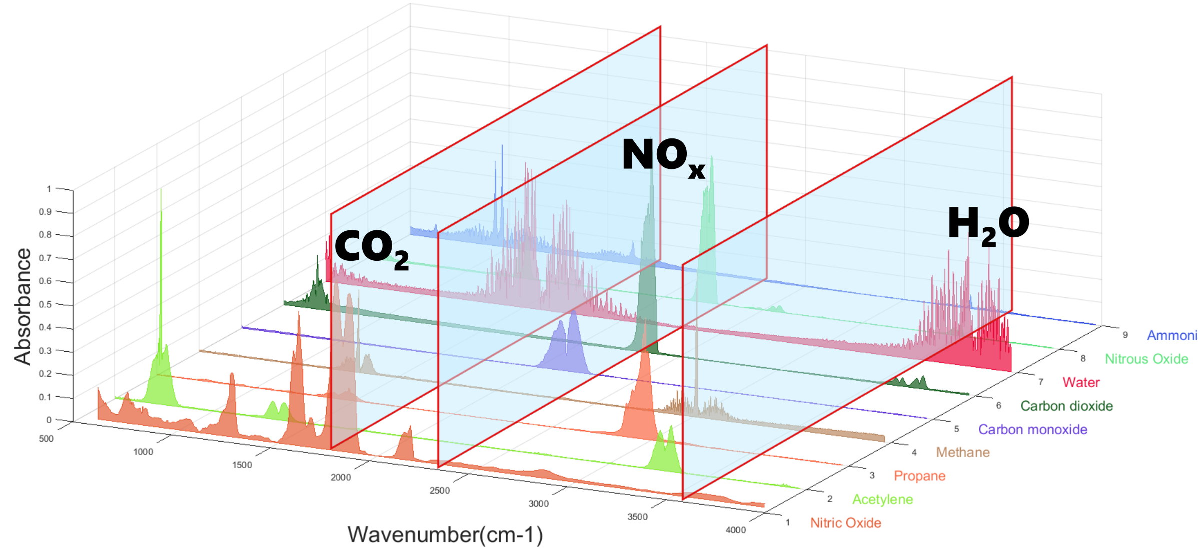
Ultrahigh-Resolution Needed!

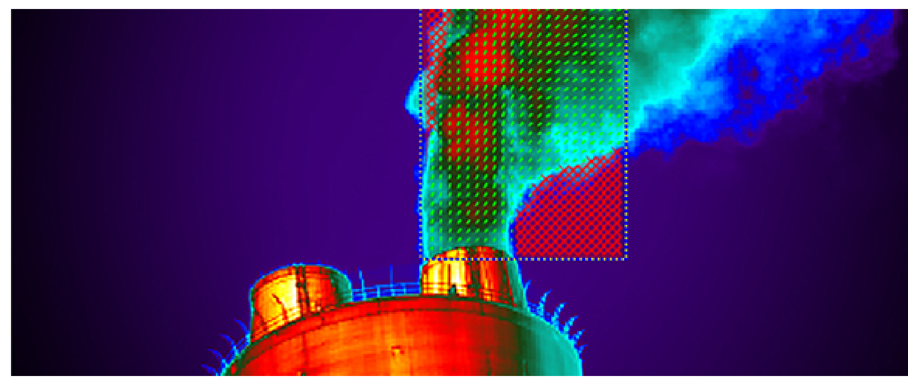


Application in Gas Sensing and Imaging

Wavelength Resolution





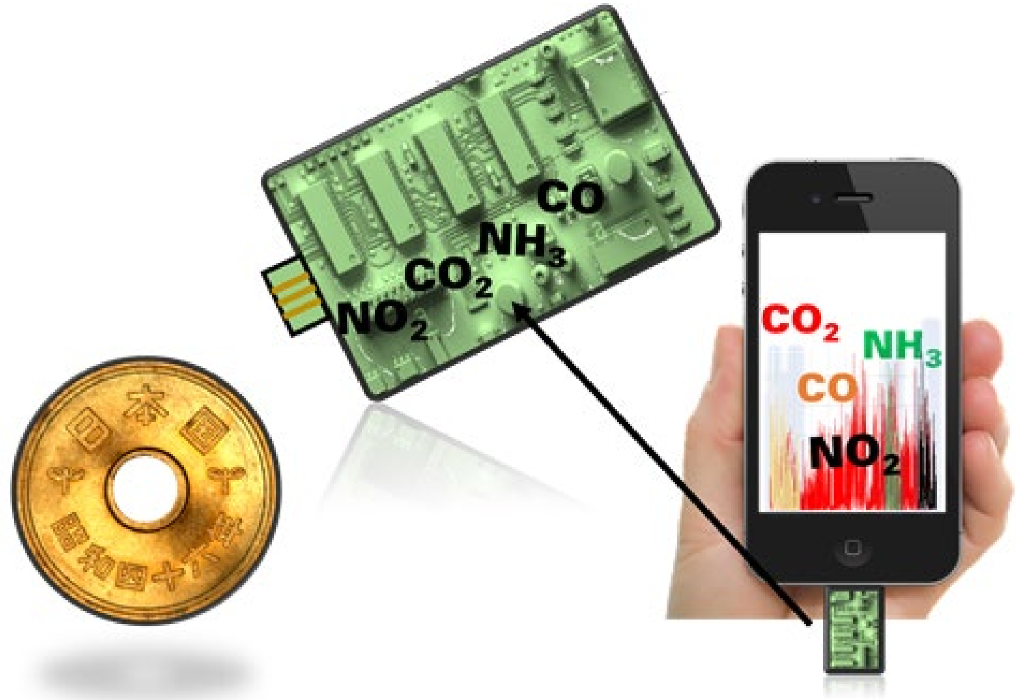


- Gas Leak Detection: CO_2, CH_4, CO, H_2O
- Leak Detection of Insulator Gas: SF_6
- Toxic gas detection: Sarin, VX gas

Application in NDIR Gas Sensing

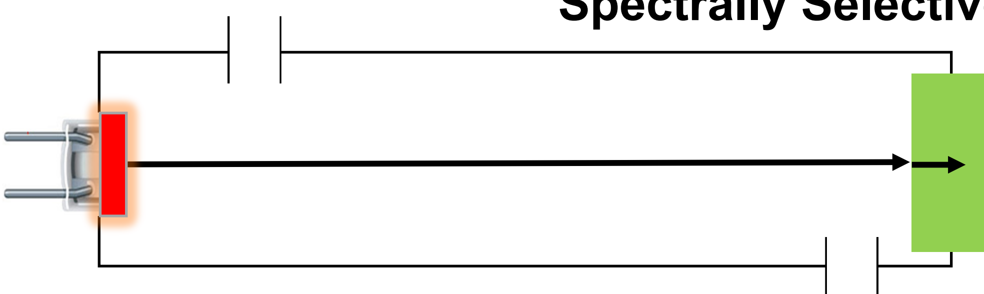
Wavelength Resolution

Wavelength [µm]



Non-dispersive InfraRed Sensing (NDIR)

Spectrally Selective Detector

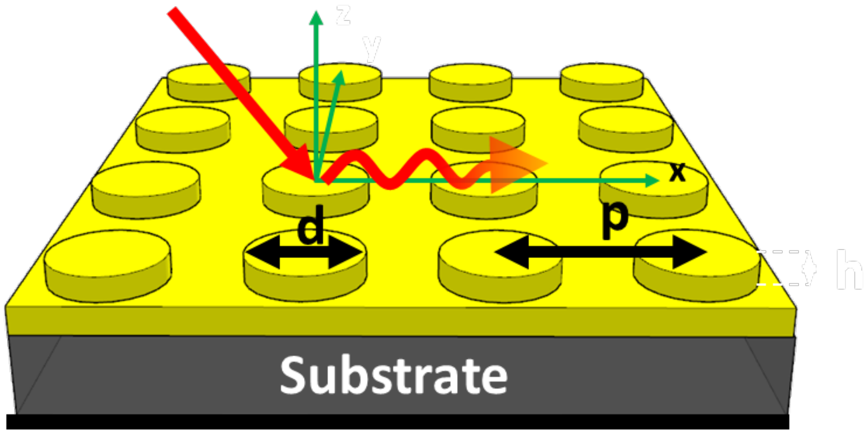


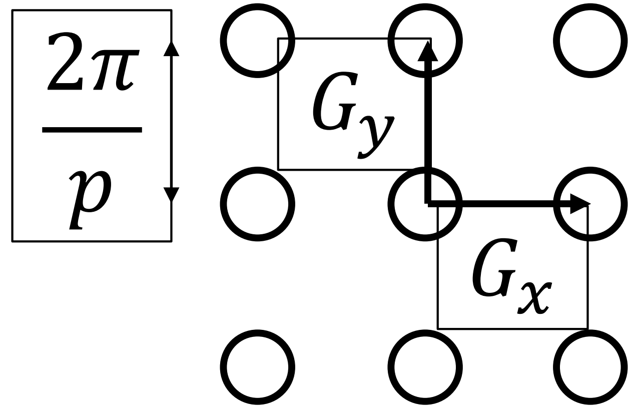
Spectrally Selective Emitter

Excitation of surface-plasmon polaritons

$$\vec{k}_{SPP} = \vec{k}_{||} + i\vec{G}_x + j\vec{G}_y$$

$$|\vec{k}_{||}| = k_0 \sin\theta$$



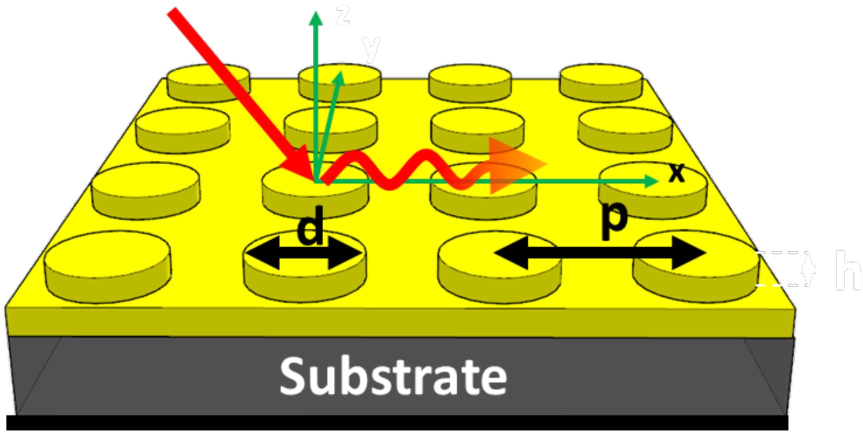


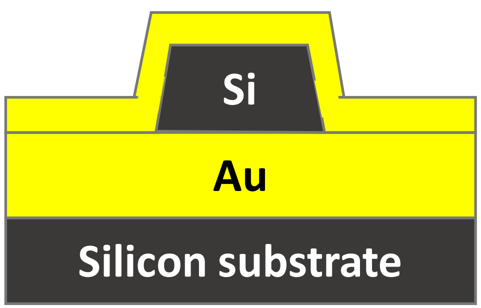
$$|\vec{k}_{SPP}|^2 = |(\vec{k}_{\parallel} + i\vec{G}_x) + j\vec{G}_y|^2$$

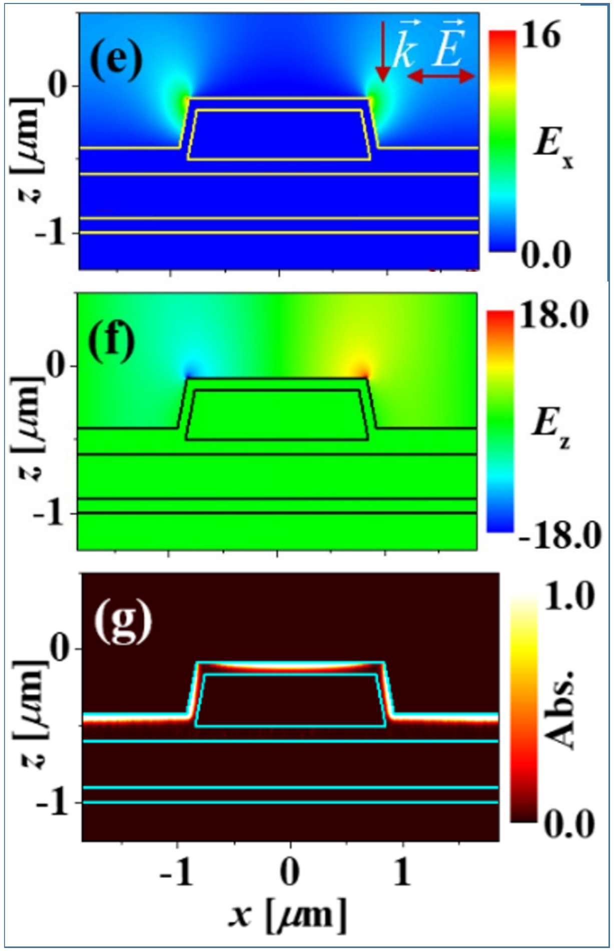
$$\lambda = \frac{p}{\sqrt{i^2 + j^2}} \sqrt{\frac{\varepsilon_m}{\varepsilon_m + 1}}$$

Tune the excitation resonance by changing periodicity of metallic disks

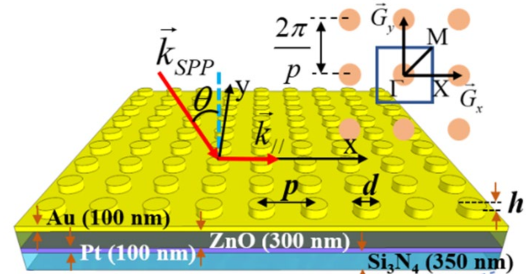
WOOD'S ANOLMALIES 2D GRATING

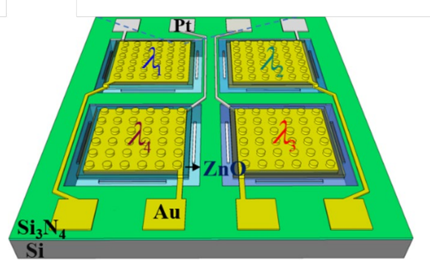


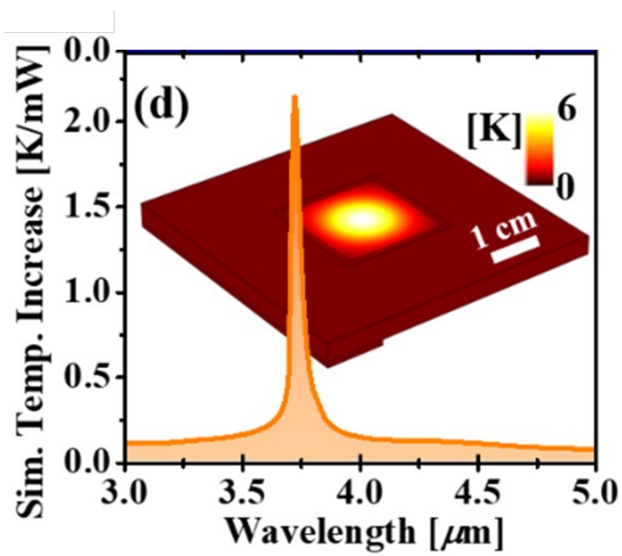


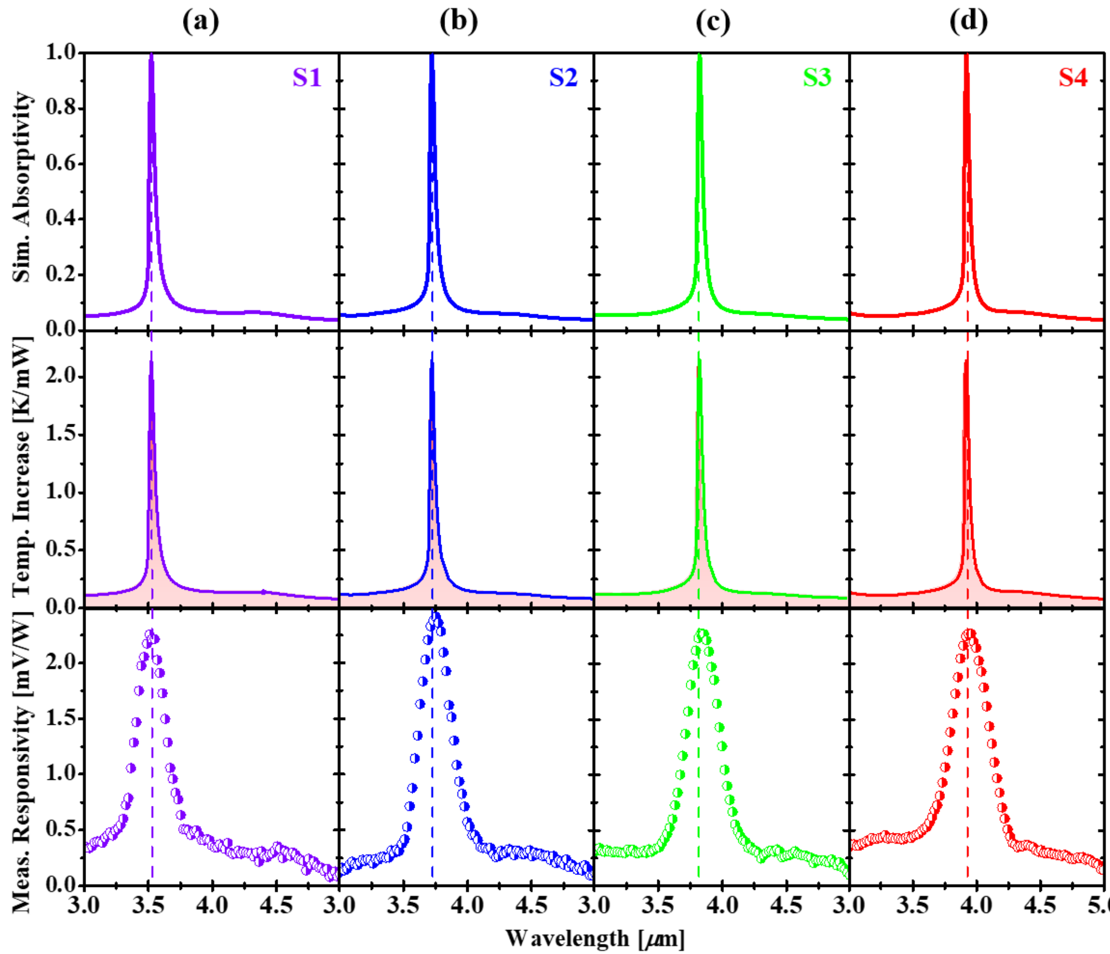


Hybrid Pyroelectric Detector (with Wood's Anomaly absorber)









Dao, **Doan**, et al. "On-Chip Quad-Wavelength Pyroelectric Sensor for Infrared Spectroscopy", published in "Advanced Science" and it "Advanced Science news"

Conclusions

1) Plasmonic Materials for IR Signal/Energy Conversion (Spectroscopic IR Devices)

2) Sub 100nm resolution, Spectroscopic IR Devices: Thermal Emitters, Ultranarrowband Multiband Pyroelectric Sensors,

NIMS

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JST 独立行政法人 科学技術振興機構 Japan Science and Technology Agency

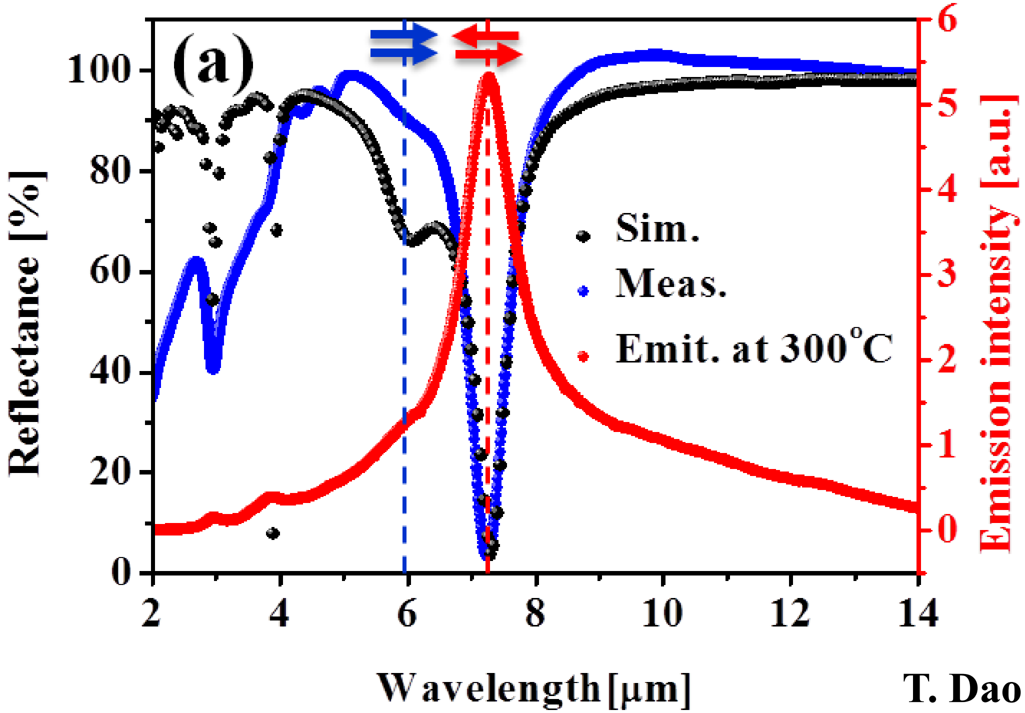
CREST

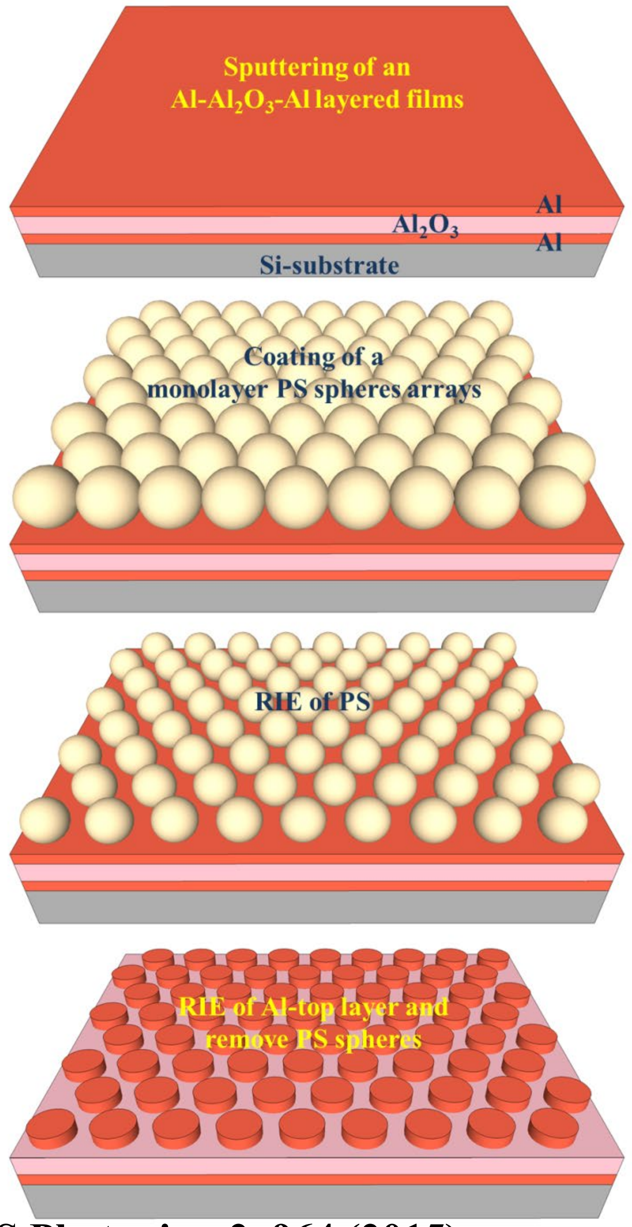
Thank you very much for your attention!!

MIM Emitter fabrication process

Colloidal lithography and RIE

- Sputtering deposition of the layered Al-Al2O3-Al films
- Deposition of a monolayer PS spheres
- RIE of PS (O2 gas -20[sccm], 1 [Pa], 200/5[W])
- RIE of Al (BCl3/Cl2 – 3/3[sccm], 0.15 [Pa], 50/10 [W])
- Remove PS (sonication and toluene solution)
- Al disk-100nm/Al2O3-200nm/Al film-100nm.





T. Dao et al., ACS Photonics, 2, 964 (2015).