Agency for Science, Technology and Research
SINGAPORE

INFRARED METROLOGY WITH VISIBLE LIGHT

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Talk at the MSU Quantum Technology Center

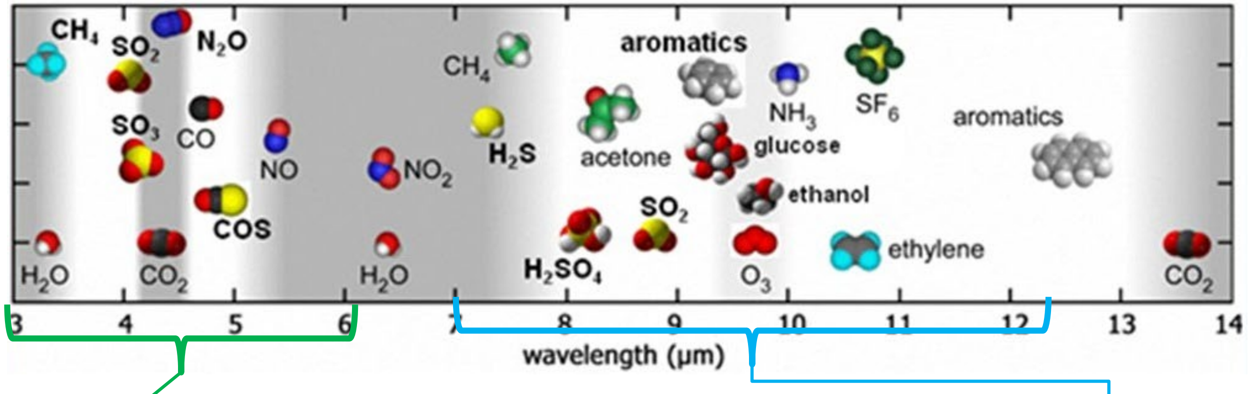
23 Oct 2021

Outline

CREATING GROWTH, ENHANCING LIVES

Introduction and motivation

Infrared light for materials fingerprinting & sensing



Industrial use:

- ✓ Greenhouse gas and pollution
- ✓ Semiconductor manufacturing
- ✓ Pharmaceutical analysis

Defence and security:

- ✓ Threat detection (chemical, explosive)

Medical diagnostics:

- ✓ Breath analysis
- ✓ Tissue pathology
- ✓ Stem cell research

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Challenges of IR metrology

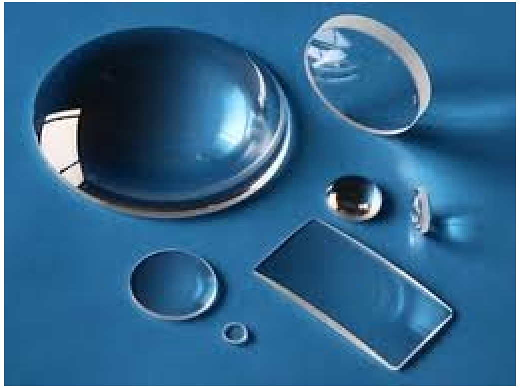
Capability gap: High cost and limited performance of existing IR-range spectral instruments

- Requires specialized IR-range optics
- Inferior performance of light sources and detectors
- High cost (~25.000-250.000)

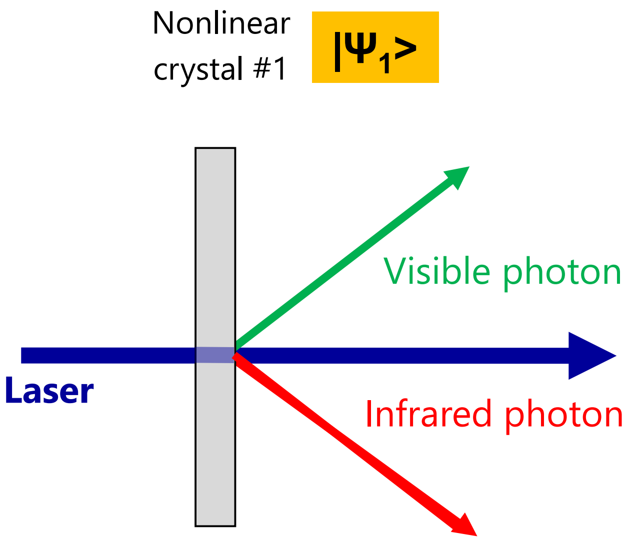
IR metrology with visible light?

Value proposition: exploit effects of quantum optics to measure IR properties using visible range equipment

- Well developed optical materials
- A variety of lasers and detectors
- Low-cost and efficient



Nonlinear interferometer w/ correlated photons



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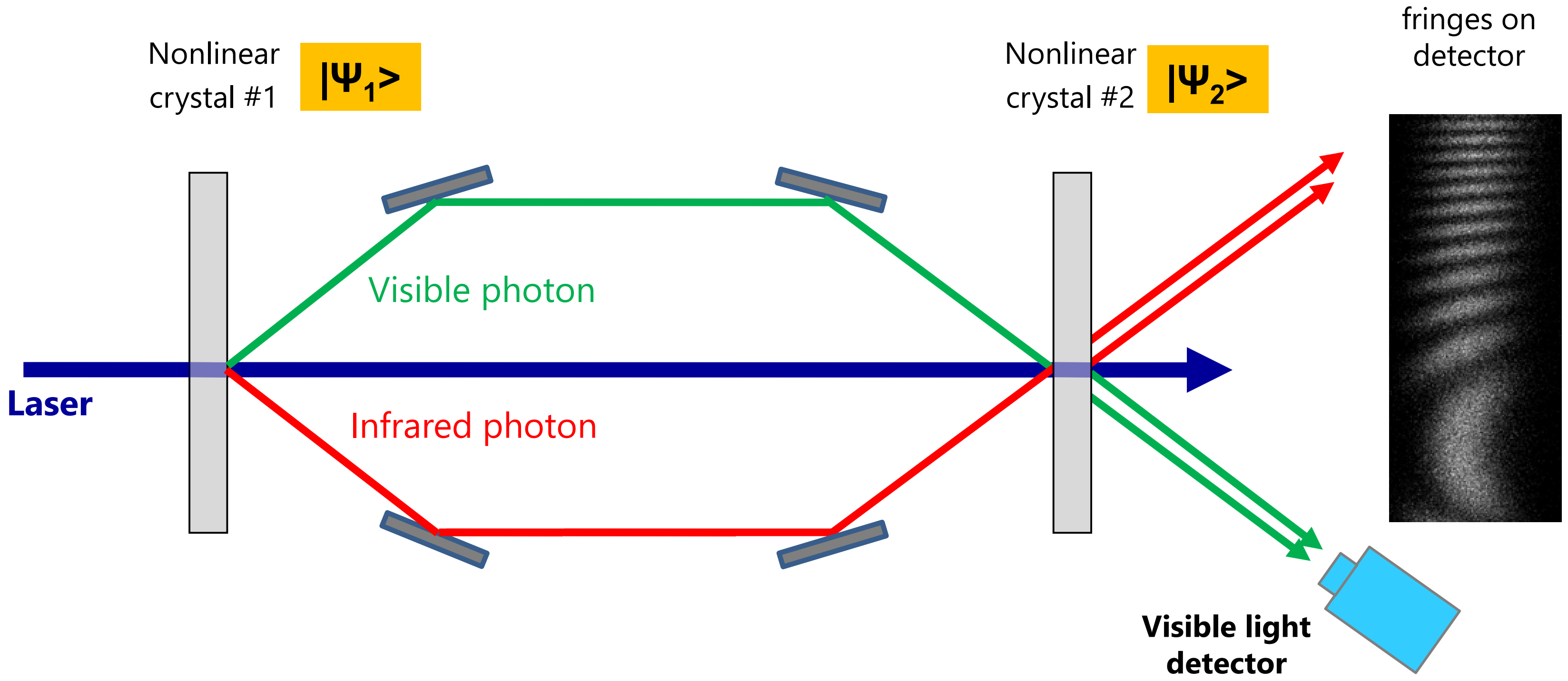

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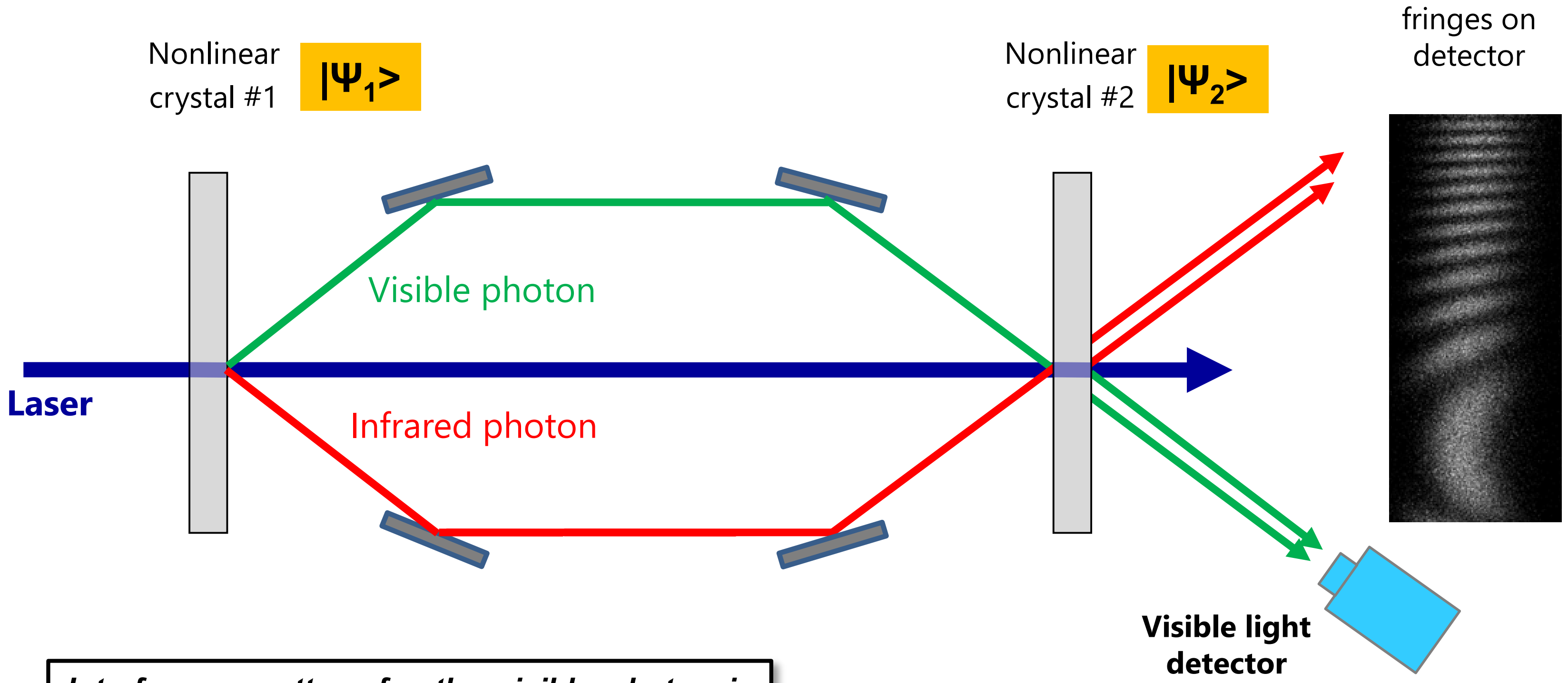

Interference pattern for the visible photon is affected by the absorption of the IR photon

$$|\Psi\rangle = |\Psi_1\rangle + |\Psi_2\rangle$$

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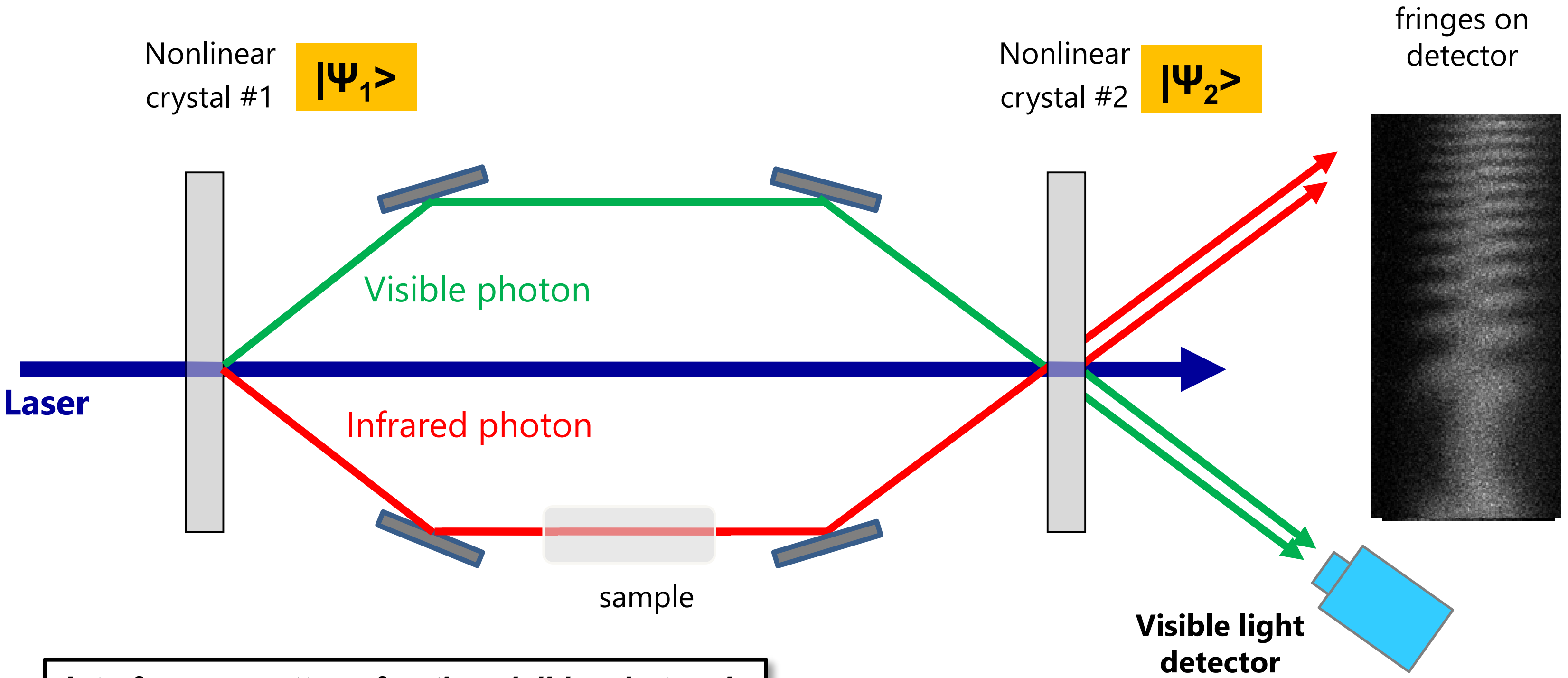

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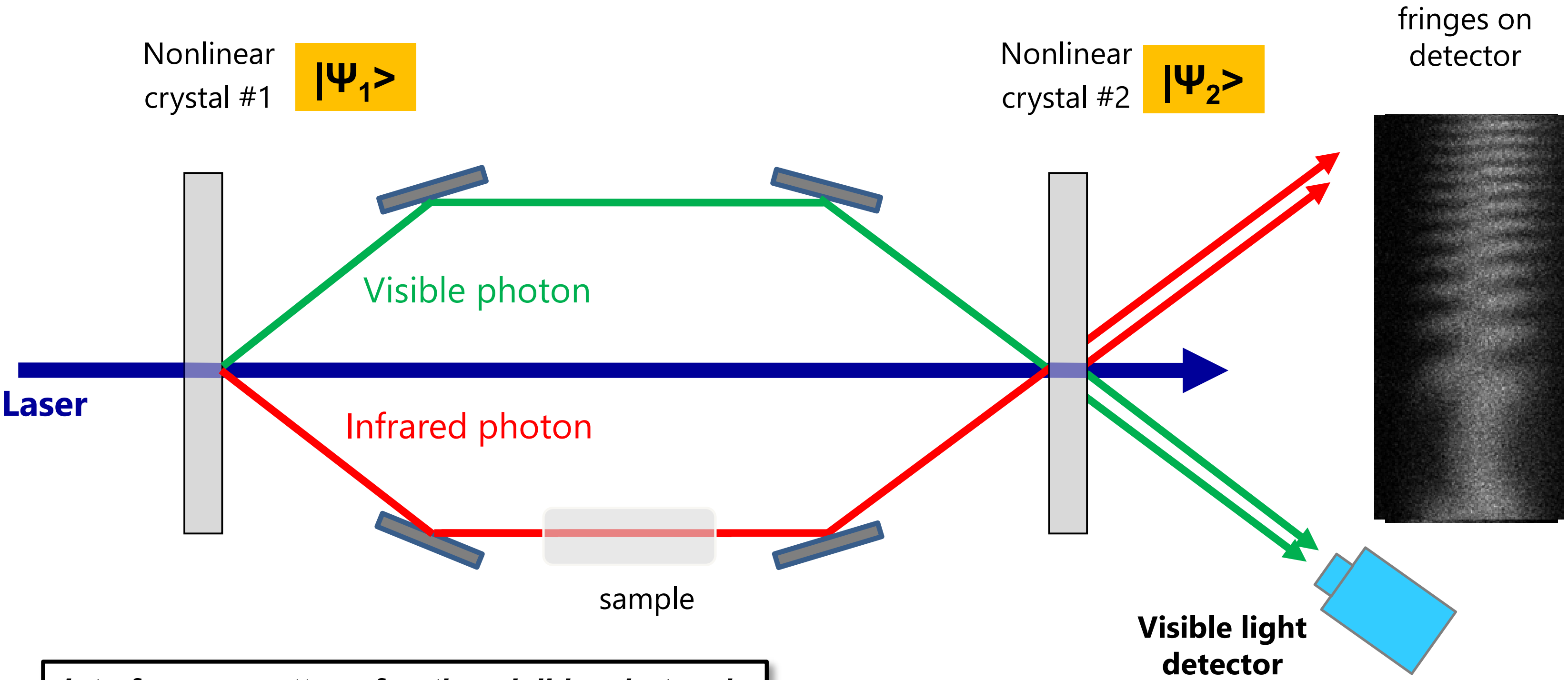

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$$|\Psi\rangle = |\Psi_1\rangle + |\Psi_2\rangle$$


news & views

QUANTUM OPTICS

Spooky spectroscopy

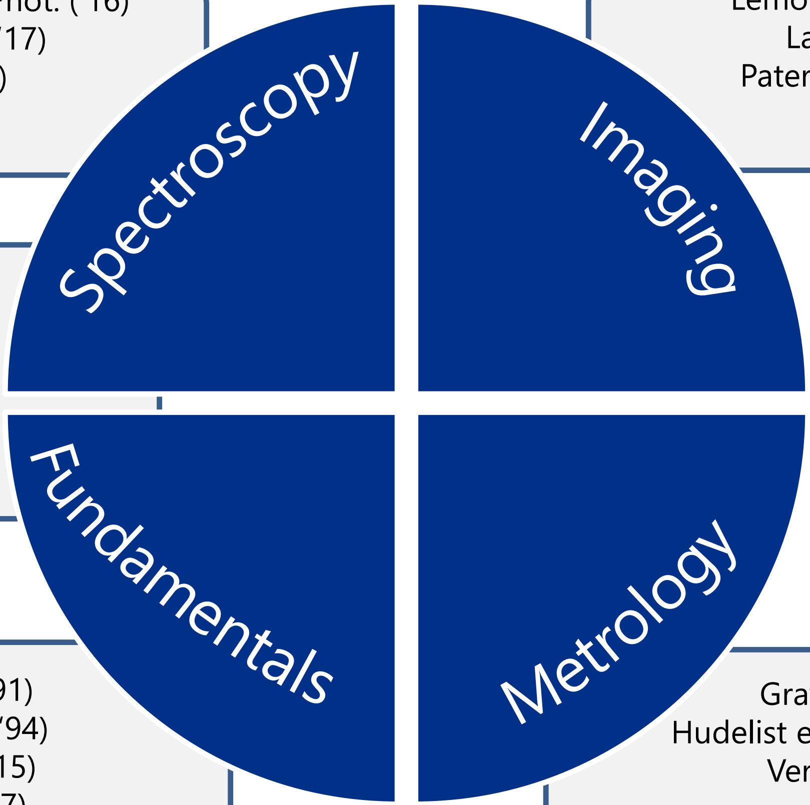
The quantum concepts of entanglement and interaction-free measurements are applied to spectroscopy to successfully sense carbon dioxide in air.

Jean-Pierre Wolf and Yaron Silberberg

Applications of NL interferometers

Kalashnikov et al Nat.Phot. ('16)
Paterova et al SciRep ('17)
Paterova et al NJP ('18)
....

Lemos et al Nature ('14)
Lahiri et al PRA ('15)
Paterova et al QST ('18)
....



Reviews:

Yurke et al PRA ('86)
Chekhova, Ou Adv in Opt & Phot ('16); Ou, Li APL Phot ('20)

Wang et al PRA ('91)
Herzog et al PRL ('94)
Heuer et al PRA ('15)
Lahiri et al PRA ('17)
....

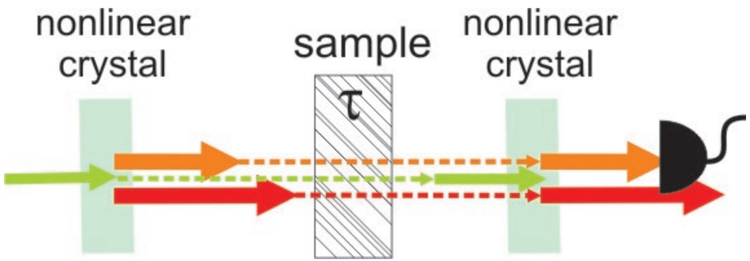
Grayson et al PRA ('94)
Hudelist et al NatComm ('14)
Vergyris et al APL ('20)
....

IR spectroscopy with visible light

- D Kalashnikov et al. *Nature Photonics* **10**, 98–101 (2016)
- A Paterova et al. *Scientific Reports* **7**, 42608 (2017)
- A Paterova et al. *New Journal of Physics* ***20****, 043015 (2018)*

Single-rail nonlinear interferometer

$$I_s \propto \mathrm{sinc}^2\left(\Delta k \cdot L/2\right)\left(1 + |\tau| \cdot \cos\left(\varphi_s + \varphi_i - \varphi_p\right)\right)$$



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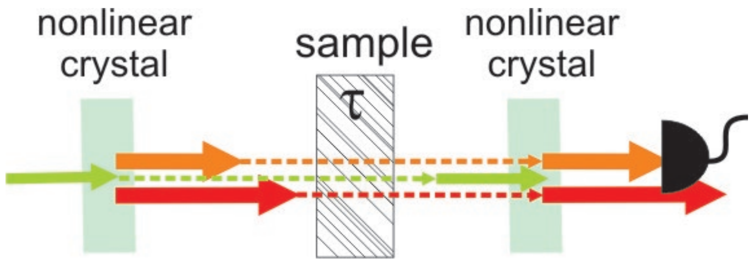

$$\varphi_p = \frac{2\pi \cdot n_p'\left(\lambda_p\right)}{\lambda_p} l'$$

$$\varphi_s = \frac{2\pi \cdot n_s'\left(\lambda_s\right)}{\lambda_s} l'$$

$$\varphi_i = \frac{2\pi \cdot n_i'\left(\lambda_i\right)}{\lambda_i} l' = ?$$

λ_p → UV/Visible; λ_s → Visible; λ_i → Infrared

- **Measurements of the IR properties of the material**
- **Tunable range of wavelengths**

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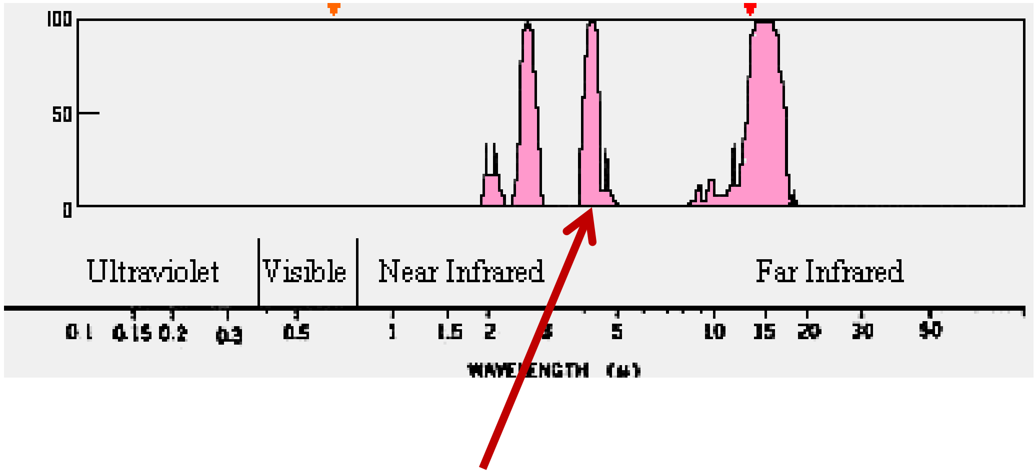
CO2 absorption

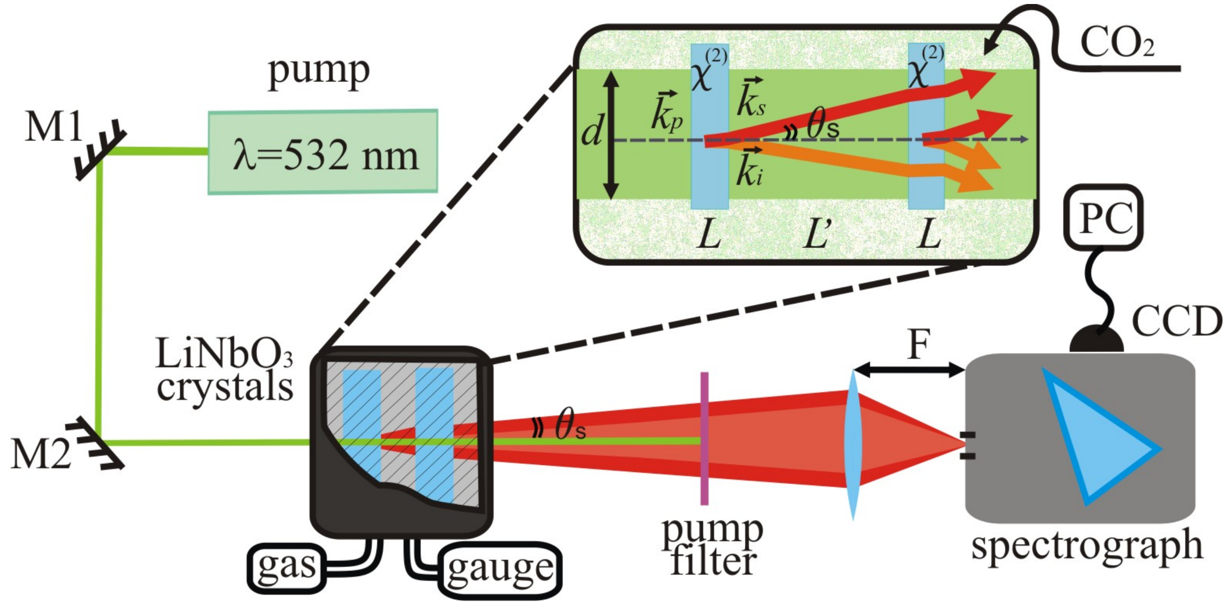


Studied media: CO_2 gas with absorption line @ 4.3 micron

λp=532nm ; λs=608nm ; λi=4.3 µm

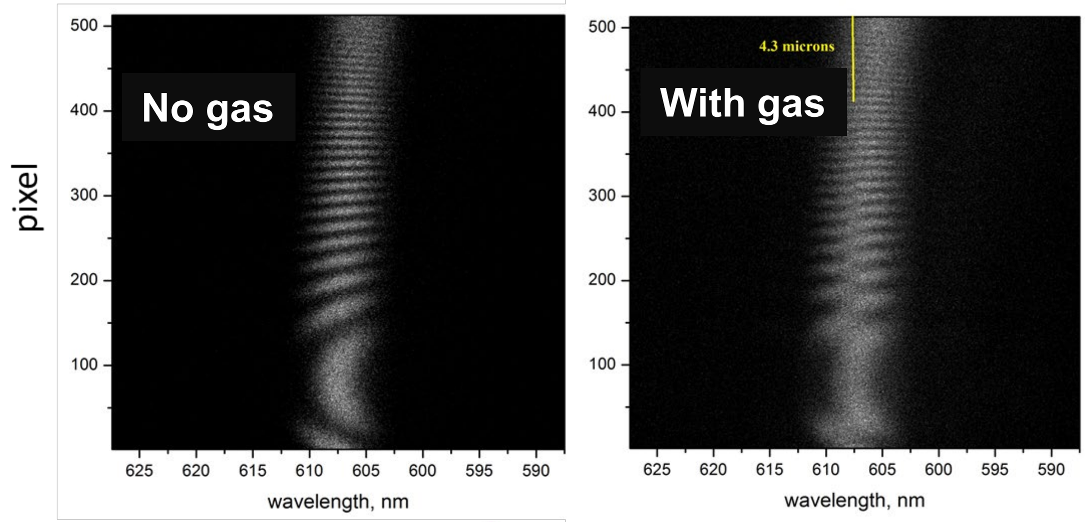
Source: wikipedia

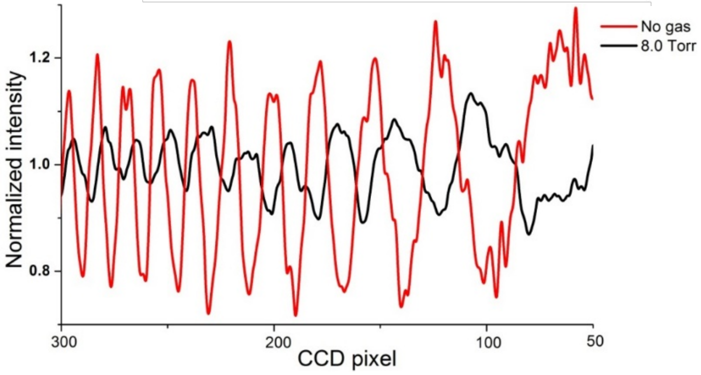
Experimental setup



D. A. Kalashnikov, A. V. Paterova, S. P. Kulik and L. A. Krivitsky,
«Infrared spectroscopy with visible light», *Nature Photonics*, **10**, 98–101 (2016).

Injecting the CO_2 gas





- Carbon dioxide absorption resonance **λ=4.3 μm**
- Detection wavelength in interferometer **λ=608nm**

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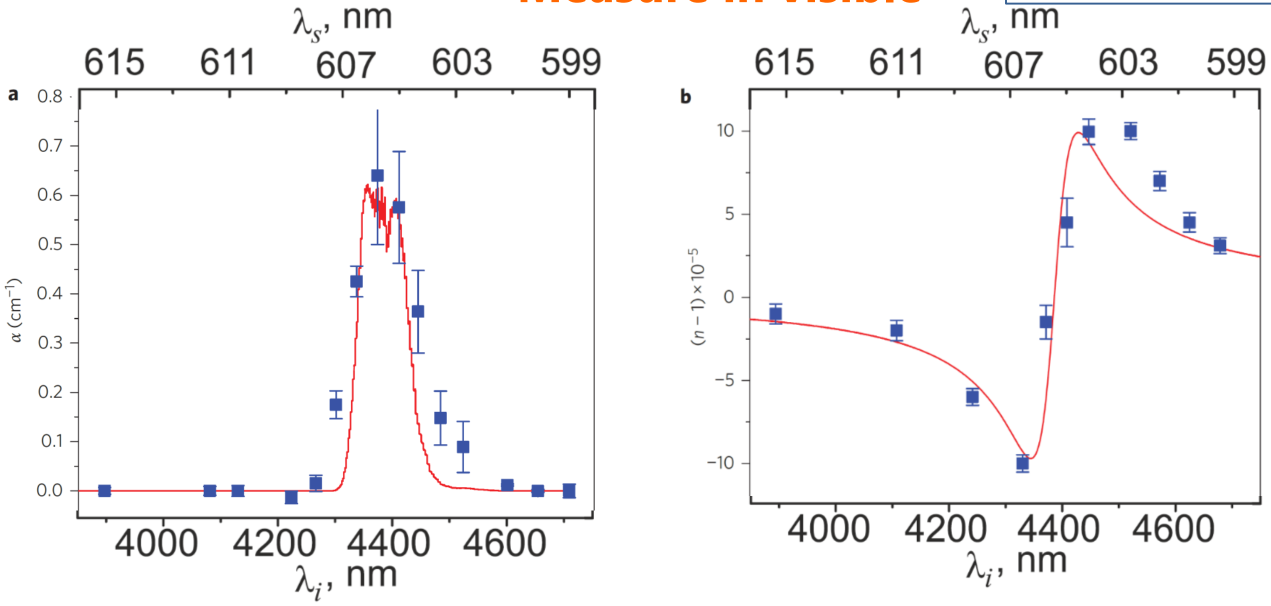
Results

- $\Delta n \sim 5 \cdot 10^{-6}$
- $\Delta\alpha \sim 0.02$ to $0.2\ cm^{-1}$

Measure in visible



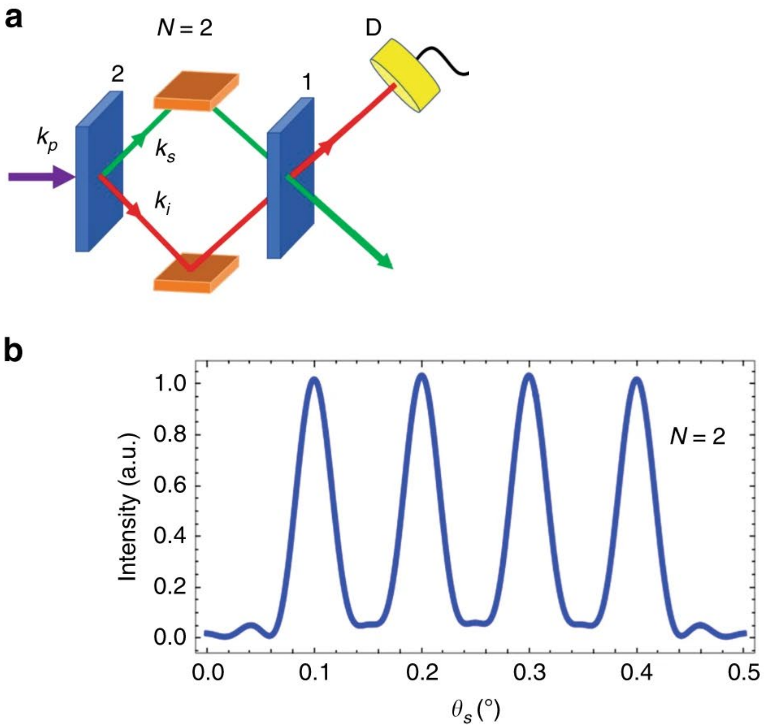
Properties of the sample in IR

Theoretical data: http://hitran.iao.ru

Nonlinear interference in crystal superlattices

- A Paterova, L. Krivitsky *Light: Science and Applications* 9, 82 (2020)
- D. Toa et al., *Quantum Science and Technology* (accepted) arXiv:2109.00690

Cascaded NL interferometer a.k.a. superlattice (2020)



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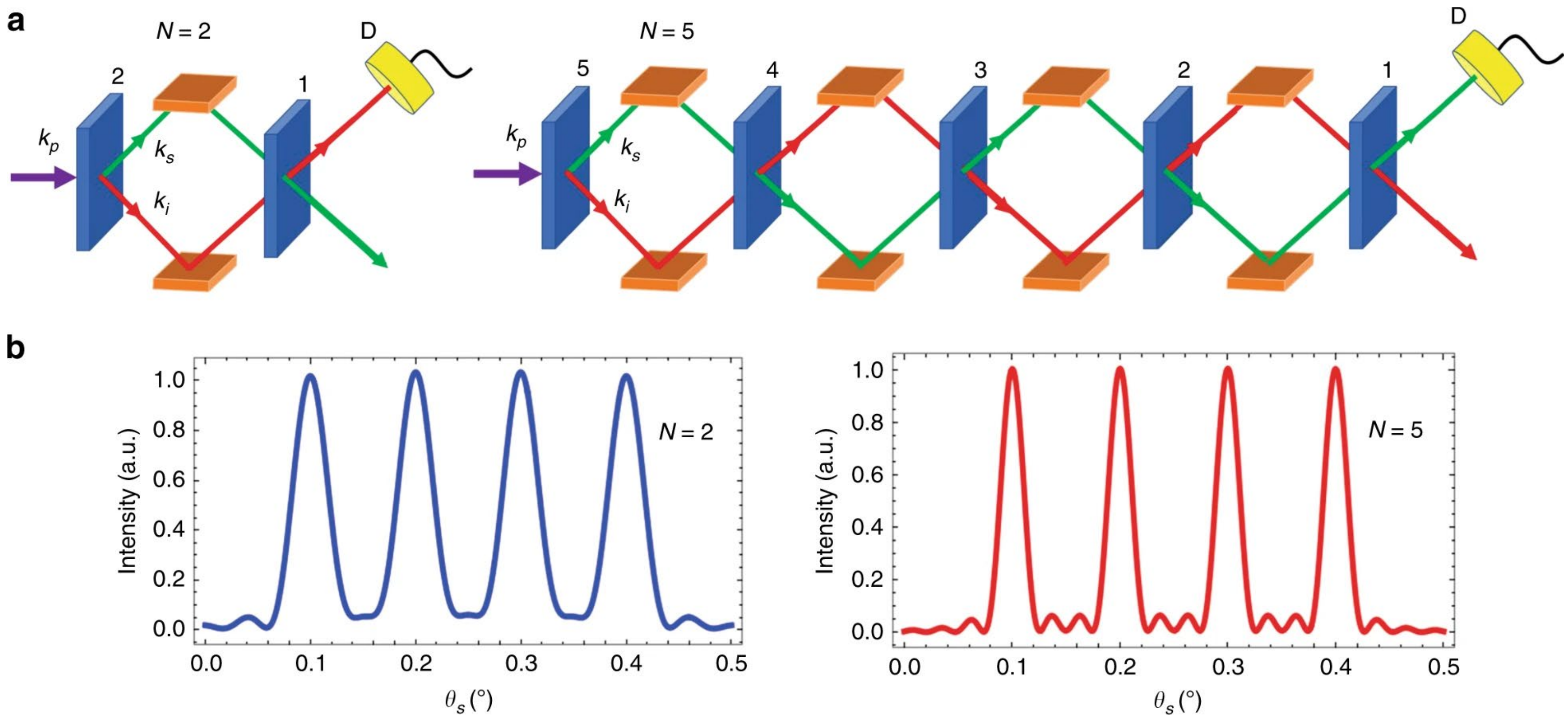

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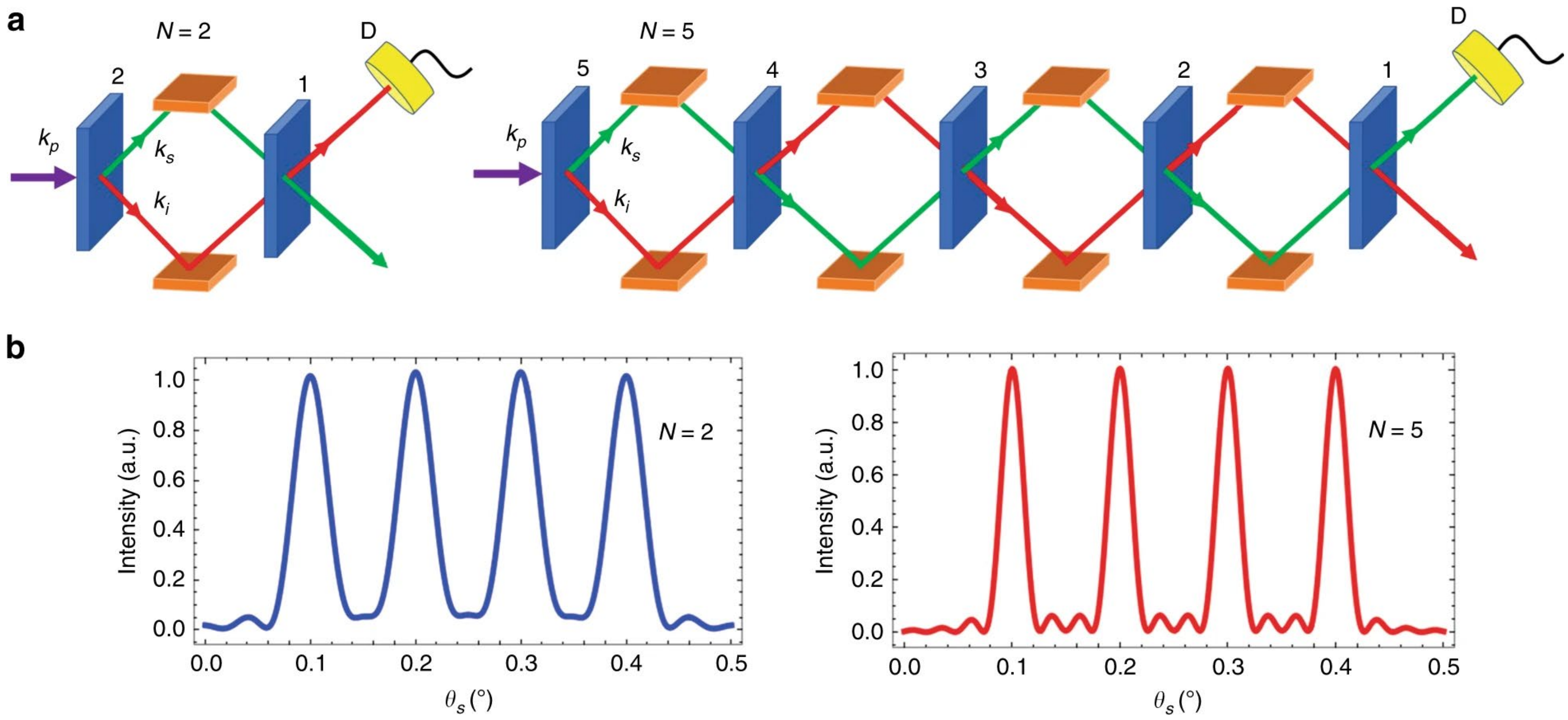
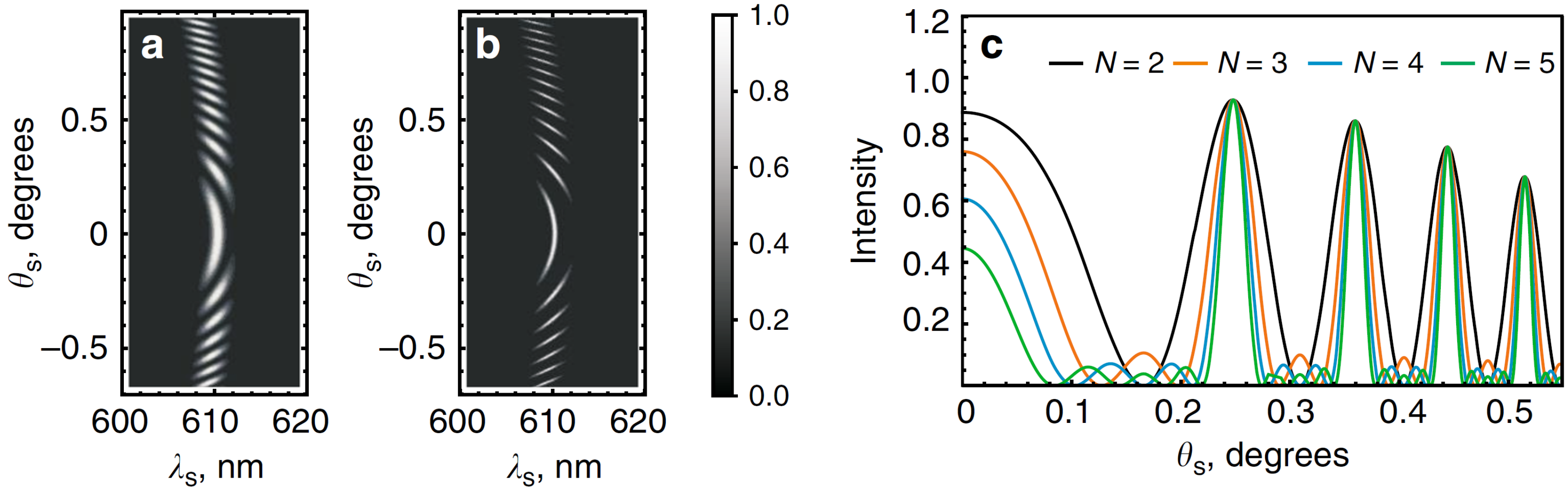


First theoretical proposal D Klyshko JETPh 1993

Adapted from K. E. Dorfman Light: Science & Applications 9, 123 (2020)

Interference fringes in superlattice



$$I_N(\omega_s, \theta_s) = |F|^2 \propto \left\{ \mathrm{sinc}\left(\frac{\Delta k l}{2}\right) \cdot \frac{\sin[N\phi/2]}{\sin[\phi/2]} \right\}^2$$

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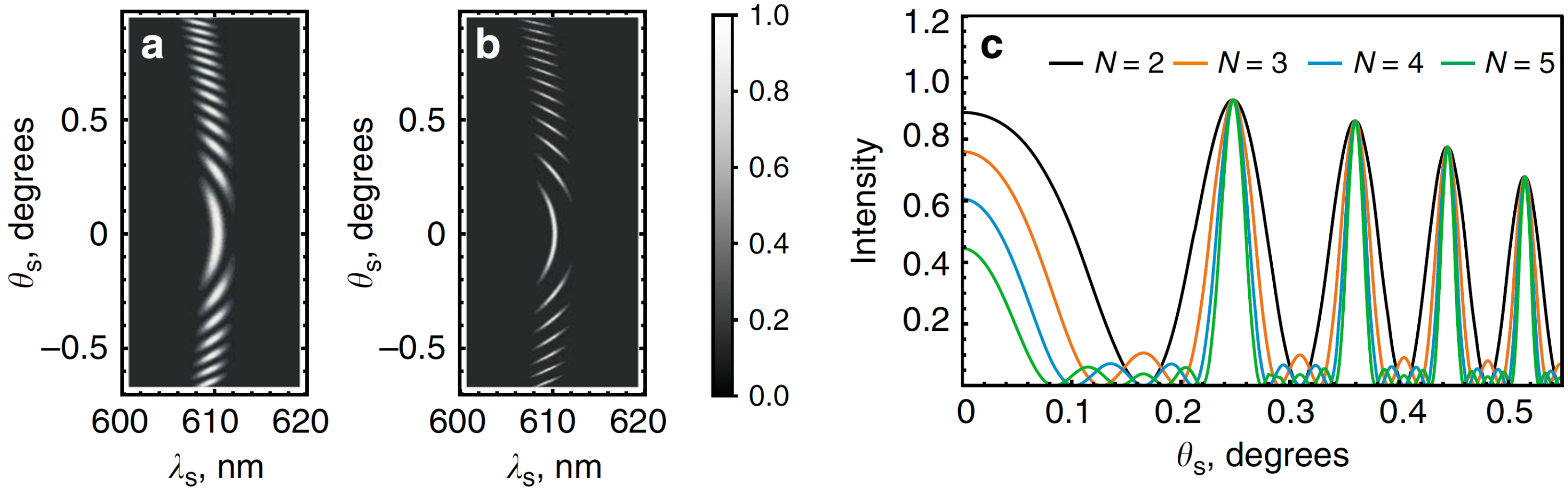

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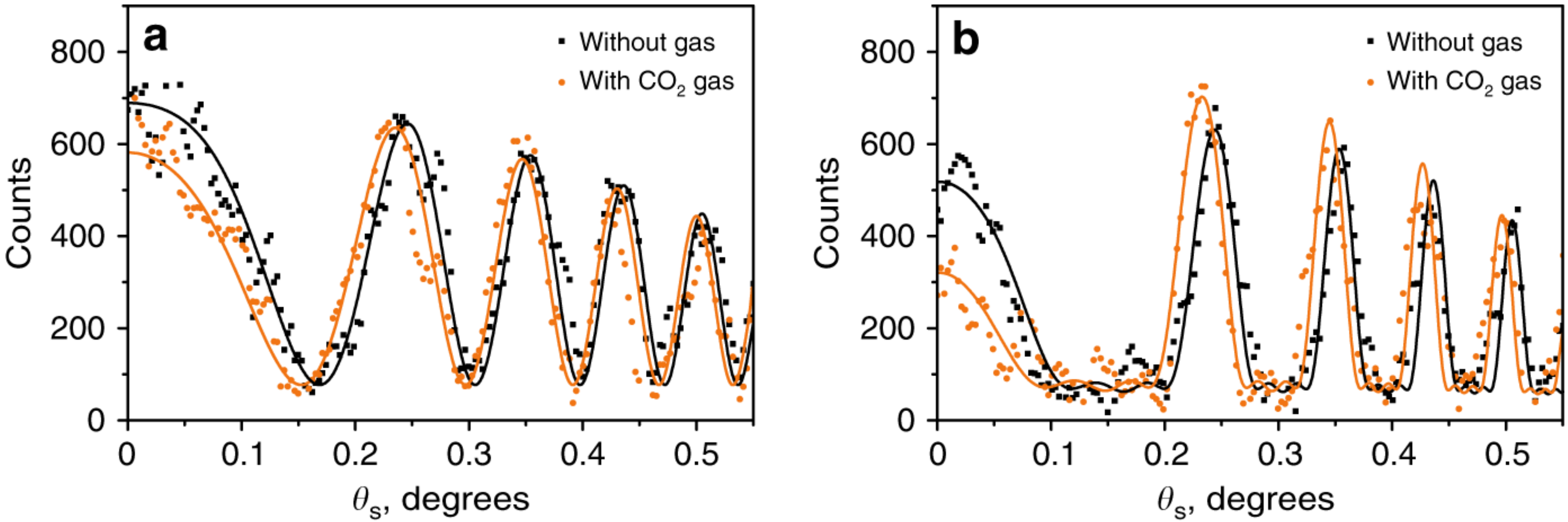
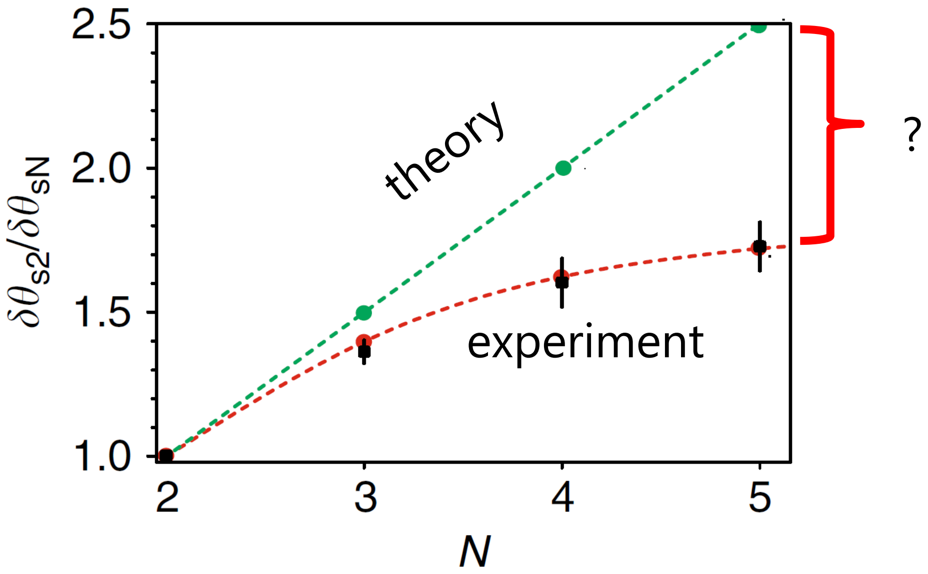
- Increased sensitivity
- Hard to realize experimentally

Measurement of the fringes



- 2-crystal interferometer: $\Delta\varphi_2 = -(0.167 \pm$ **0.015**$)\pi$
- 5-crystal interferometer$\Delta\varphi_5 = -(0.187 \pm$ **0.009**$)\pi$.

Scaling of the width of the fringes



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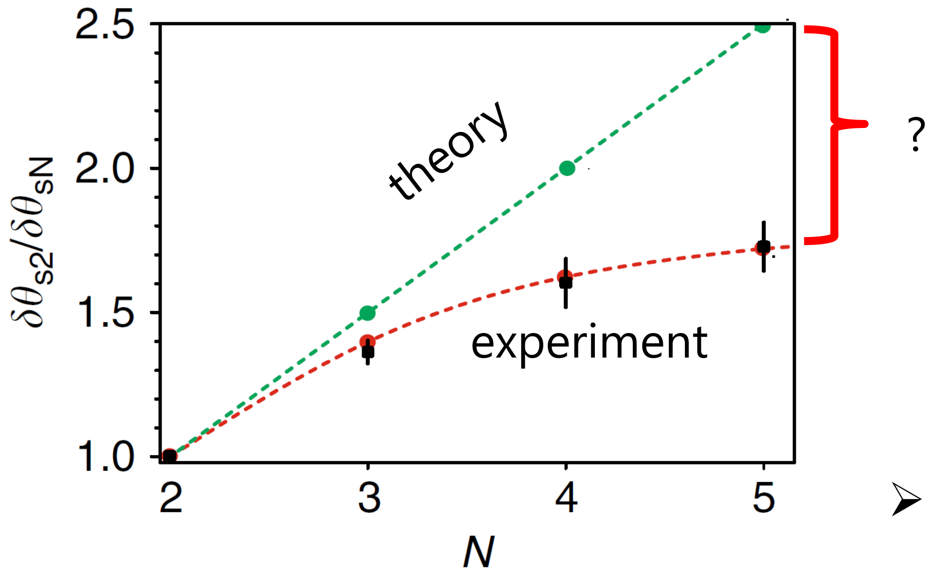
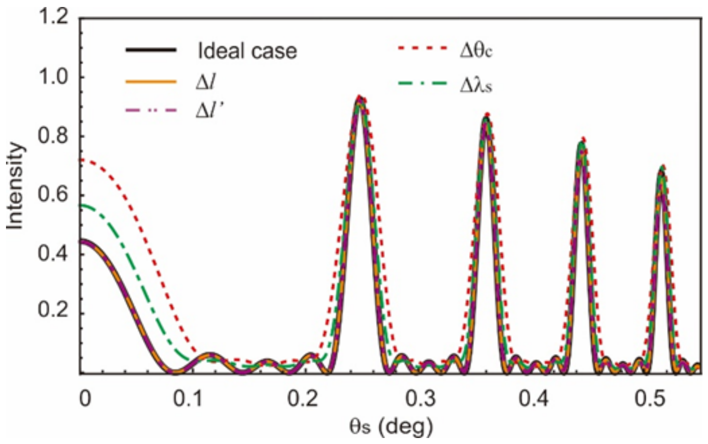


Sensitivity study



➢ Major factor: Uncertainty in crystal orientation

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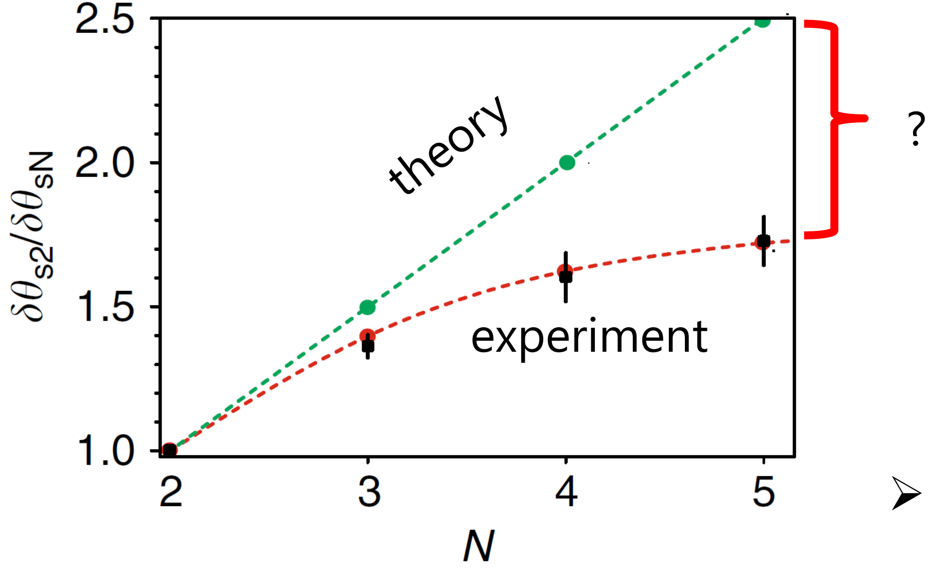

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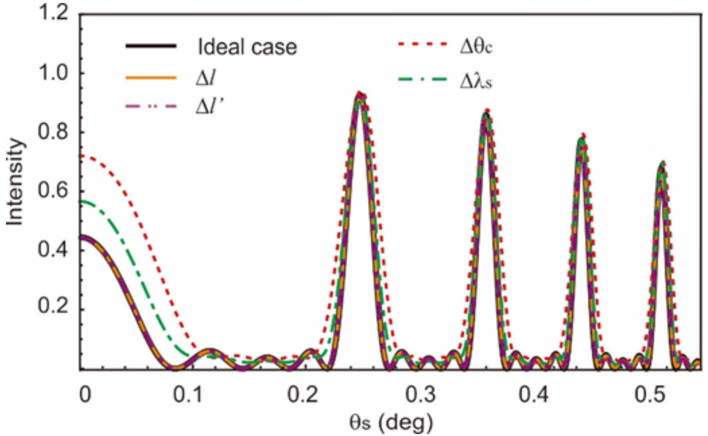
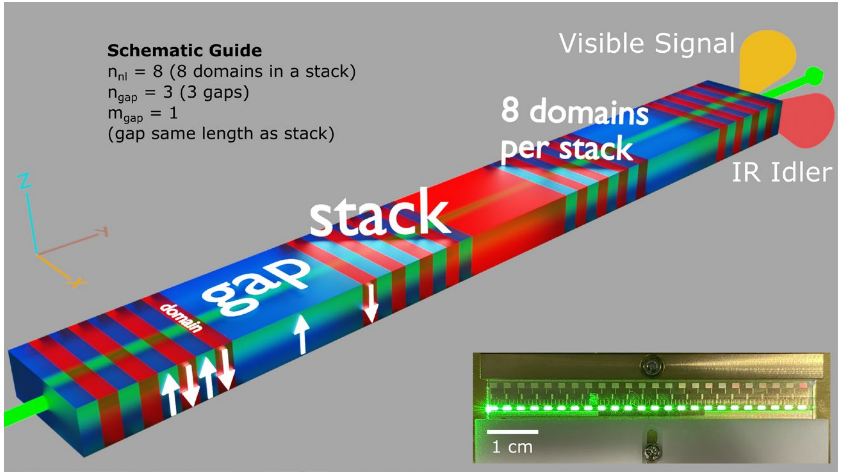
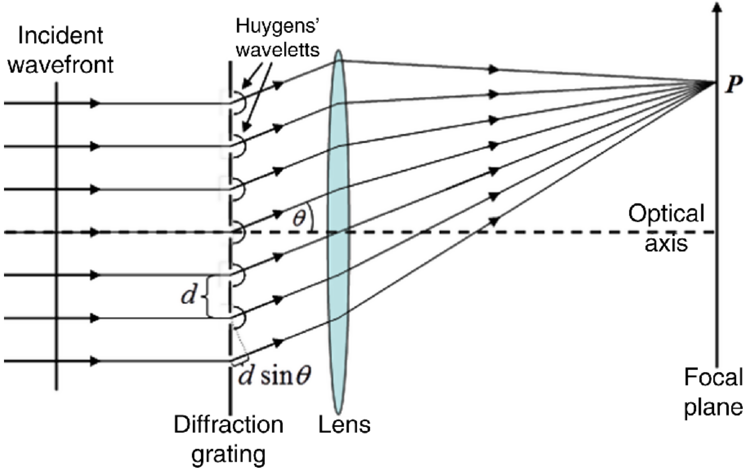


- Major factor: Uncertainty in crystal orientation

Price to pay: stronger dependence on the uncertainty of the experimental parameters

Bi-PPLN Superlattice





Concept

- Consider the stacks as individual emitters
- Interference occurs between stacks
- Like classical diffraction

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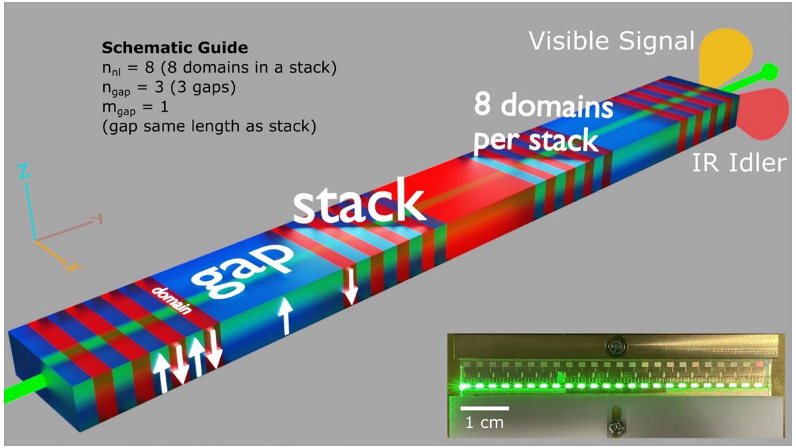
Schematic of biPPLN Superlattice



$$\lambda_{pump} = 532\, nm$$
$$l_{domain} = 5.16\, \mu m$$
$$l_{stack} = n_{nl} \times l_{domain}$$
$$l_{gap} = m_{gap} \times l_{stack}$$

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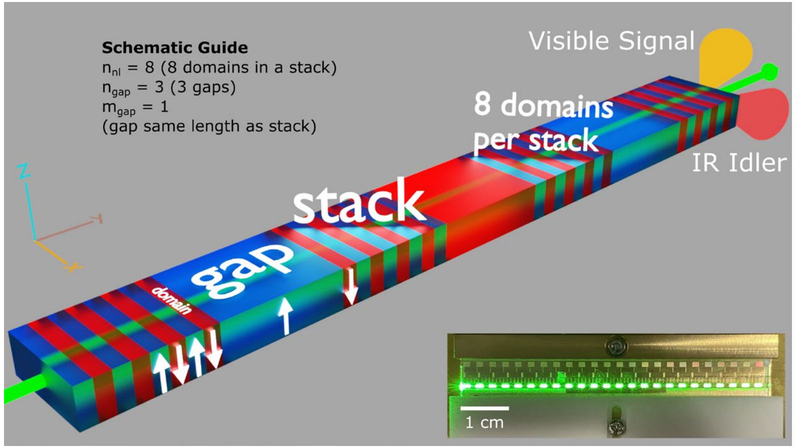

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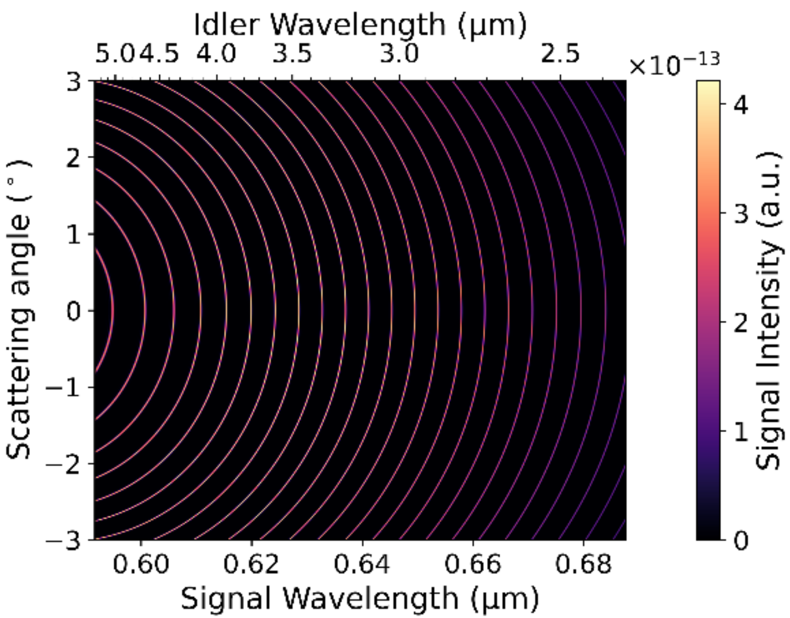
$$n_{nl} = 4,\ n_{gap} = 16, m_{gap} = 32$$



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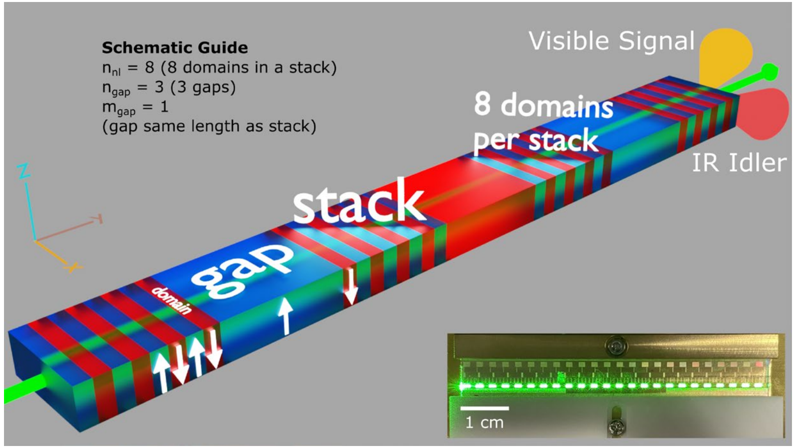

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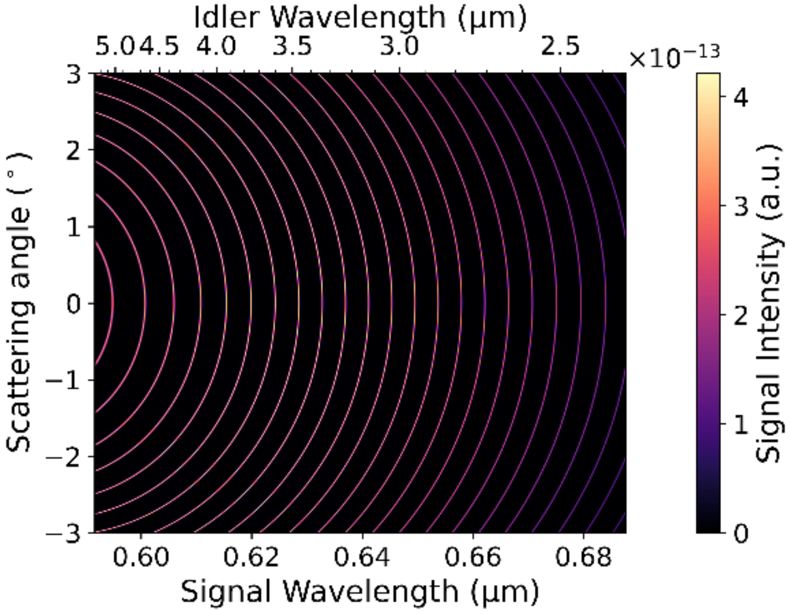

Customizable comb-like IR spectra

Exploring the parameter space

Design	Design Parameters		
	n_{nl}	n_{gap}	m_{gap}
1	16	**85 (!)**	8
2	64	**21**	8
3	16	**23**	32

λ_{pump} = 532 nm (CW)
λ_{signal} ~ 647 nm; λ_{idler} ~ 3 μm

Crystal Physical Dimensions:
63.5 mm (L) × 8.2 mm (W) × 0.5 mm (H)

Toa, Z.S., A.V. Paterova, and L.A. Krivitsky, *Broadband diffraction of correlated photons from crystal superlattices. Quantum Science and Technology* **arXiv preprint arXiv:2109.00690**, 2021

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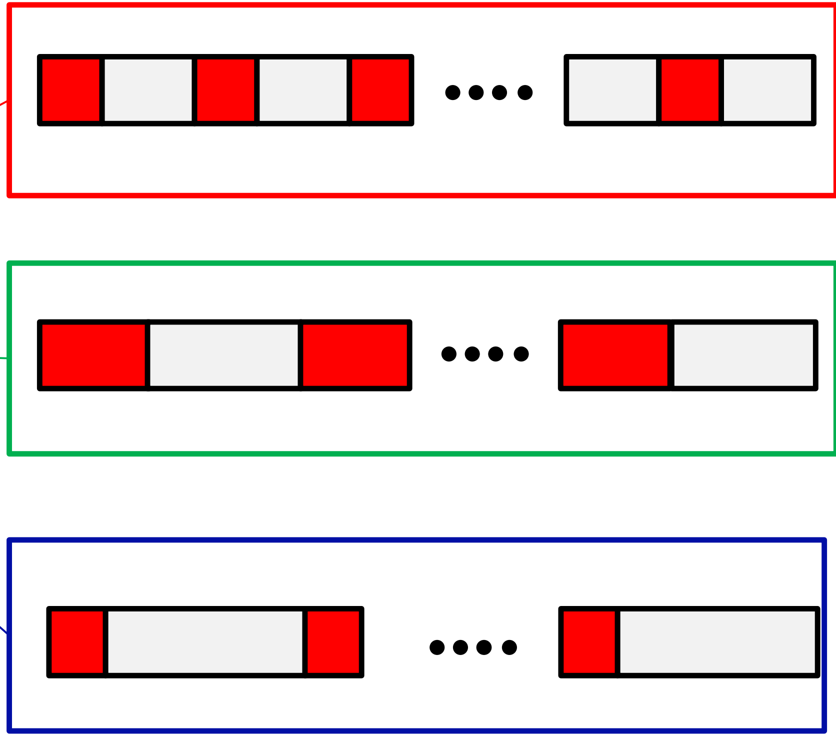

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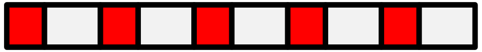
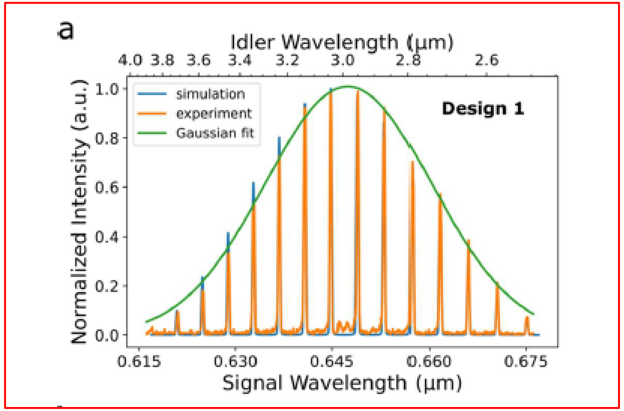
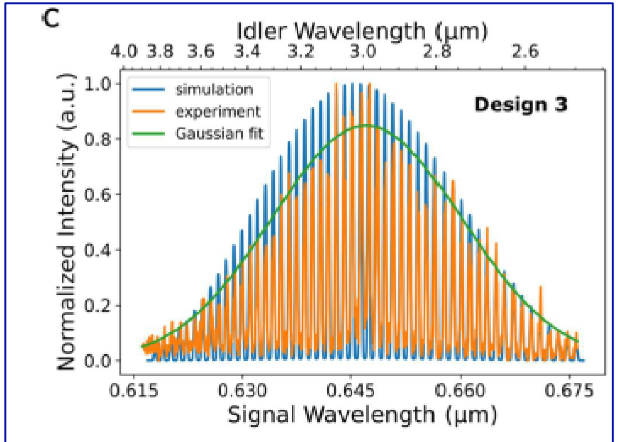
Results: combs

Design #1





Design #3



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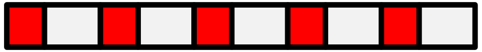
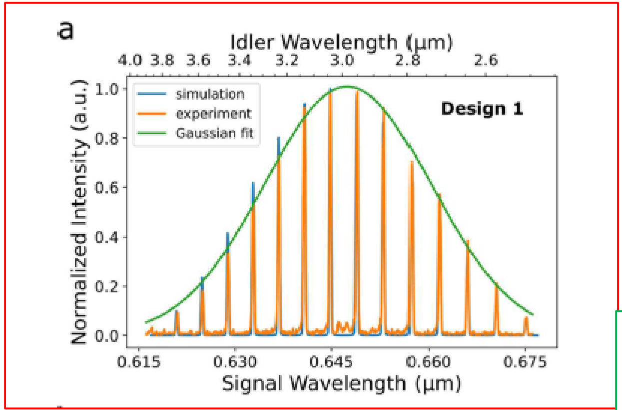
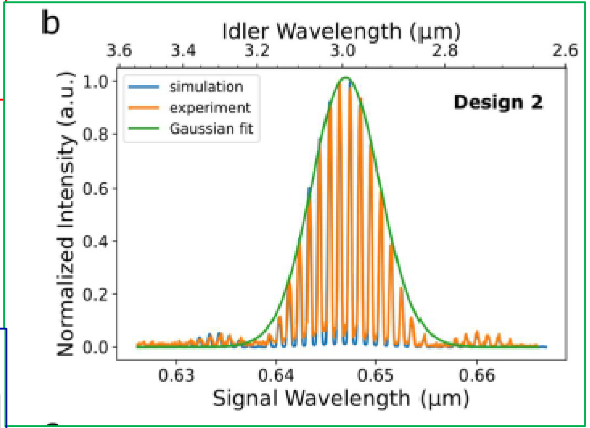
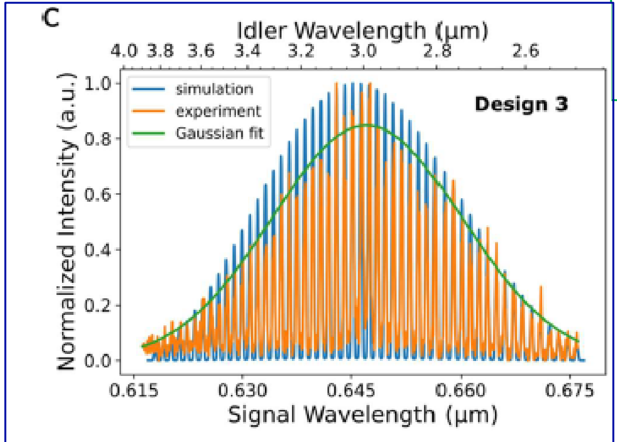


Design #2

Design #3







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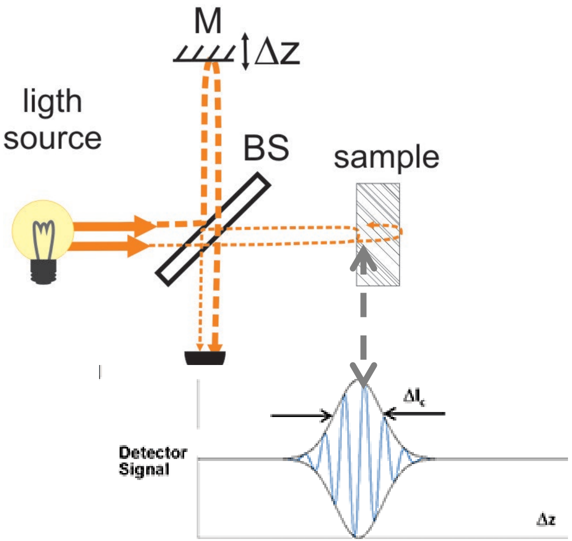
IR optical coherence tomography

- A Paterova et al. *Quantum Science & Technology* 3, 025008 (2018)

Optical coherence tomography (OCT)



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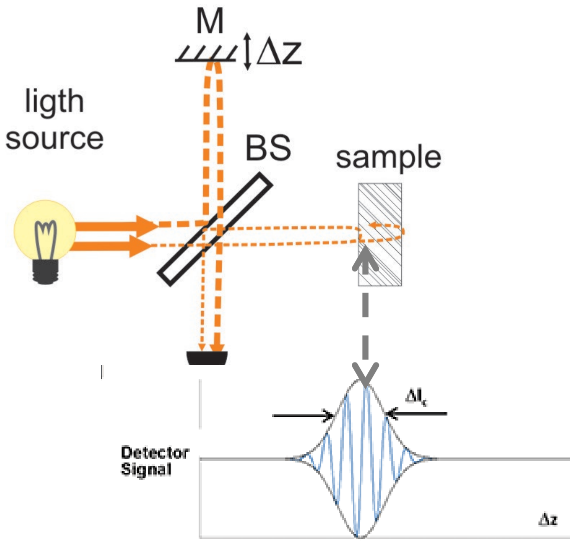
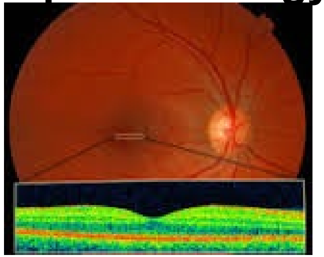
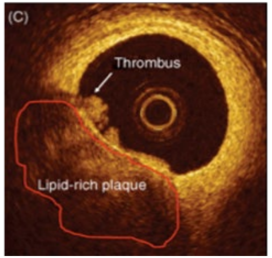


ophthalmology



cardiology



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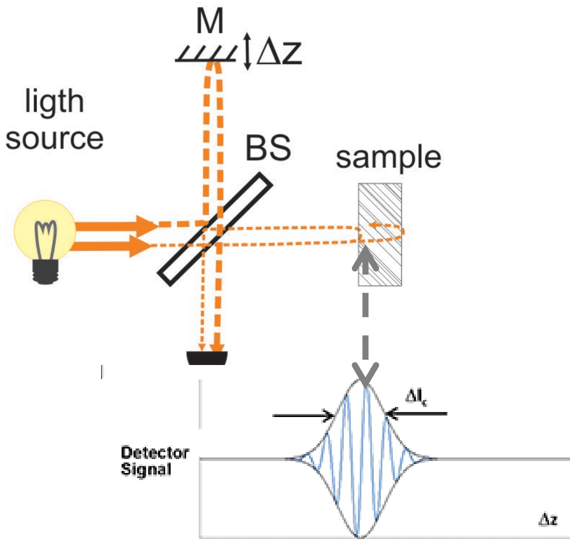
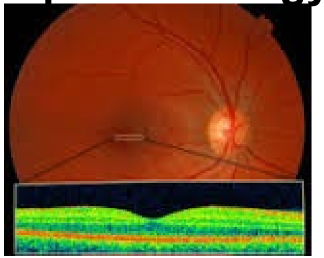


Well developed for :

- ✓ 850 nm
- ✓ 1300 nm
- ✓ 1500 nm

ophthalmology



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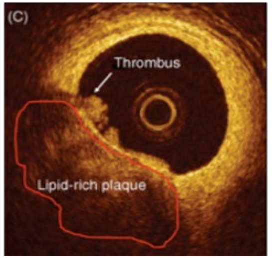
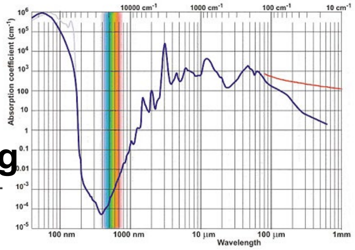
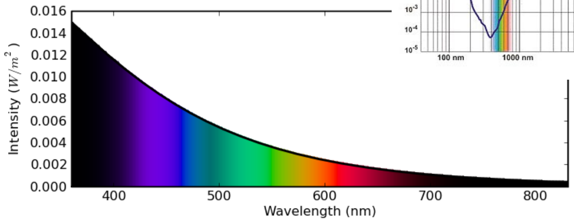
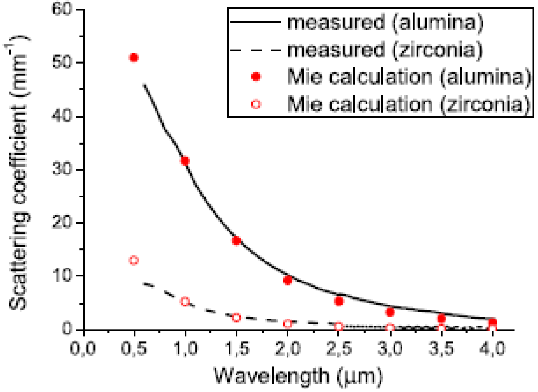


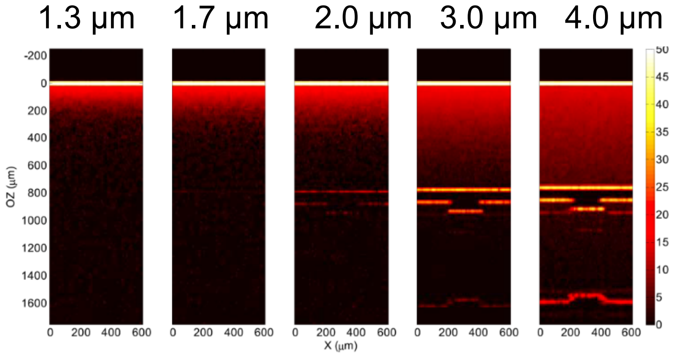
Water absorption



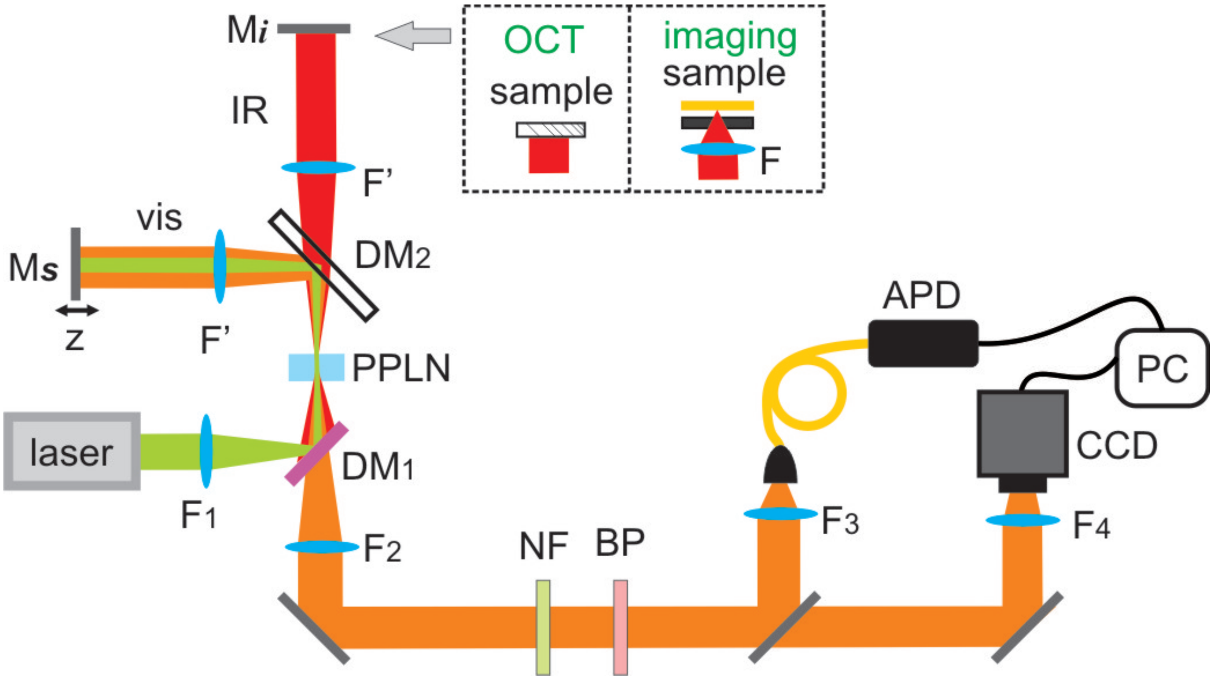
Rayleigh scattering





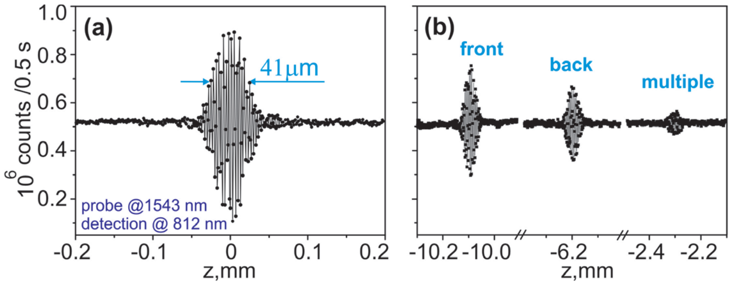


R. Su et al, Perspectives of mid-infrared optical coherence tomography for inspection and micrometrology of industrial ceramics, Opt. Exp. 22(13), 15804-19 (2014)



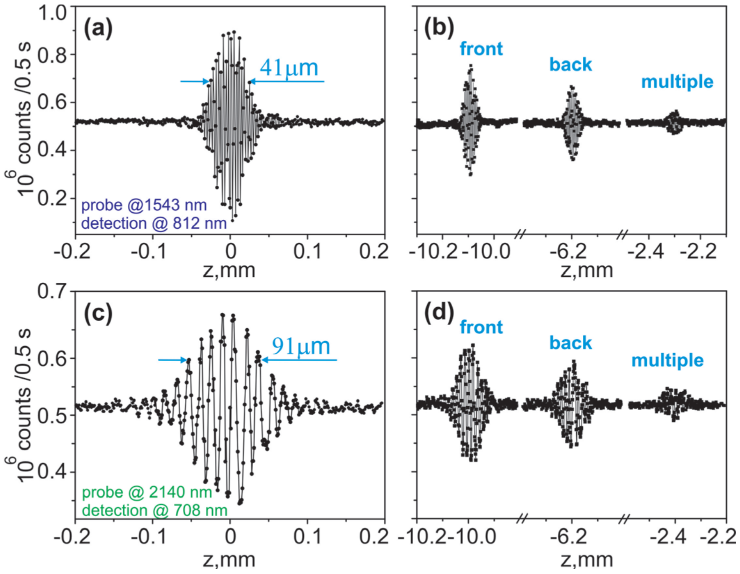
A. Paterova, et al "Tunable Optical Coherence Tomography in the Infrared Range Using Visible Photons", *Quantum Science and Technology* **3** 025008 (2018)

Results: axial scans



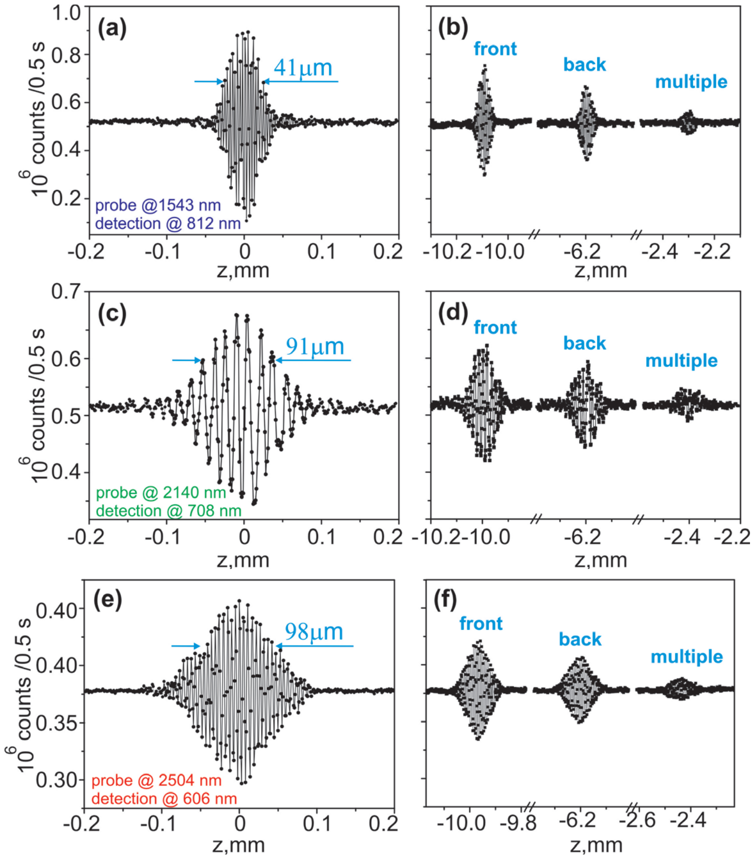
Silicon window

Results: axial scans



Silicon window

Results: axial scans



Silicon window

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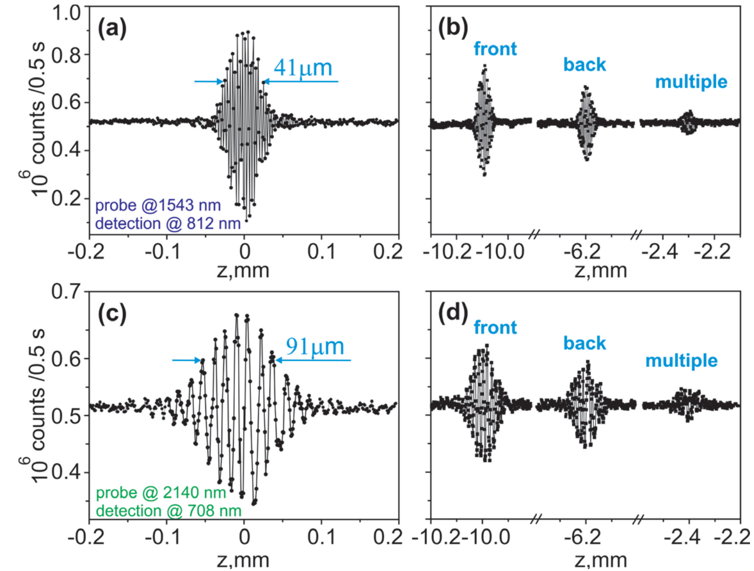
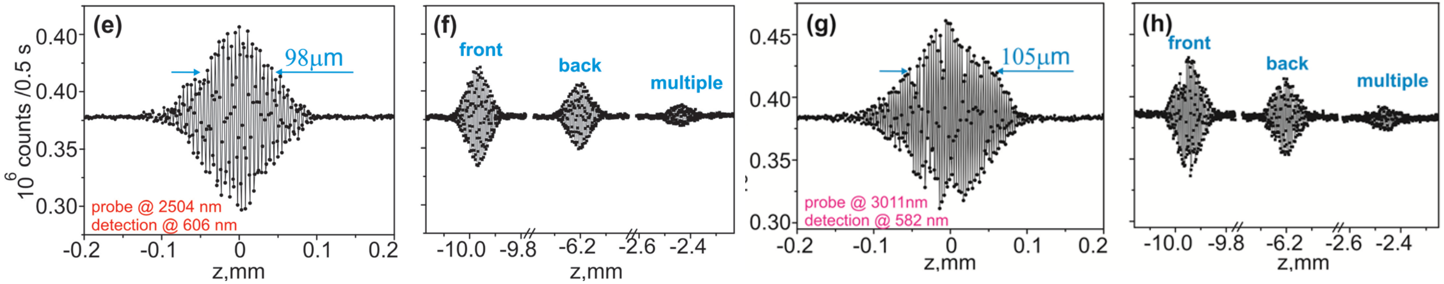




Silicon window

•All measurements with the same configuration

CREATING GROWTH, ENHANCING LIVES

Wide field hyperspectral imaging

- A Paterova et al *Science Advances*, 6, 44, eabd0460 (2020);
- A Paterova et al *Appl. Phys. Lett.* 117, 054004 (2020);
- A Paterova et al *Nanophotonics* 10 (6), 1775-1784 (2021)

Conventional IR imaging techniques

- ✓ IR imaging over wide range of wavelengths
- ✓ Measurement of chemical maps
- ✓ High resolution

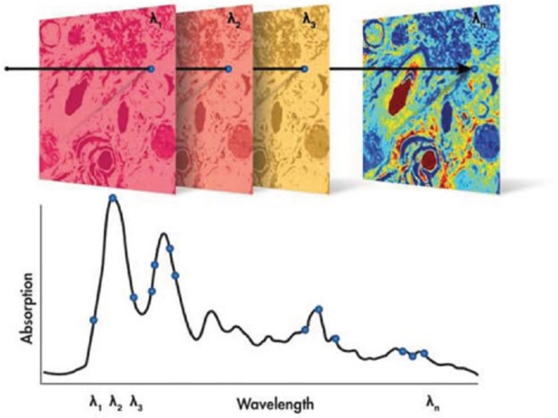
BRUKER

ThermoFisher SCIENTIFIC

SHIMADZU

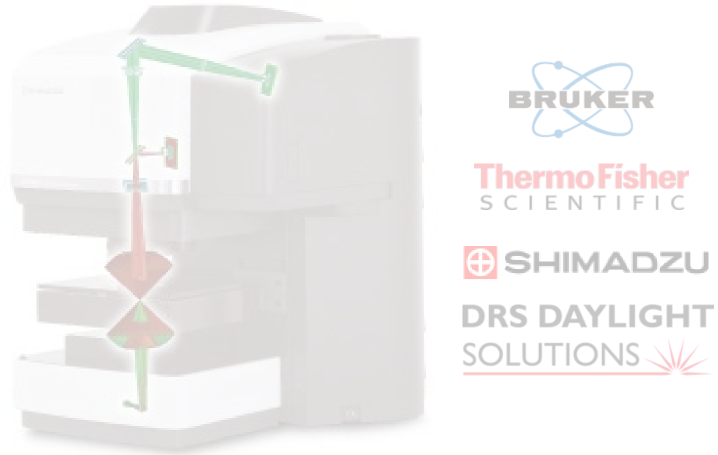
DRS DAYLIGHT SOLUTIONS

- x IR array detectors =>expensive
- x Often point by point imaging =>slow
- x Cryogenically cooled
- x Dual use => EC restrictions



CREATING GROWTH, ENHANCING LIVES

Conventional IR imaging techniques



- ✓ IR imaging over wide range of wavelengths
- ✓ Measurement of chemical maps
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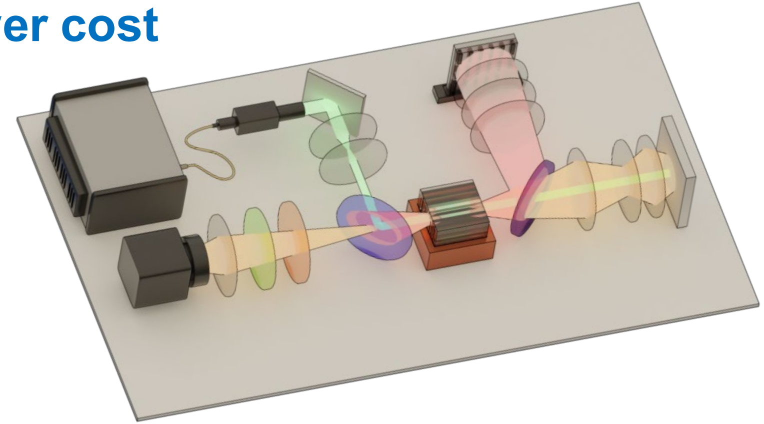
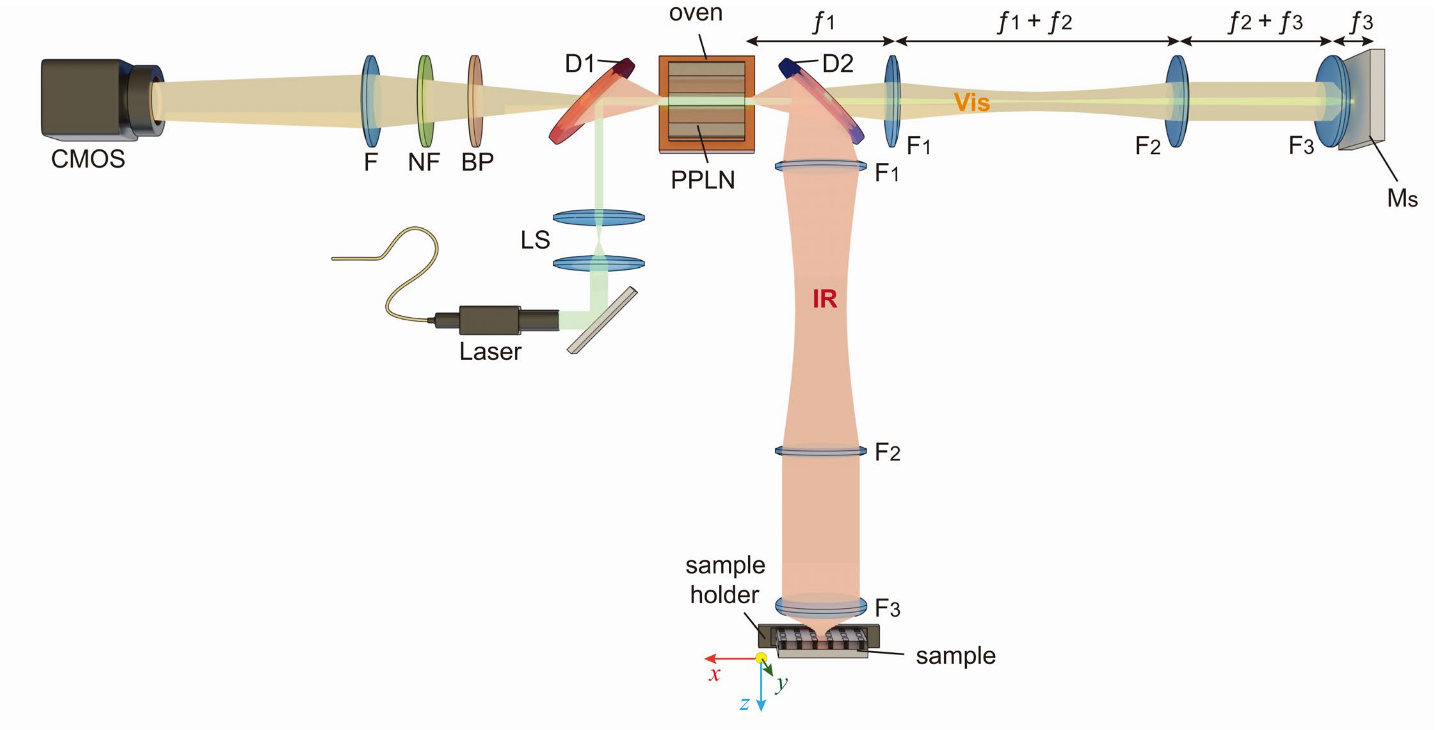


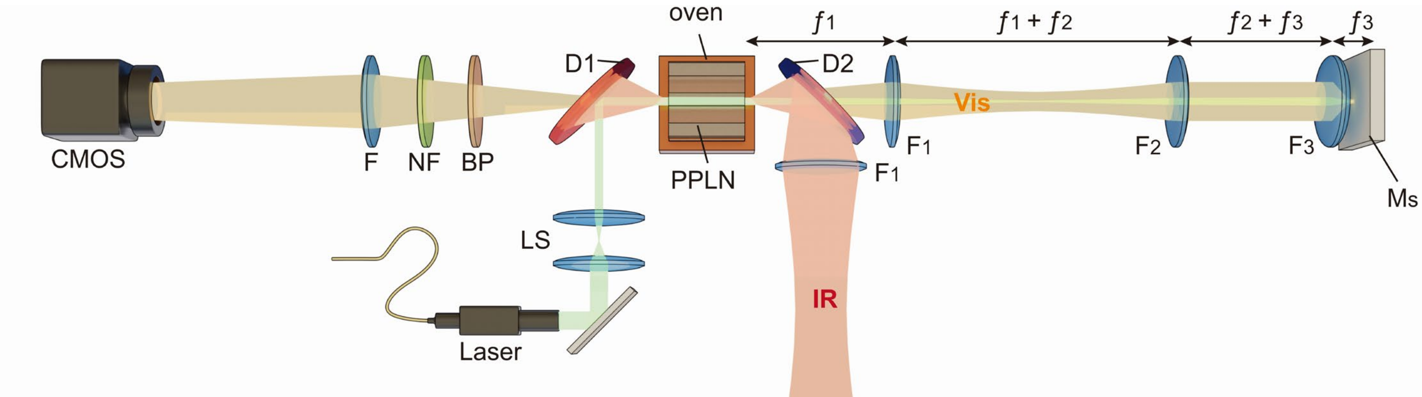
- ✓ Visible range laser and camera => lower cost
- ✓ Wide field imaging => faster
- ✓ Room temperature operation
- ✓ No EC components

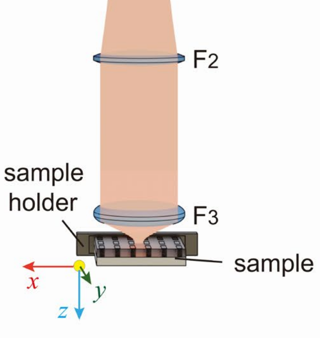
CREATING GROWTH, ENHANCING LIVES

Experimental setup

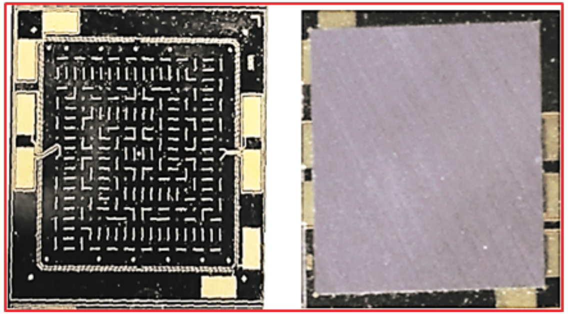


Experimental setup

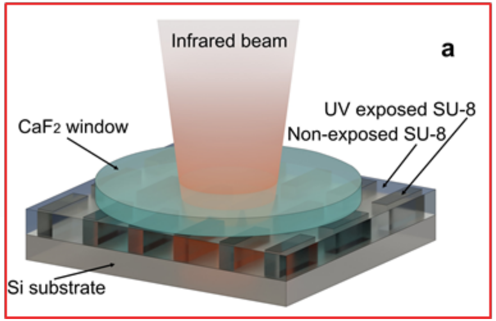




Imaging through opaque layer



Hyperspectral imaging



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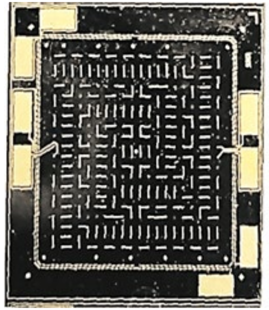
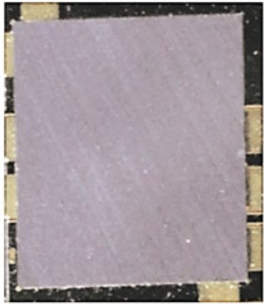
Quality control of silicon chips





A Paterova et al Appl. Phys. Lett. **117**, 054004 (2020) (Editor's Pick);

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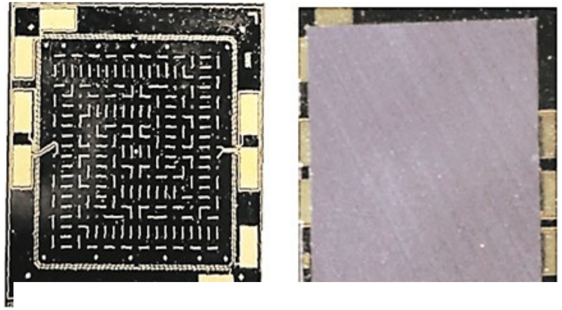
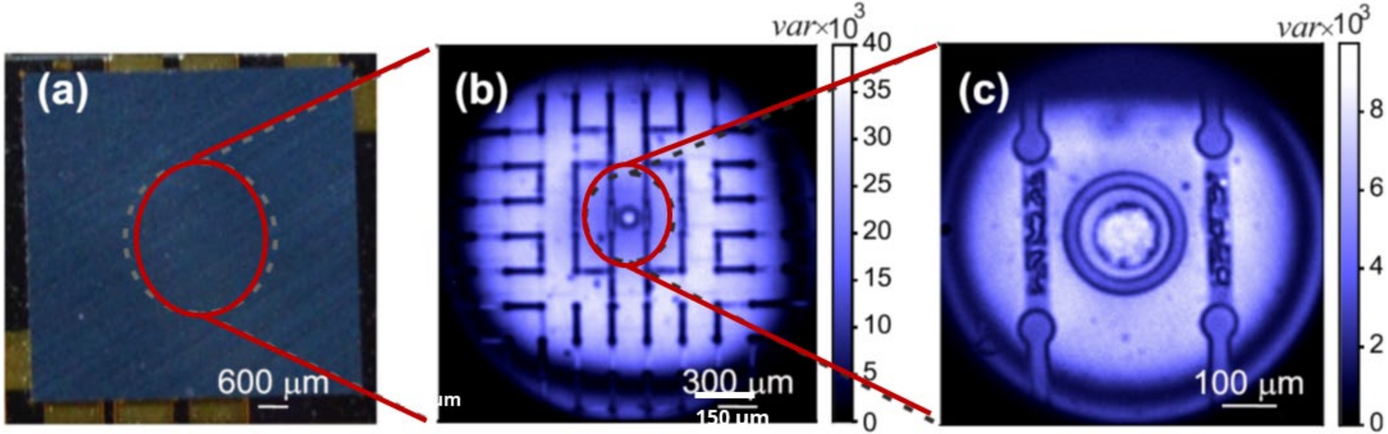
Quality control of silicon chips



- ✓ Imaging at 1550 nm with detection at 810 nm
- ✓ Fast readout of the system ~ 1 min
- ✓ Adjustable magnification
- ✓ Achieved 2 µm spatial resolution

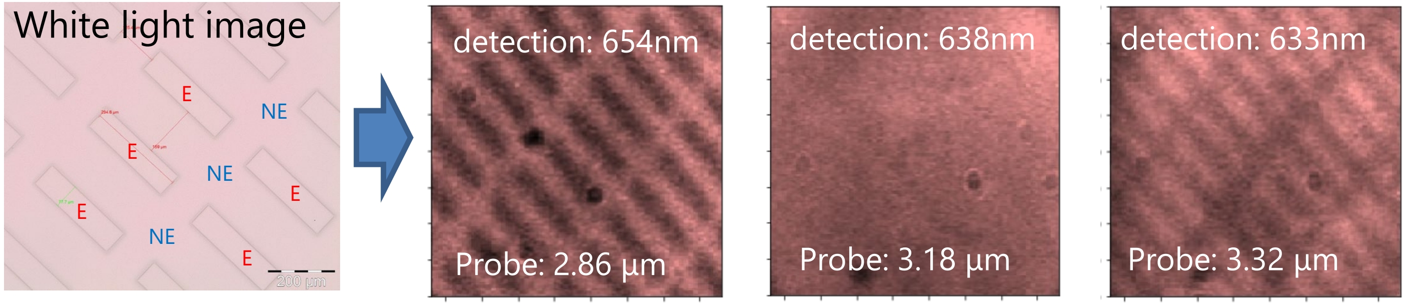


Wide field imaging through opaque Silicon layer

A Paterova et al Appl. Phys. Lett. **117**, 054004 (2020) (Editor's Pick);

CREATING GROWTH, ENHANCING LIVES

Hyperspectral microscopy



A Paterova et al *Science Advances*, 6, 44, eabd0460 (2020)

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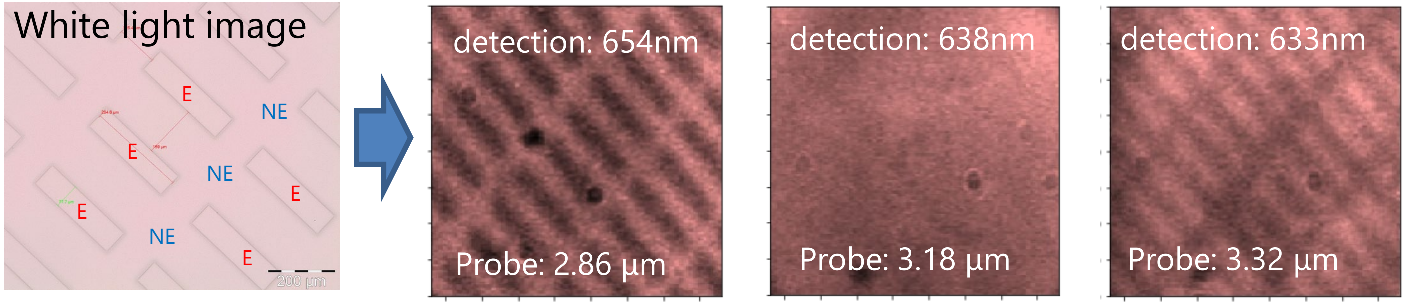
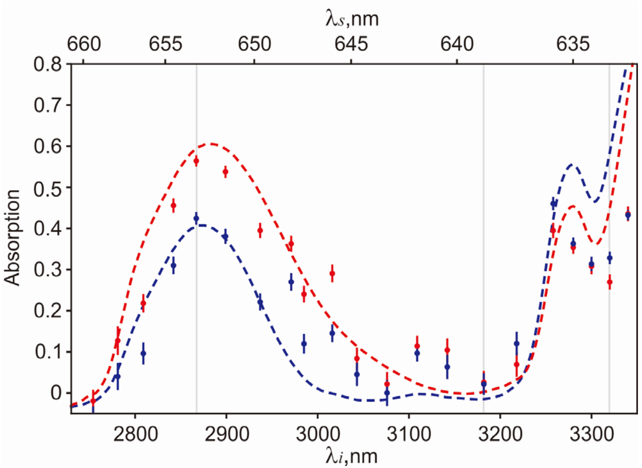
Hyperspectral microscopy





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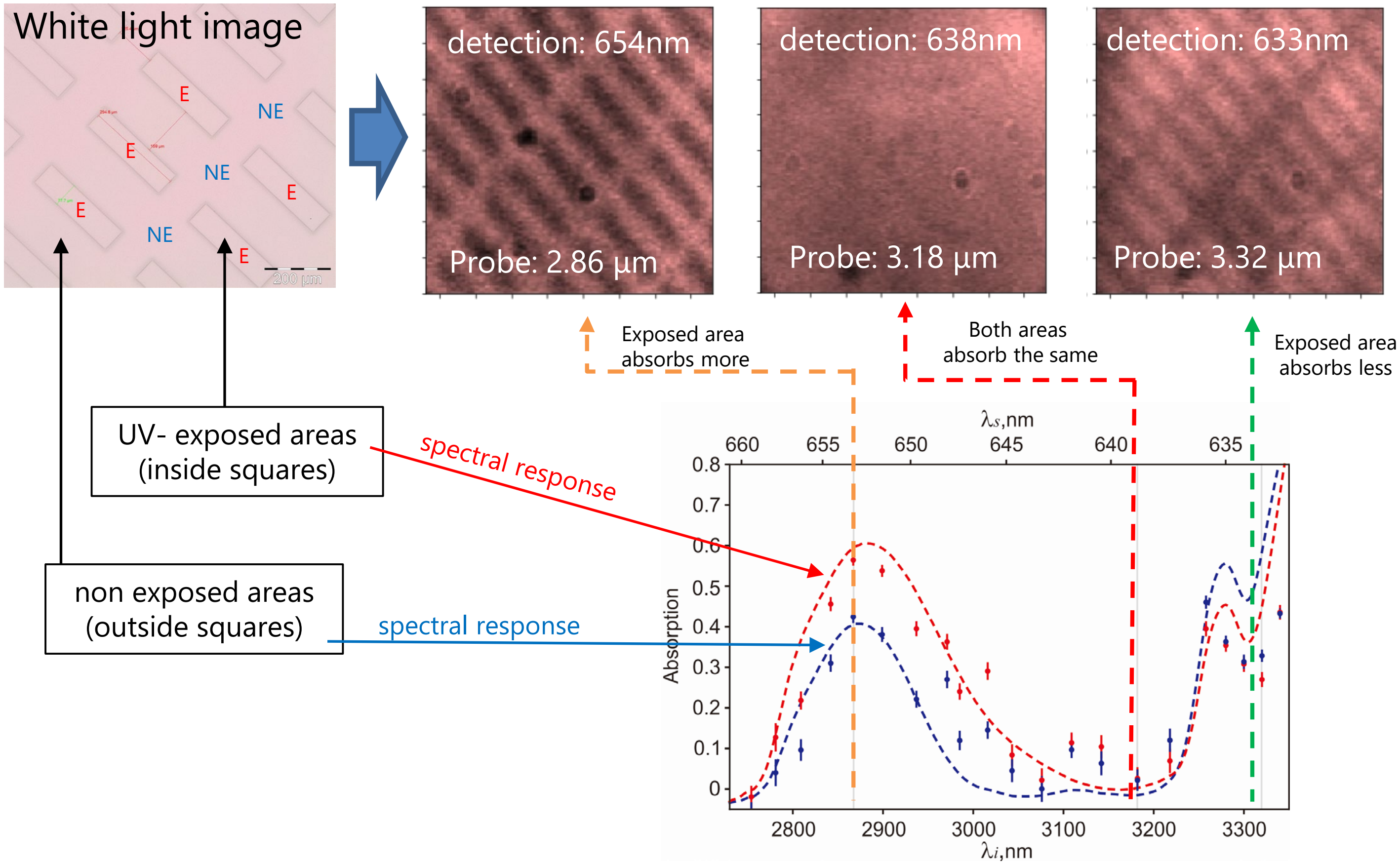
Hyperspectral microscopy



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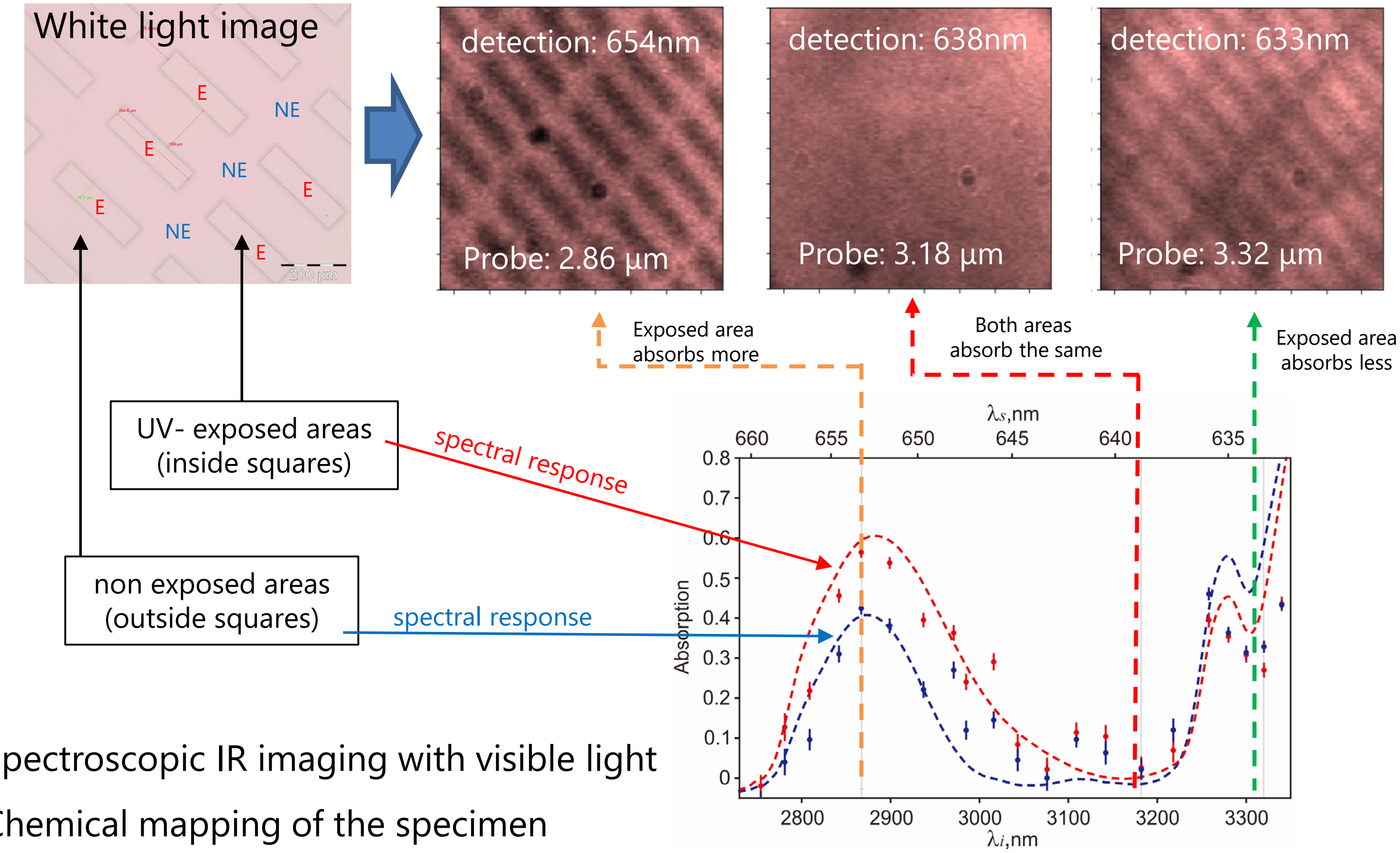
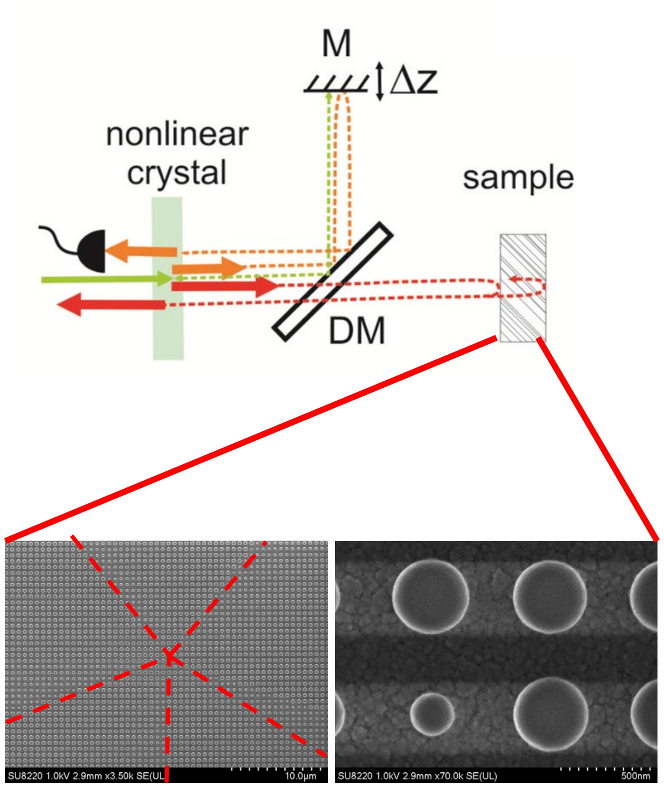
Hyperspectral microscopy

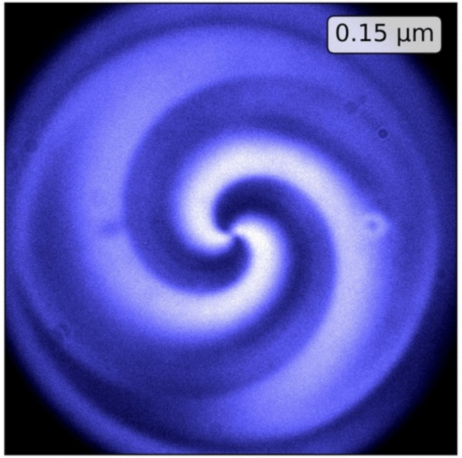


- ✓ Spectroscopic IR imaging with visible light
- ✓ Chemical mapping of the specimen

A Paterova et al *Science Advances*, 6, 44, eabd0460 (2020)

Si- based metasurface with phase gradient

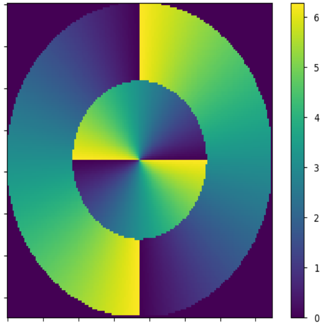


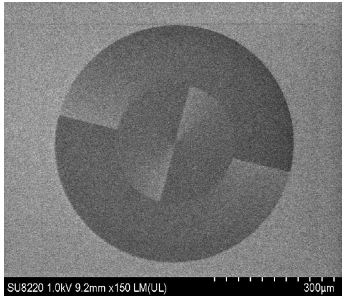


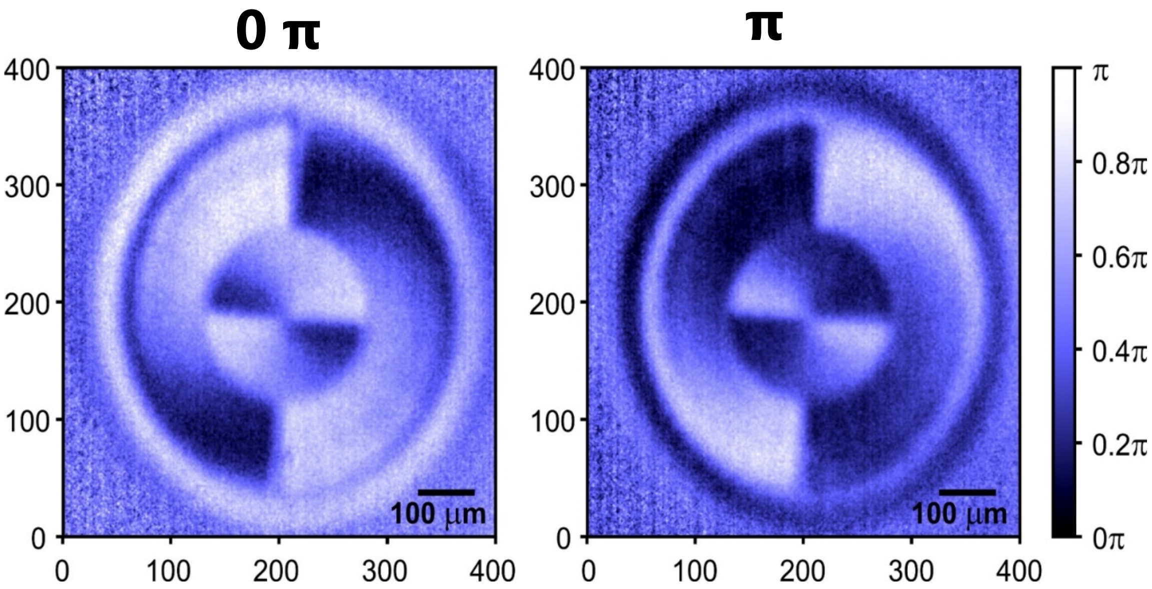
IR probe wavelength: **1550nm**
Detected wavelength: **812 nm**

Our technique reveals the phase image of the object (metasurface) in the IR beam

Imaging of IR metasurface







- A Paterova, D Kalashnikov et al *Nanophotonics* 10 (6), 1775-1784 (2021)

Summary and future work

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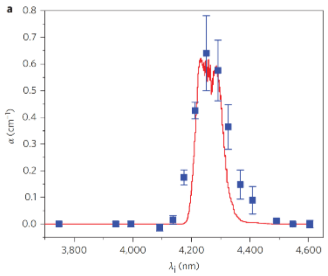
We can substitute and/or complement conventional IR-methods, as we use well-developed components for the visible range.

Spectroscopy



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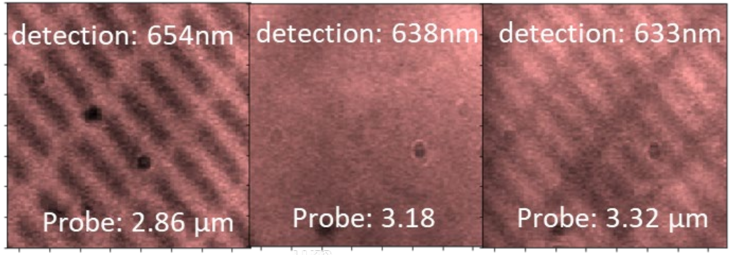
Wide field imaging



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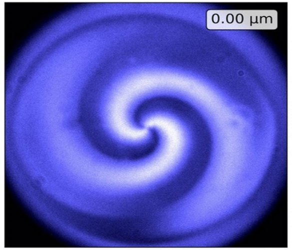
Interferometry



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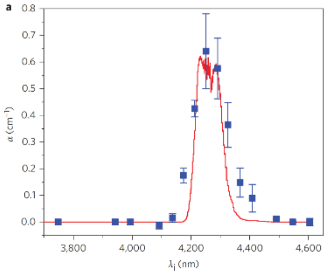
Spectroscopy



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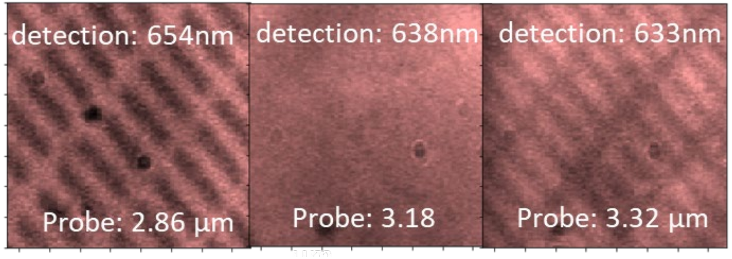
Wide field imaging



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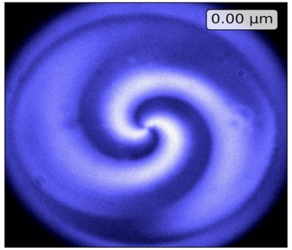

Ongoing work:

- On-chip realization of nonlinear sensors
- Investigation of materials in far-IR
- Developing practical imaging system

QTE department at A*STAR

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QTE department at A*STAR

MBI
MECHANOBIOLOGY INSTITUTE
National University of Singapore

QTE department at A*STAR

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MECHANOBIOLOGY INSTITUTE
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Publications:

- D Kalashnikov et al. *Nature Photonics* **10**, 98–101 (2016)
- A Paterova et al. *Scientific Reports* **7**, 42608 (2017)
- A Paterova et al. *New Journal of Physics* ***20****, 043015 (2018)*
- A Paterova et al. *Quant. Science & Technology* ***3****, 025008 , 2018*
- A Paterova et al. *Optics Express 27 (3), 2589-2603 (2019)*
- A Paterova, Krivitsky Light: Science and Applications 9, 82 (2020)
- D Toa et al., Quantum Science and Technology Arxiv 2109:00690 (2021)
- A Paterova et al Appl. Phys. Lett. **117**, 054004 (2020);
- A Paterova et al Science Advances, 6, 44, eabd0460 (2020)
- A Paterova D Kalashnikov et al Nanophotonics 10 (6), 1775-1784 (2021)

IR spectroscopy

IR OCT and polarimetry

Crystal superlattice

IR imaging

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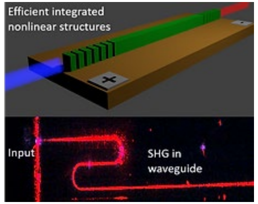
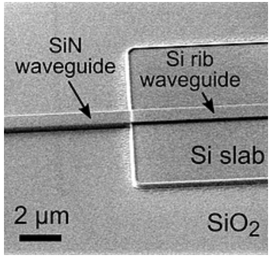
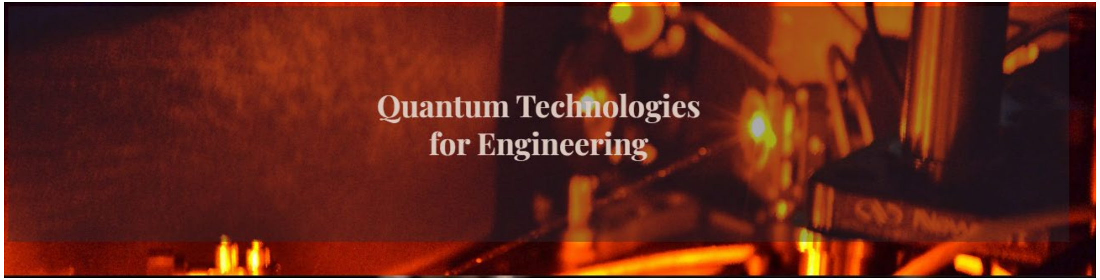
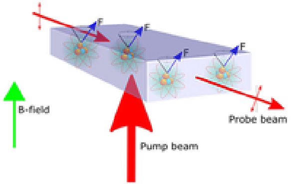
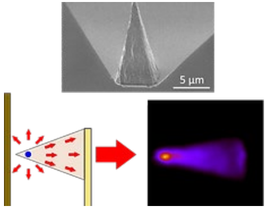
Institute of Materials Research and Engineering
IMRE











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