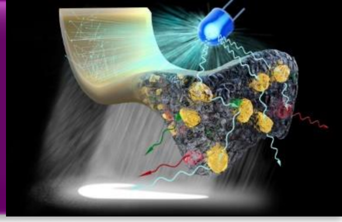
Work package D: Control direction of light by interference

Willem Vos, Aurele Adam, Manashee Adhikary, Melissa Goodwin, Duy Truong

UT + TUD

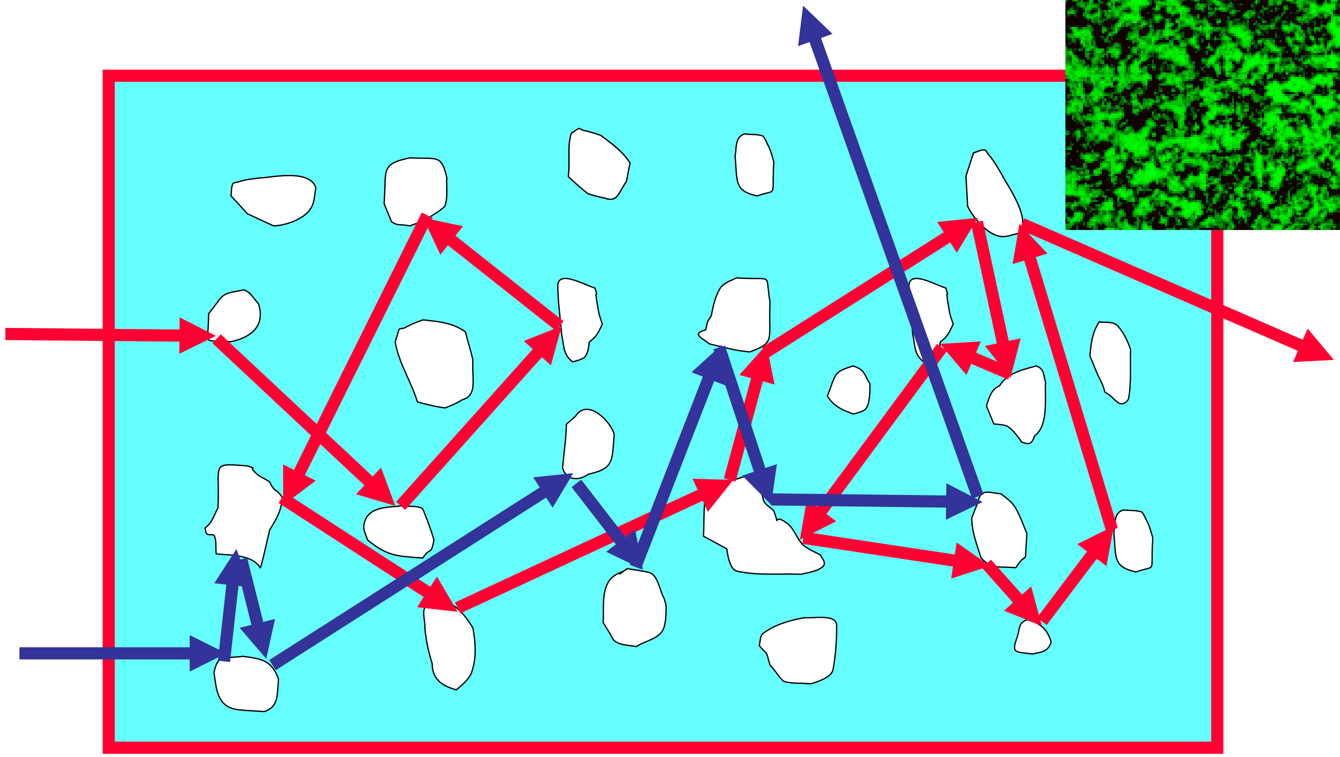
Light randomized by scattering medium

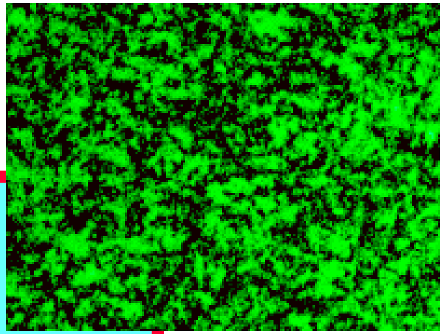


In scattering medium, light scatters many times.

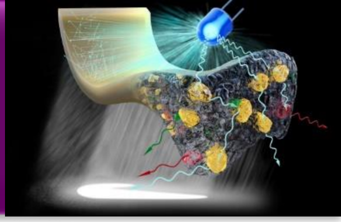
Initial direction lost – opaque.

Upon exiting, light reveals random interference pattern: ***speckle***

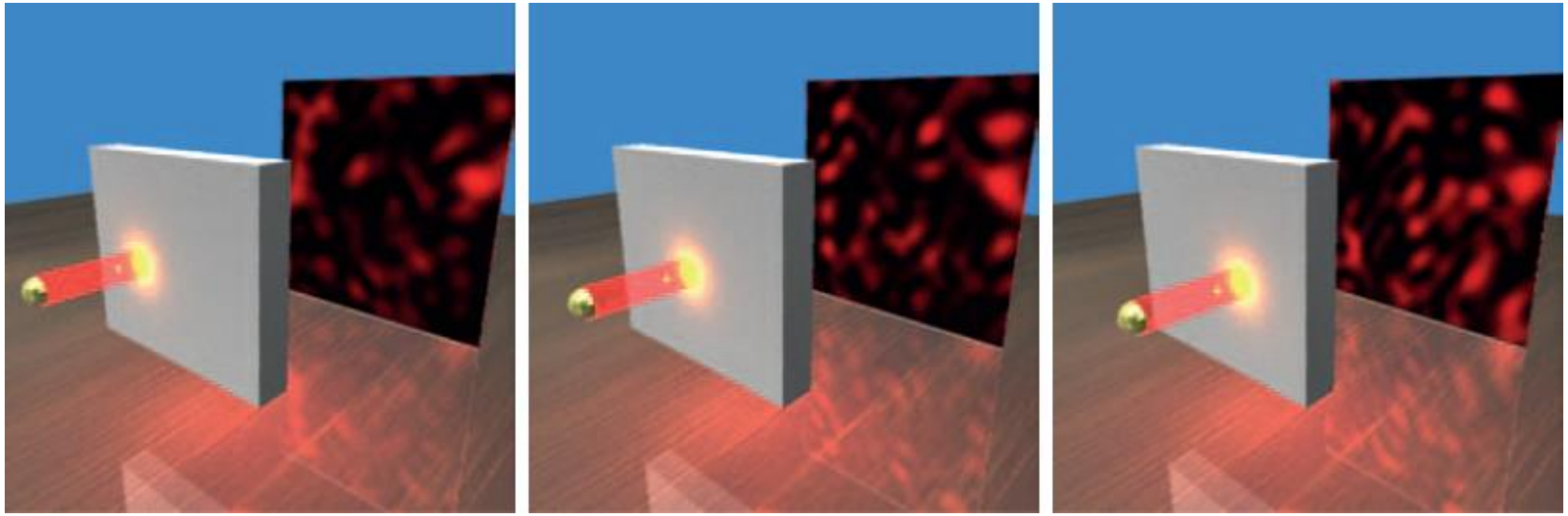




Scattered light out of control? :-(



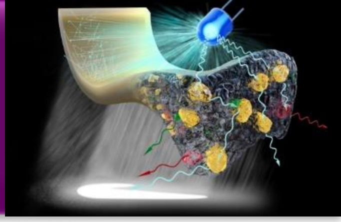
Beams at different positions on a sample yield uncorrelated speckle patterns



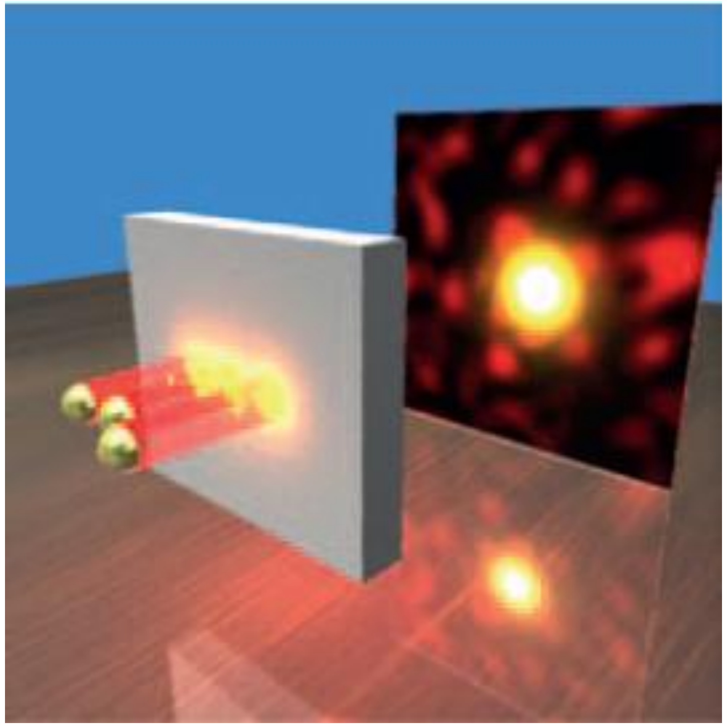
So light is “out of control”?

Vellekoop & Mosk, Opt. Lett **32** (2007) 2309
Mosk, Lagendijk, Lerosey & Fink, Nature Phot. **6** (2012) 283

Under control thanks to WFS ;-)

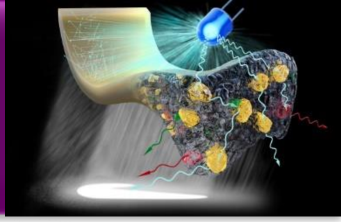


But properly phased beams incident at different positions on a scattering medium yield constructive interference and an intense spot:
Optical wavefront shaping (WFS)



Vellekoop & Mosk, Opt. Lett **32** (2007) 2309
Mosk, Lagendijk, Lerosey & Fink, Nature Phot. **6** (2012) 283

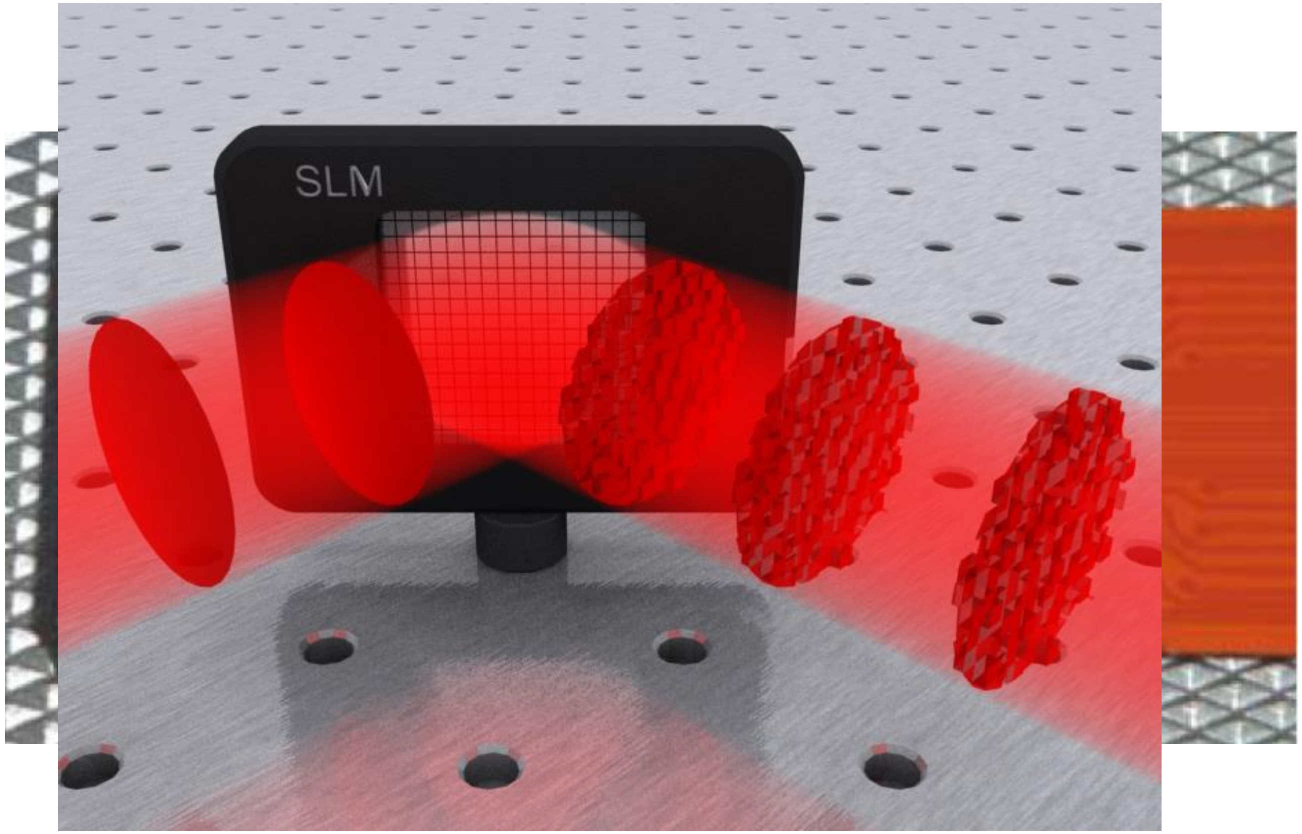
Central role of spatial light modulator



Spatial light modulator (SLM) chip contains a million segments to set phase & amplitude of light

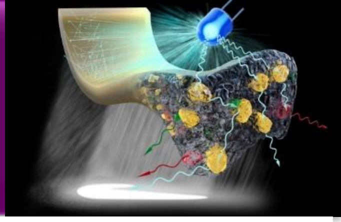
In practice, one uses liquid-crystal SLMs or digital micromirror devices (DMD)

SLM: handy for broadband light
DMD: handy for fast modulation

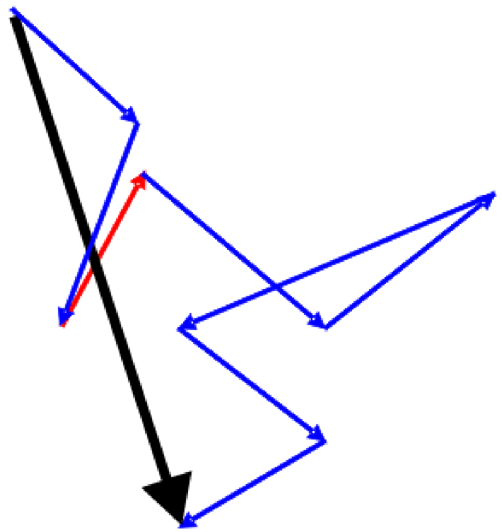


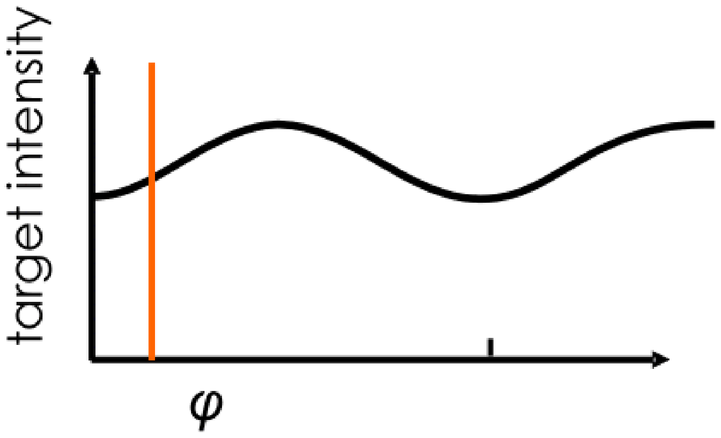
See: Goorden, Bertolotti & Mosk, Opt. Express 22 (2014) 17999

Find the optimal wavefront

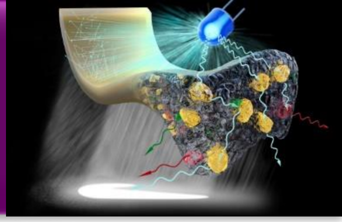


- Left: Phasors in multiple scattering
- Adjust phase of individual segment (red arrow) until contribution in phase with total field (large **bold** arrow)
- Finally: set all phases for all segments to optimal setting



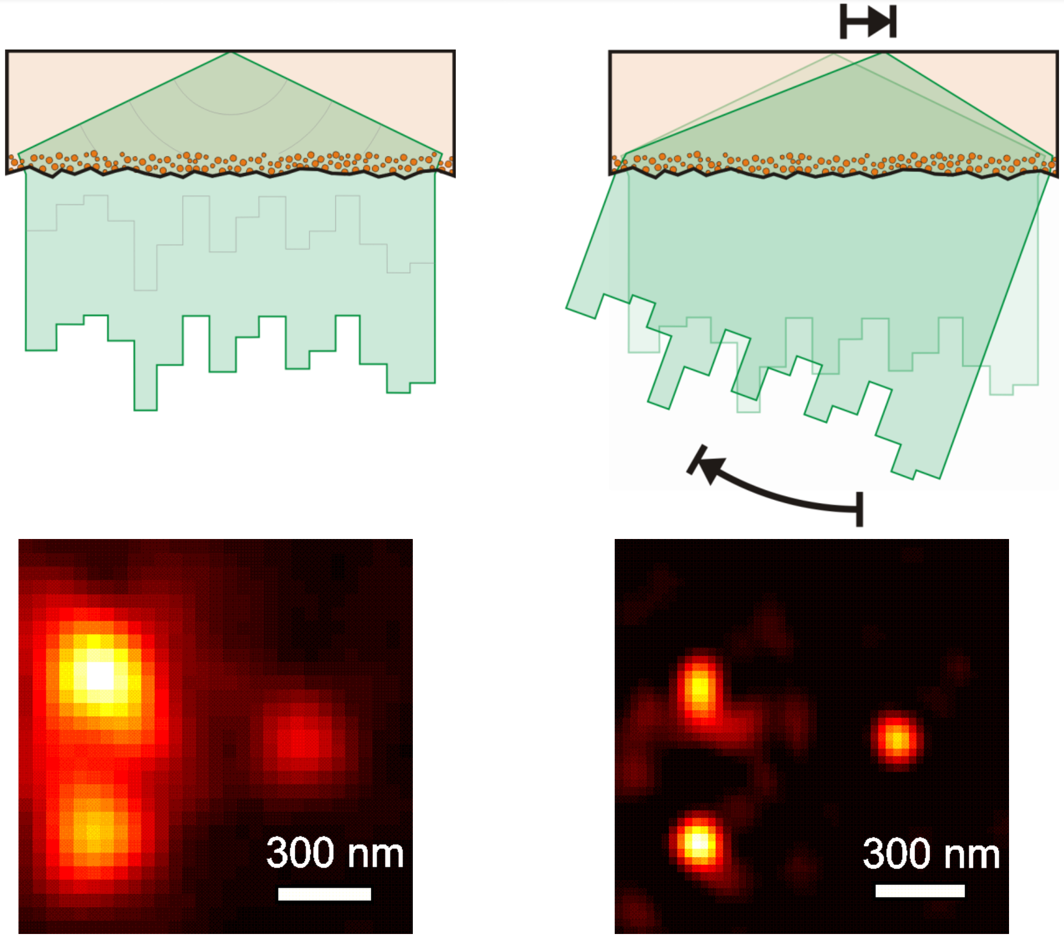


Speckle becomes bright & focused



Spot up to 1000x brighter than diffuse background

Resulting spot can become very narrow ($\varnothing \leq 100$ nm at $\lambda = 560$ nm) & position can be scanned
$\Rightarrow$ (fluorescence) microscopy

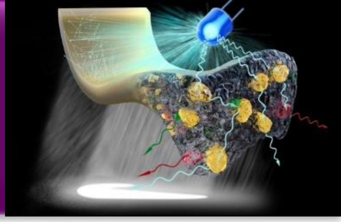


Very expensive microscope objective

High-resolution scattering lens

Van Putten, Akbulut, Bertolotti, WLV, Lagendijk & Mosk, Phys. Rev. Lett. **106** (2011) 193905
Yilmaz, van Putten, *et al.*, Optica **2** (2015) 424

Shape waves by 2 main methods

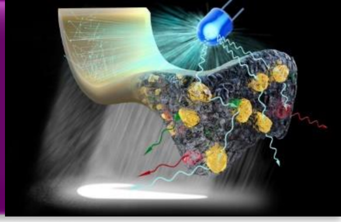


In essence there are 2 complementary methods to shape waves:

1) Control light waves by ***sample nanostructure***
Aurèle Adam – Anisotropic surface scattering
Melissa Goodwin – Volume scattering, photonic crystals
(Shravan Raghunathan – Anisotropic scatterers)

2) ***Shape incident phase fronts*** with spatial light modulators
Manashee Adhikary – Light deep in opaque media & broadband
Min Duy Truong – Can mutual extinction sense position?

Next presentations



Aurele Adam (Zheng Xi, TUD): Anisotropic surface scattering (D1)

Melissa Goodwin (UT): Nanofabrication Si photonic crystals (D2&C2)

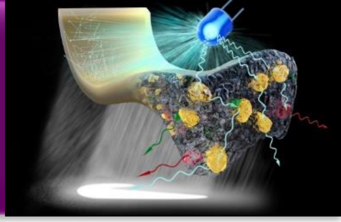
Manashee Adhikary (UT): Send light deep into opaque crystals (D2)
& Broadband wavefront shaping (D3)

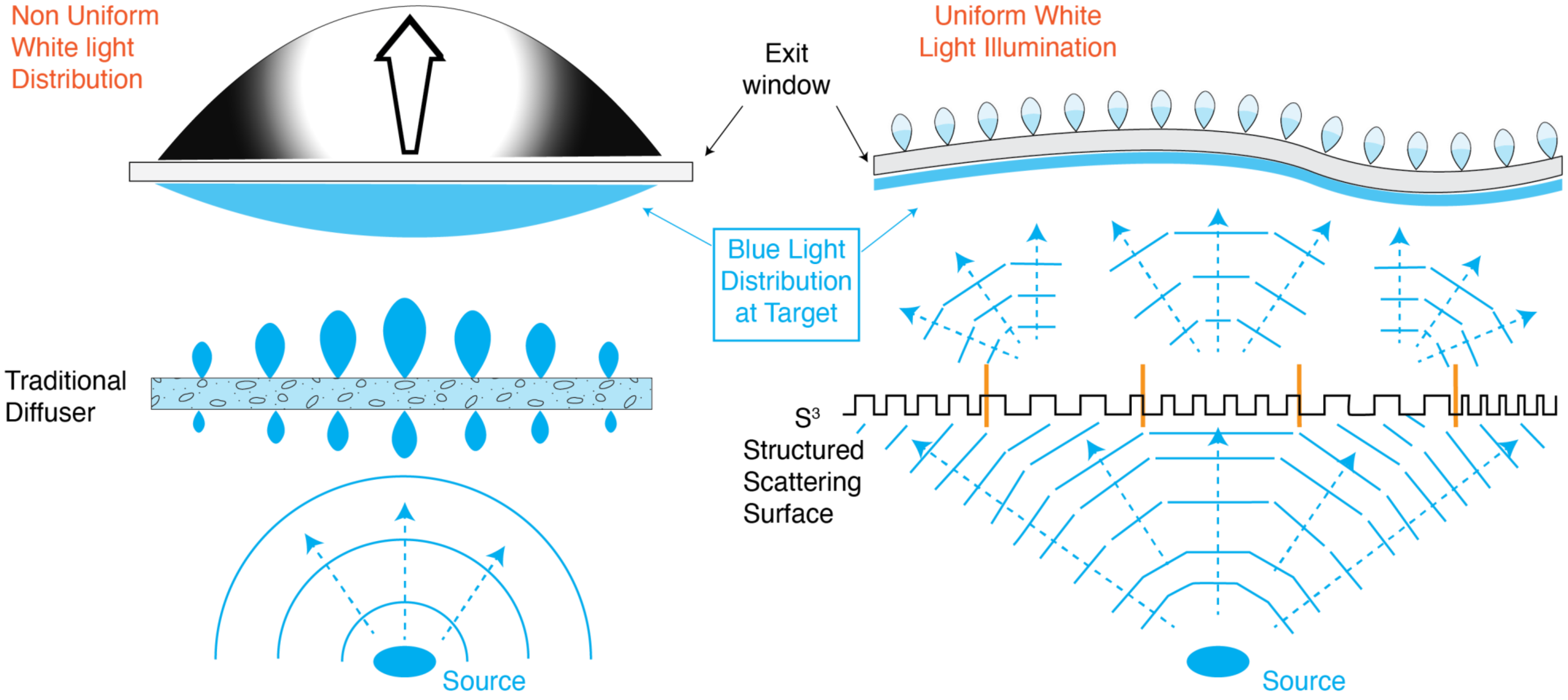
Min Duy Truong (UT): Mutual extinction as position sensor (D3)

Willem Vos: Summarizing & action points

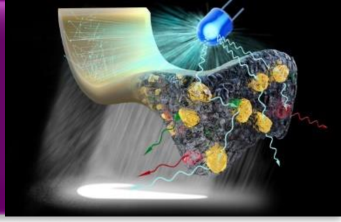
Aurele Adam

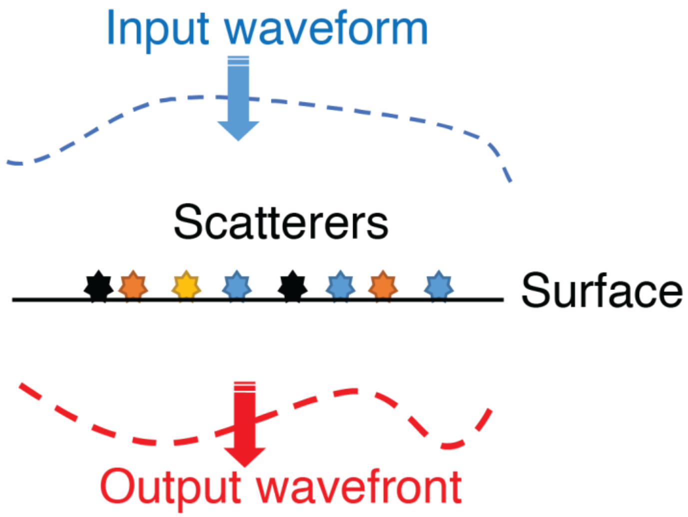
Anisotropic surface scattering: the Idea





Design Procedure





Unit Cell Simulation for large database

Simulation of a unit cell response
using COMSOL/RCWA or analytical methods

Phase distribution extraction

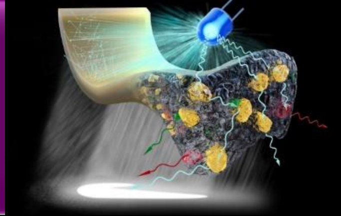
Phase retrieval methif to get the phase
distribution avove the surface scatterers

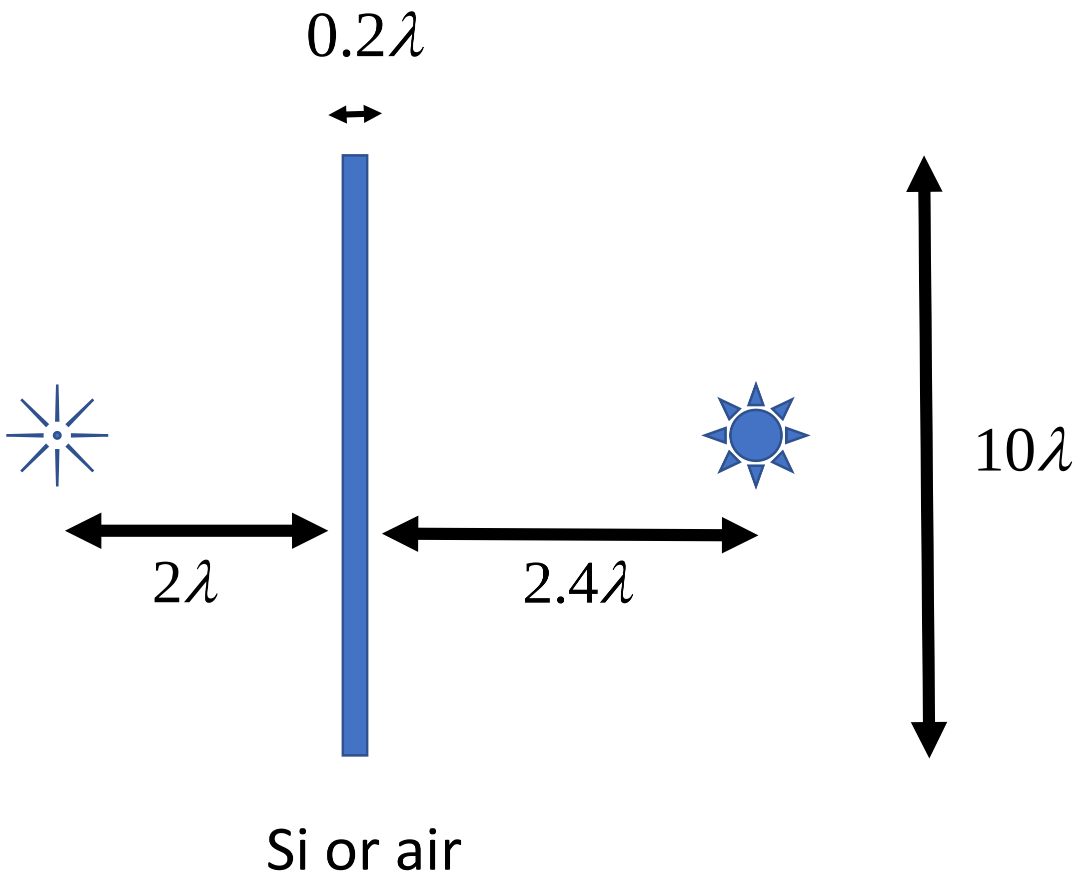
Optimisation Based on Database

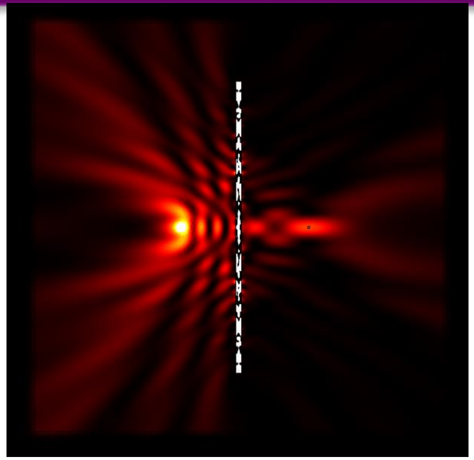
Optimisation method based on
gradient descent/genetic algorightm/AI

Generation of a design

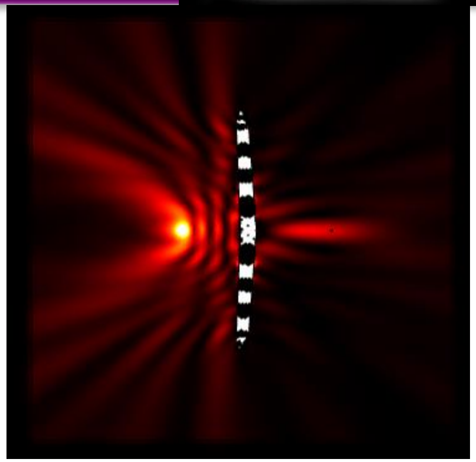
Results with binary Si



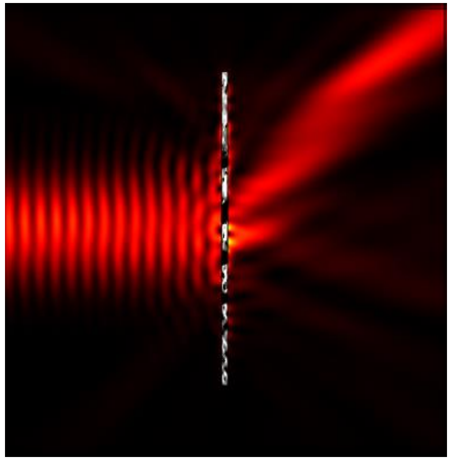




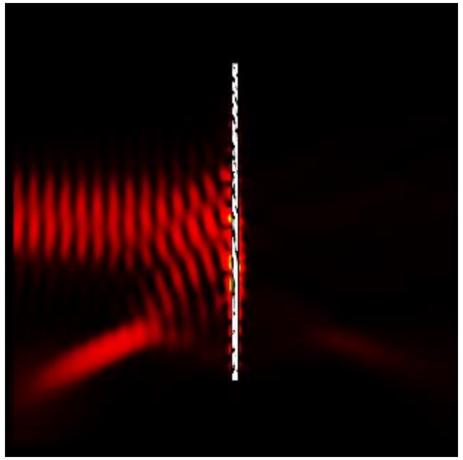
Focus Point



Curved surface

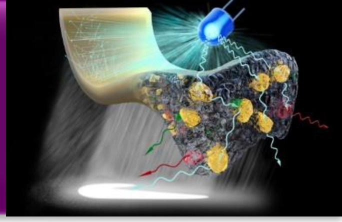


Off Axis

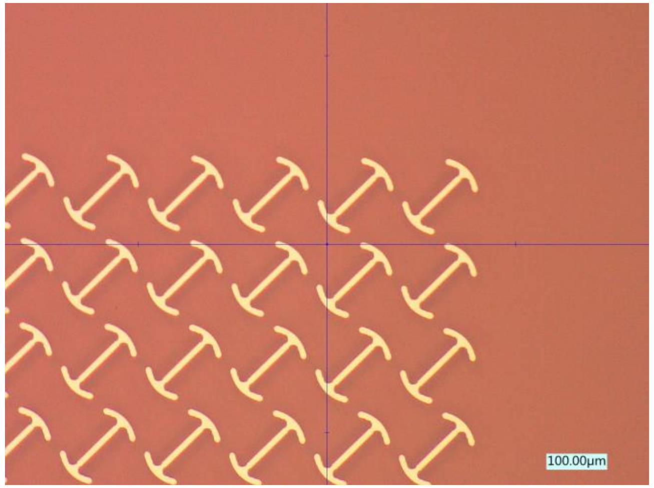


In Reflection

Results with binary Si

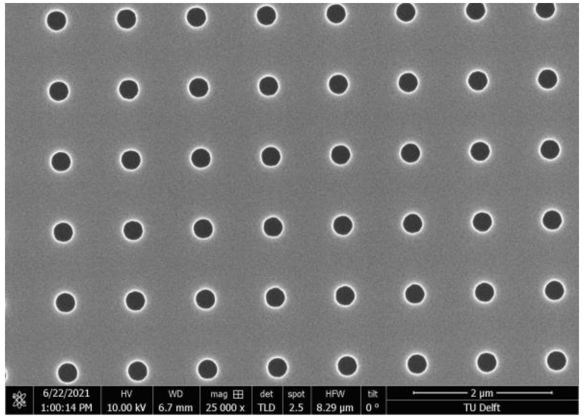


At TeraHertz wavelengths



Gold on Membrane

In the IR range

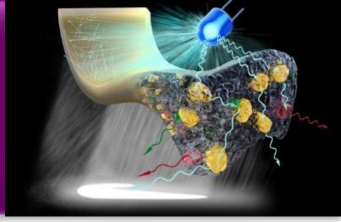


Holes in Silicon (test run)

See Poster

Melissa Goodwin

Etching of nanopores in silicon



Photonic matter: refractive index varies on distances similar to wavelength (400 – 1500 nm)
$\rightarrow$ Array of nanopores in silicon
(Si + air: large desired index contrast)

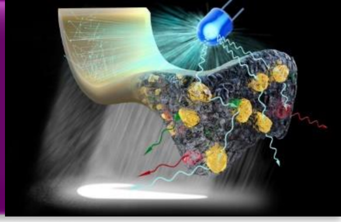
Etching: removal of material, to create a pattern[1]

For micro- and nano-scale etching of silicon, reactive ion etching (RIE) is widely used

Anisotropic applications use “Bosch process”[2,3]

[1] https://qcurtius.com/2019/07/13/the-armor-of-virtue/
[2] http://www.findmems.com/bosch/mems-bosch-automotive-applications-and-beyond
[3] Laermer & Schilp, US Patent 5501893 (1996); Review: Wu, Kumar & Pamarthy, J. Appl. Phys. 108 (2010) 051101

Reactive ion etching



Number of cycles

Start cycle

End cycle

Deposition time

Etch time

Deposition pressure

Etch pressure

SF_6 flow

C_4F_8 flow

Deposition ICP

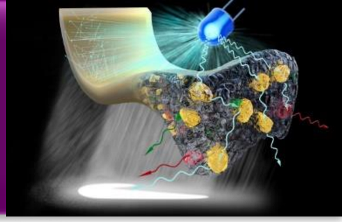
Etch ICP

Etch CPP

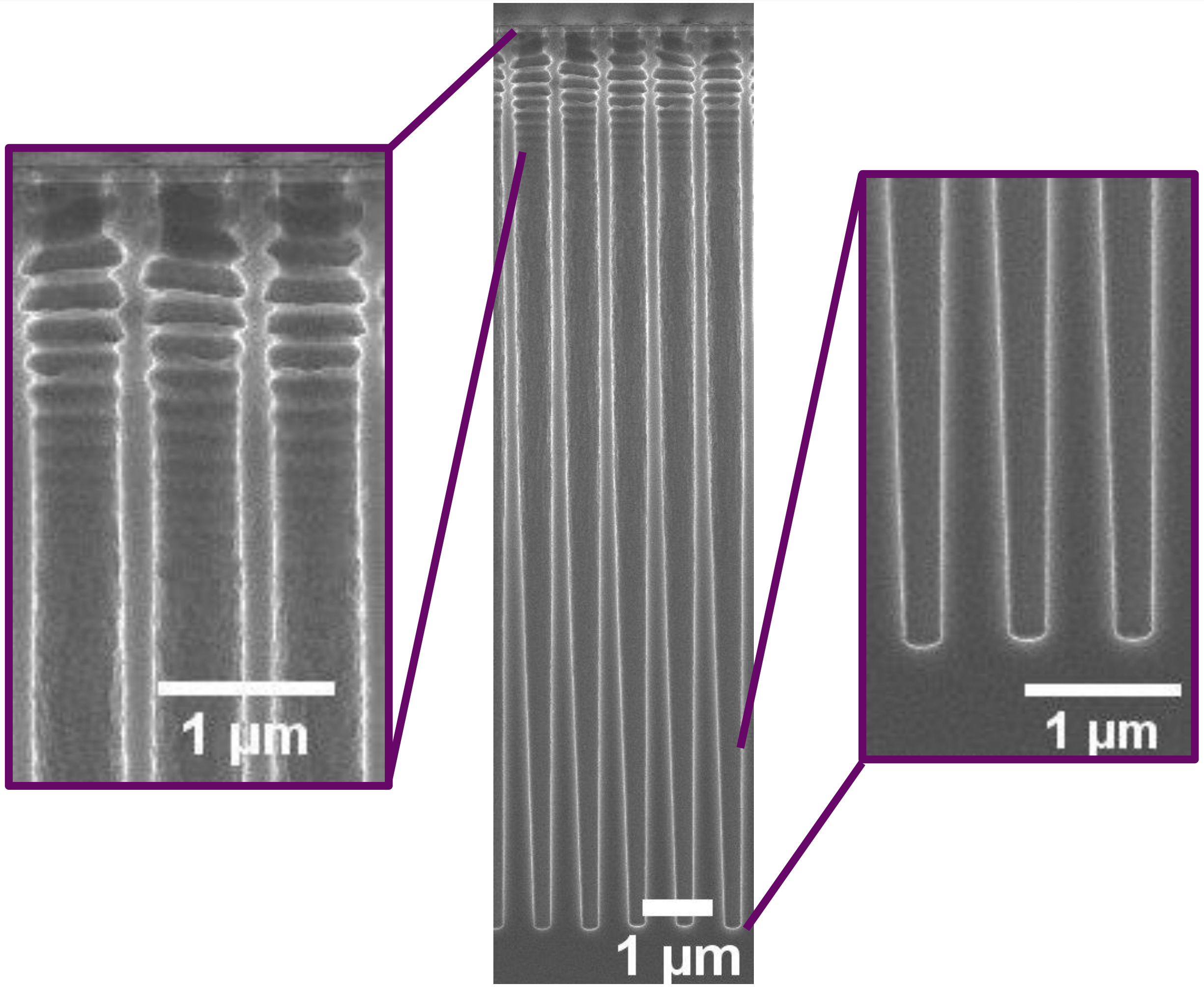
Temperature

Boost step time

Previous etching (2-step)



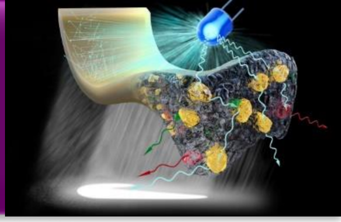
Large underetch (2r = 600 nm from a 320 nm mask)
Uneven scallops
Nevertheless: world-record deep pores :-)



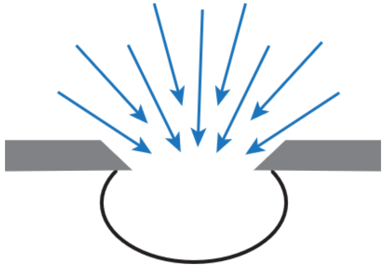
Positive taper
2r(top) = 600 nm
2r(bottom) = 220 nm

[1] Woldering, Tjerkstra, Jansen, Setija & Vos, Nanotechnology 19 (2008) 145304;
[2] van den Broek, Tjerkstra, Woldering, Segerink, Setija & Vos, Adv. Func. Mater. 22 (2012) 25

Our novelty: 3-step Bosch Process

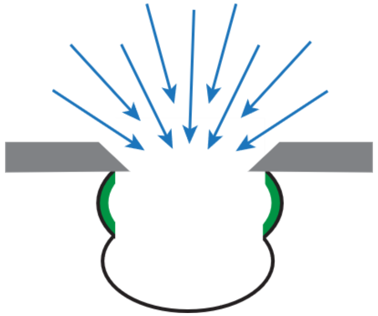


Silicon substrate with a chromium mask

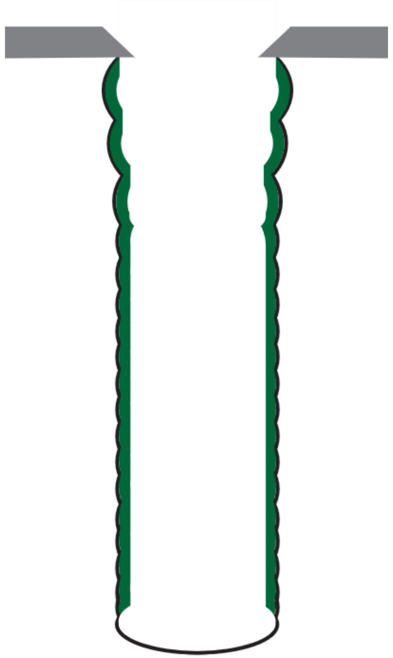


Etching Si with SF_6 - isotropic

Protection by depositing a layer of fluorocarbon using C_4F_8



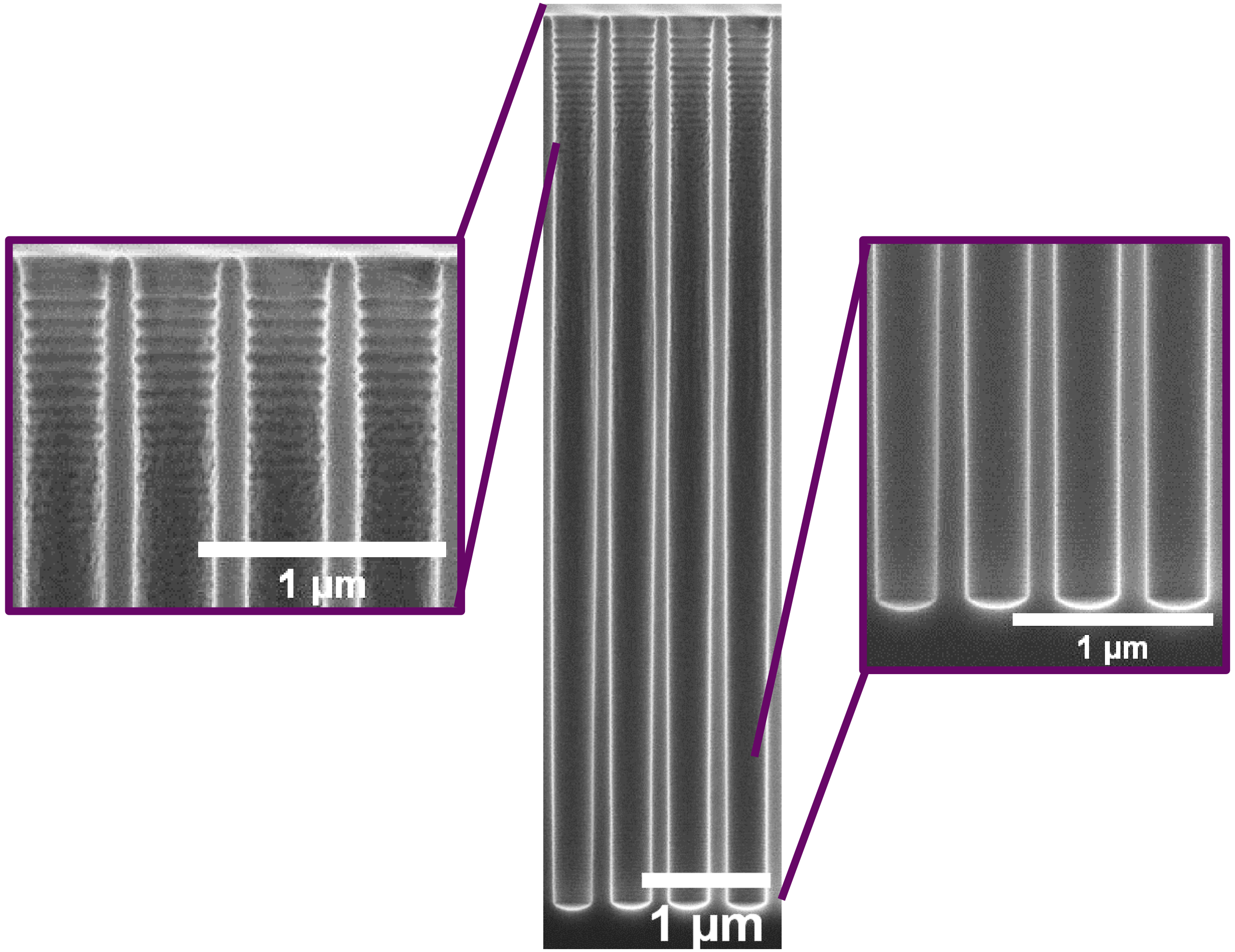
Etching again Si SF_6



Repeat deposit and etch until desired pore depth

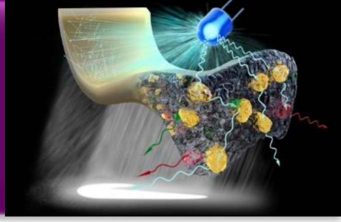
New & improved etching (3-step)

- No underetch
- Small & even scallops

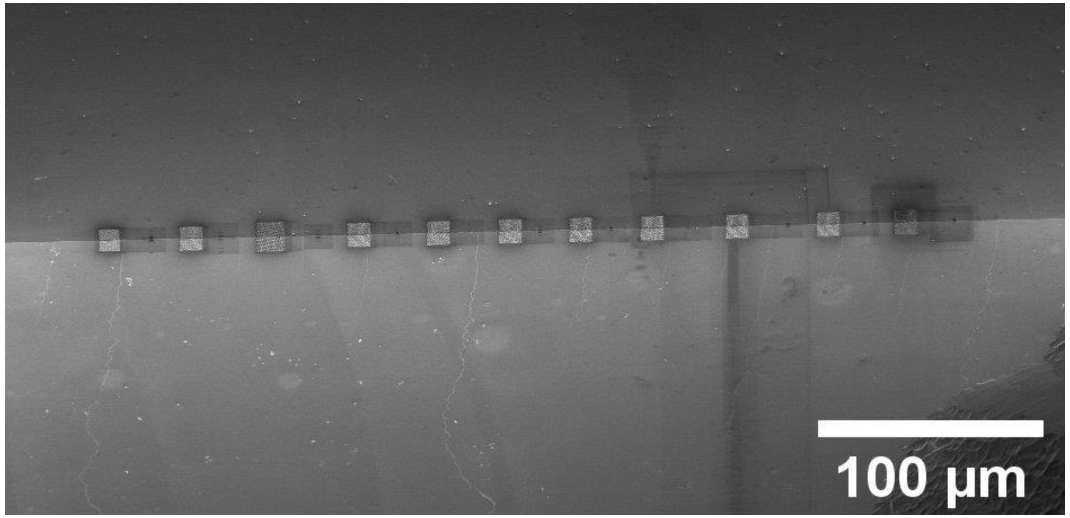


- Reduced tapering, only 20 nm variation on 2r = 320 nm pore
- Flat bottom

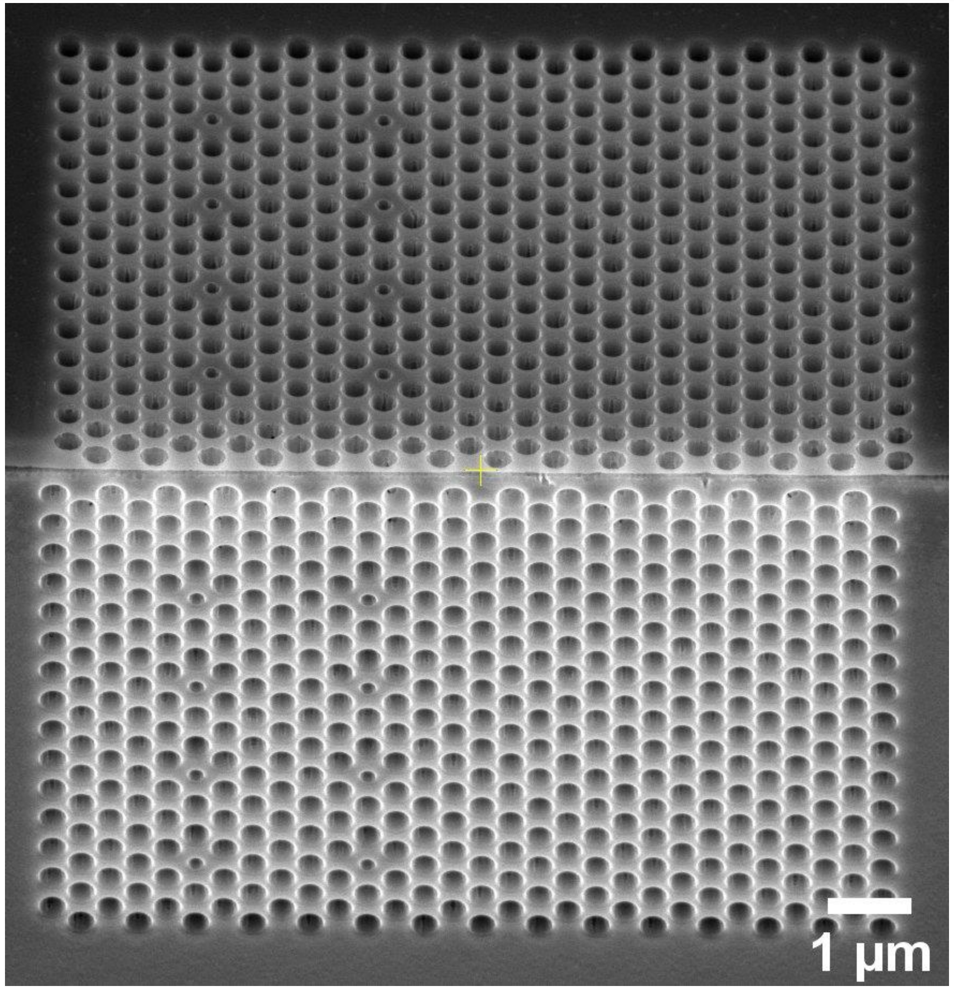
3D inverse woodpile photonic crystals



Etch side 1

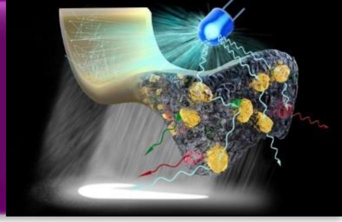


Turn 90°, etch side 2



Manashee Adhikary

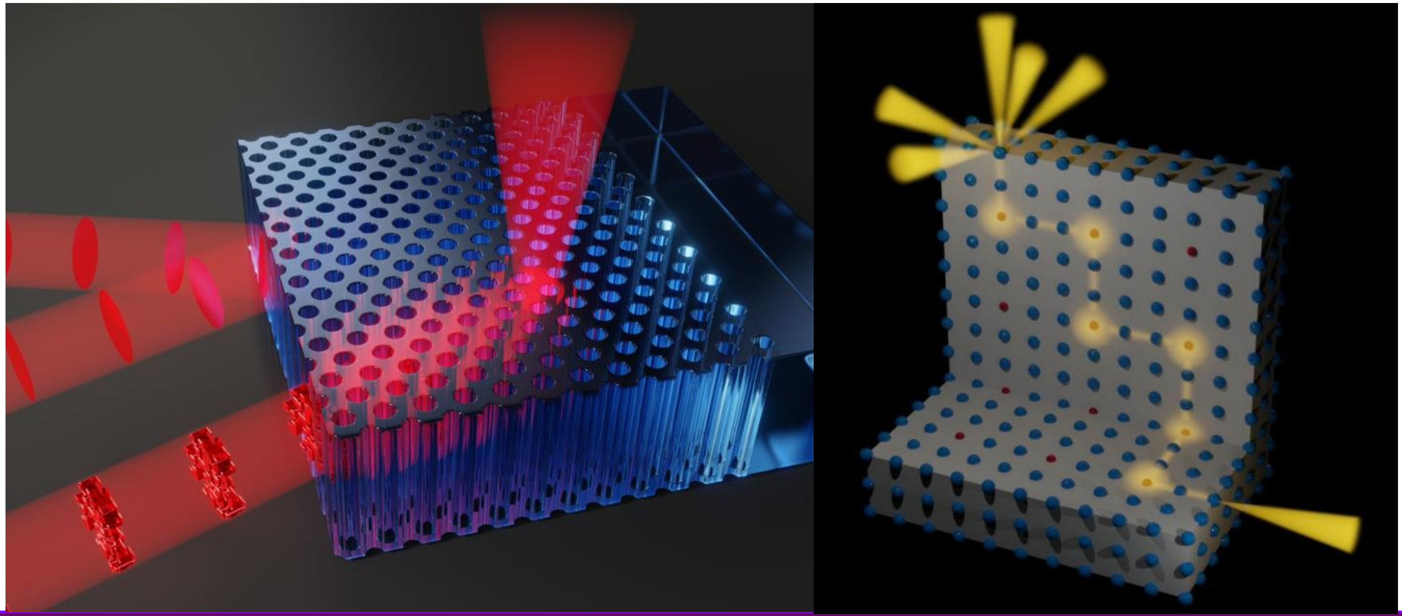
Looking inside opaque media (D2)



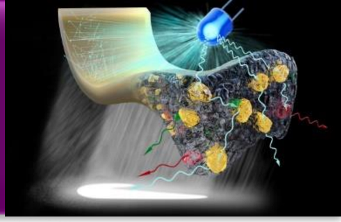
Two ways to send light inside in opaque media such as a scattering medium or a material with a photonic band gap

1. Wavefront shaping (WFS)

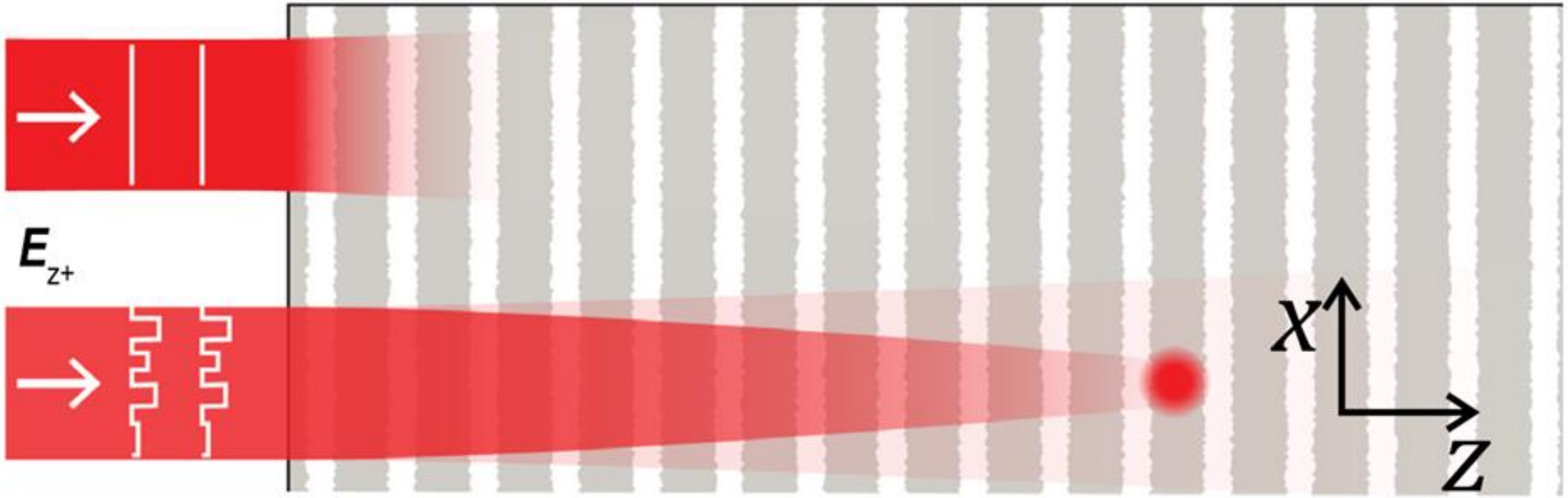
2. Coupled cavities



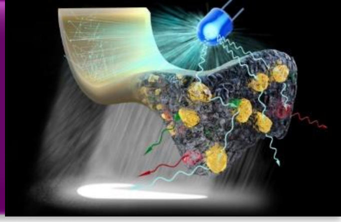
Wavefront shaping to send light inside

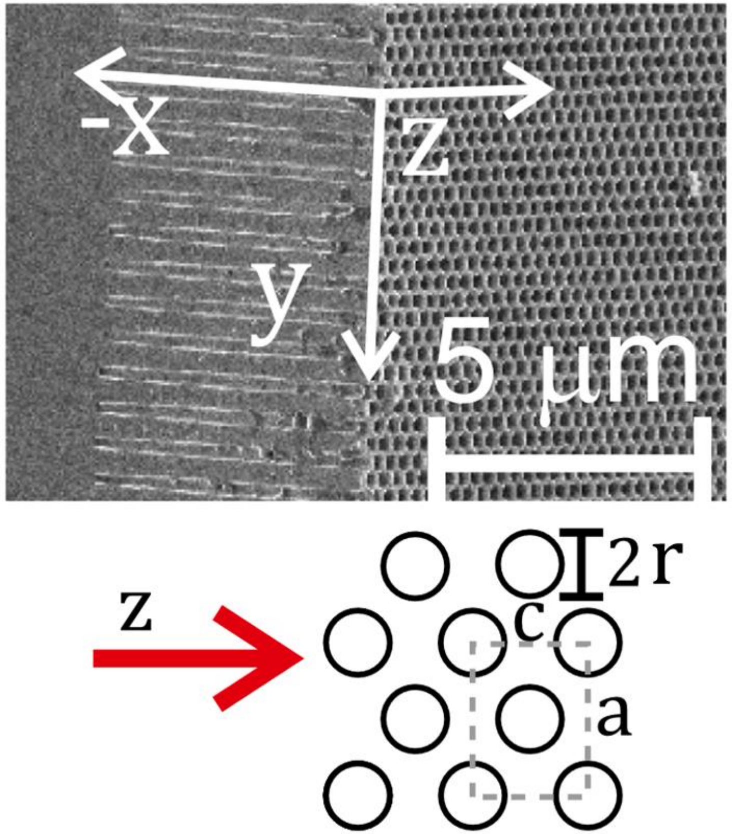


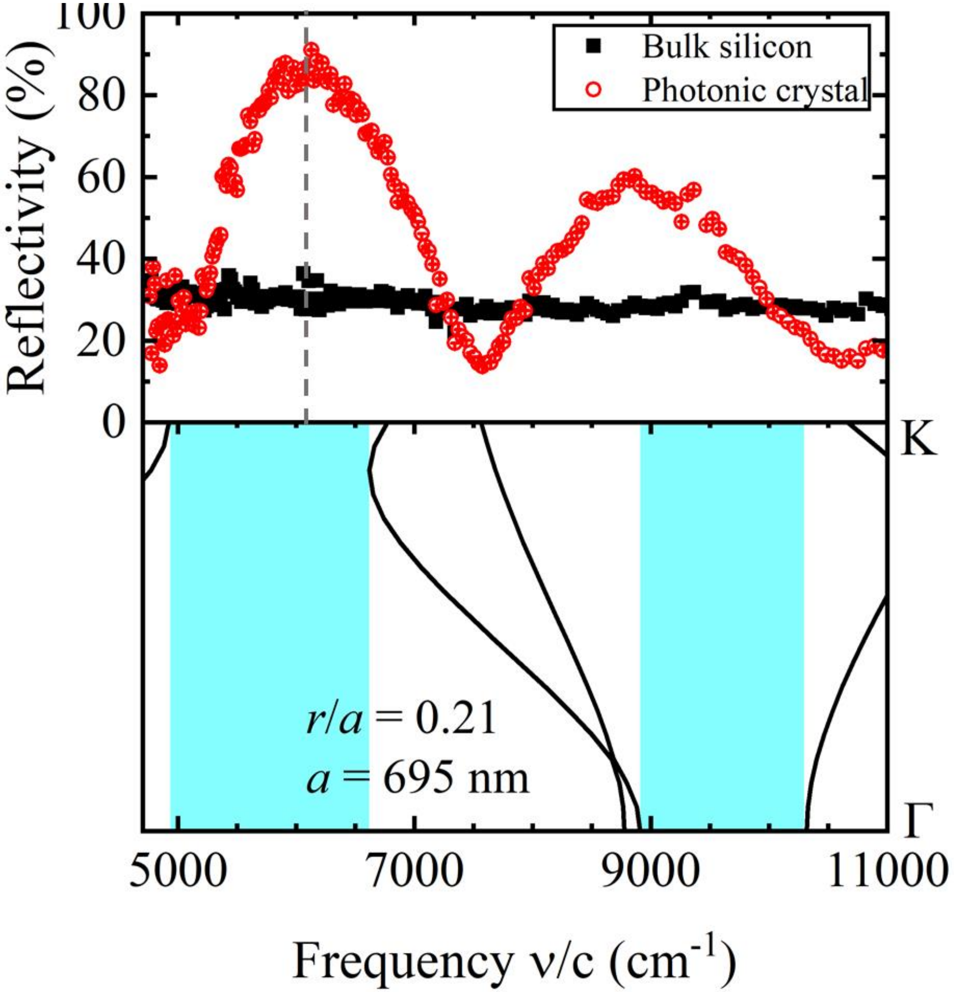
Adjust spatial wavefronts of incident light to couple to propagating mesoscopic channels



Silicon photonic crystal

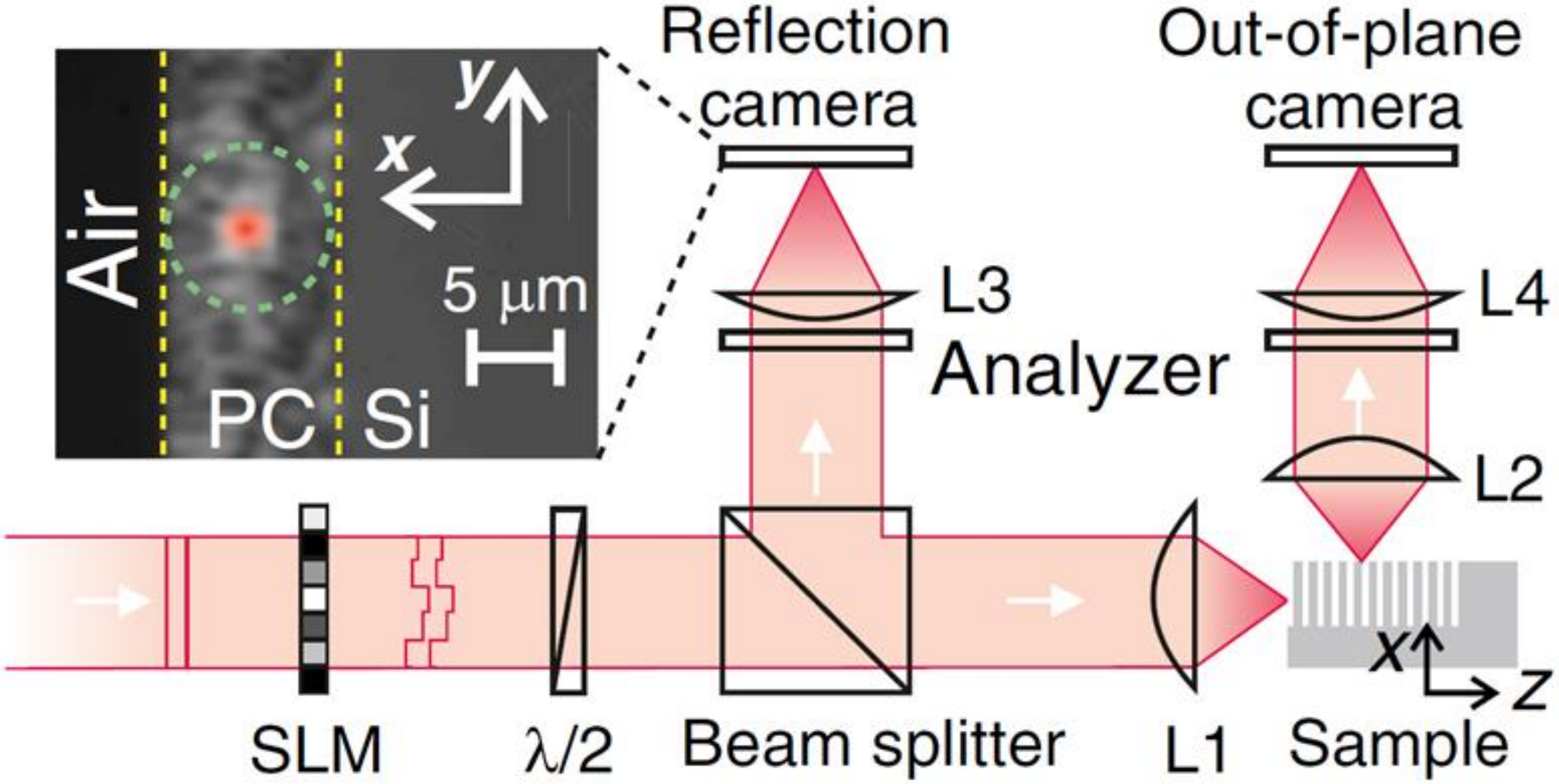






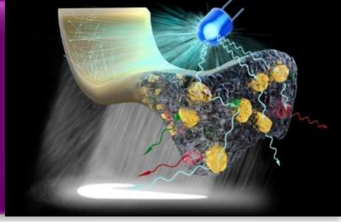
Grishina, Harteveld, Woldering, and Vos, *Nanotechnology* **26**, 505302: 1-10 (2015)
Woldering, Tjerkstra, Jansen, Setija, and Vos, *Nanotechnology* **19**, 145304: 1-11 (2008)

WFS to send light inside band gap

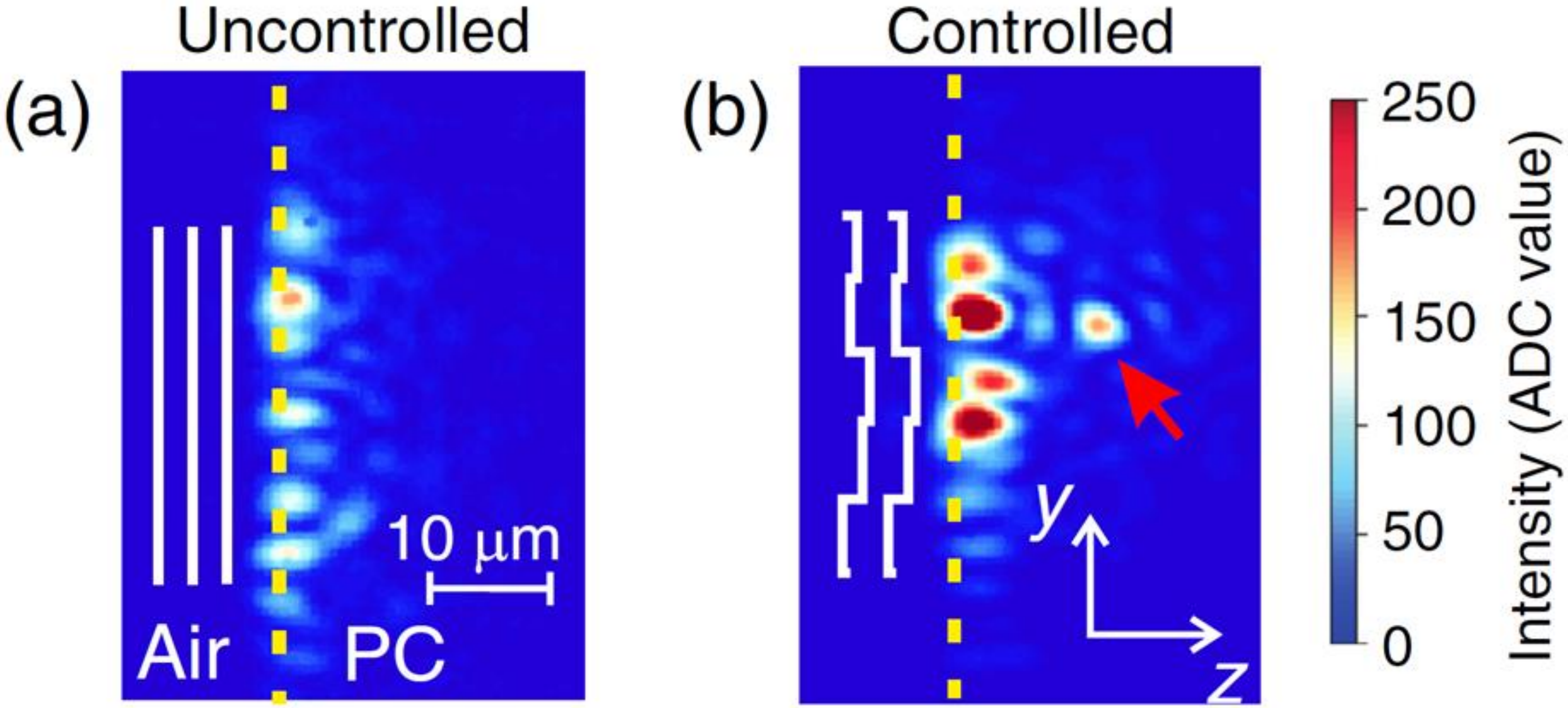


Uppu, Adhikary, Harteveld, and Vos, *Phys. Rev. Lett.* **126**, 177402 (2021)

WFS to send light inside band gap



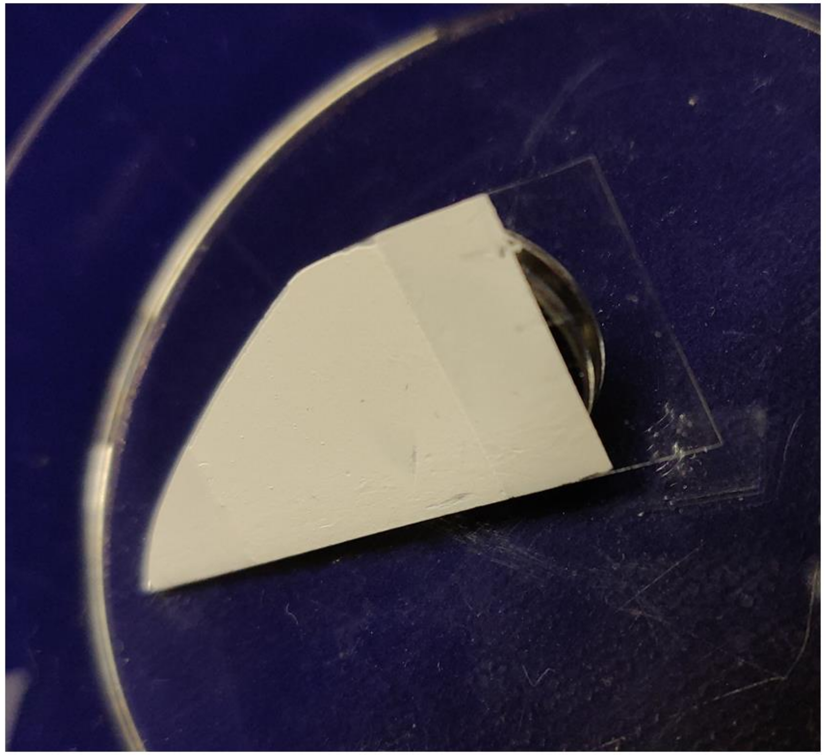
Focus produced at laterally scattered light at gap center, far beyond the Bragg length

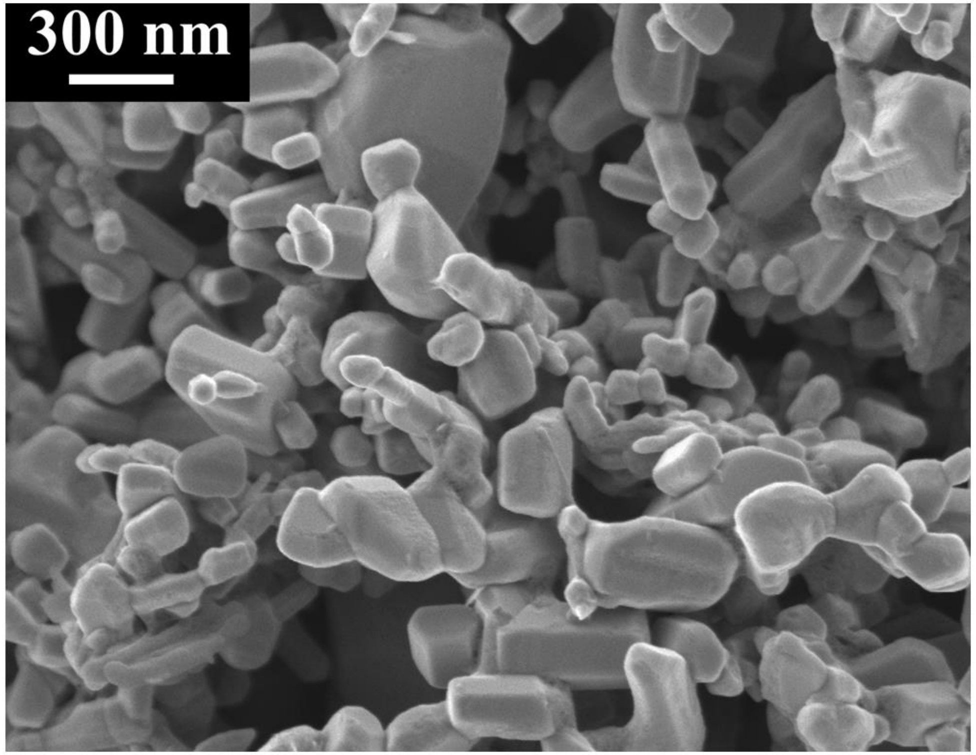


Uppu, Adhikary, Harteveld, and Vos, *Phys. Rev. Lett.* **126**, 177402 (2021)

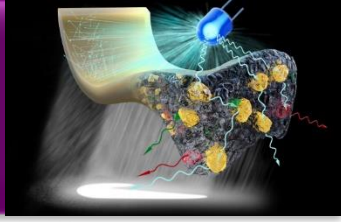
Exploring the freq. width of WFS

WFS to produce a focus behind a scattering medium

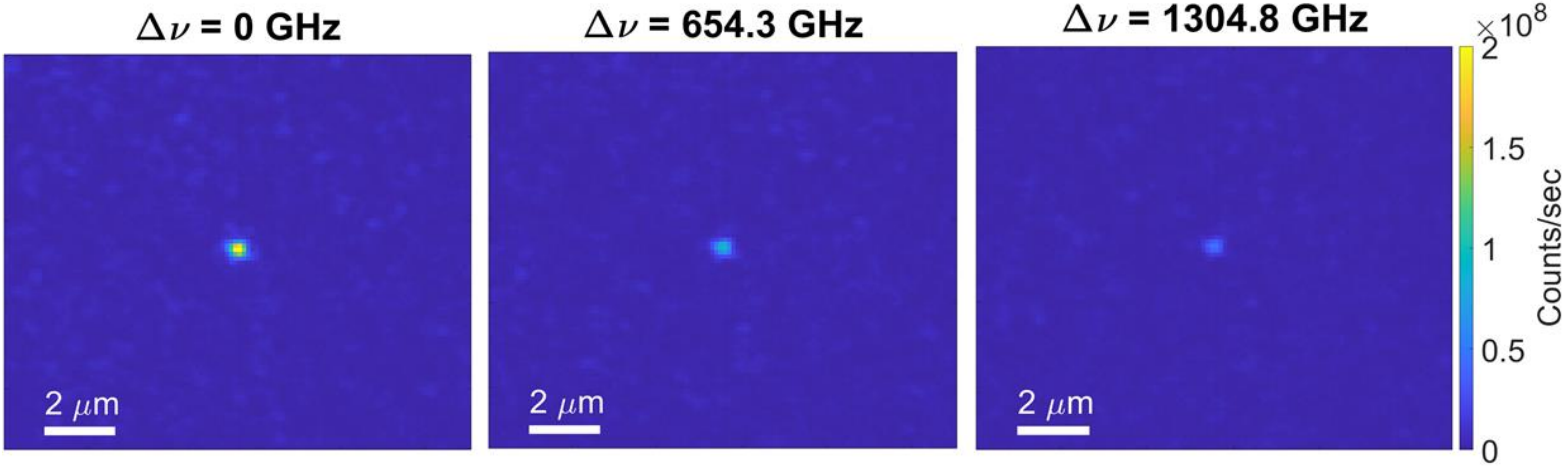




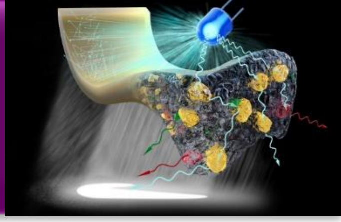
Exploring the freq. width of WFS



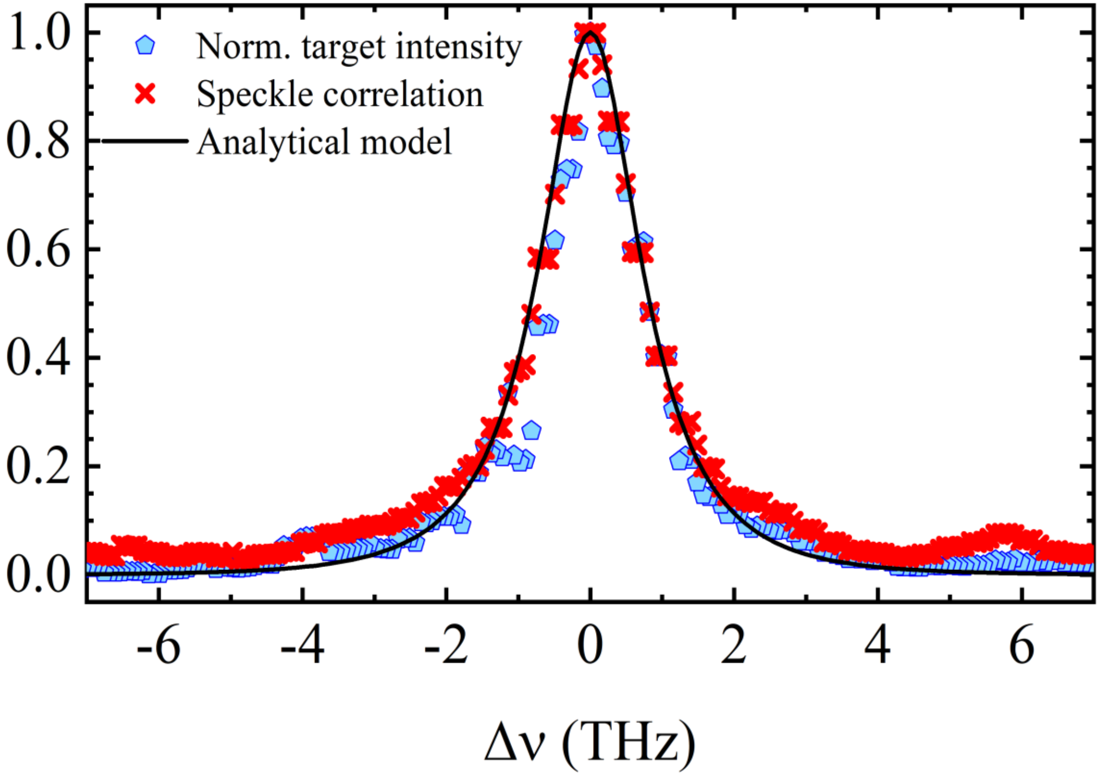
WFS with frequency detuning

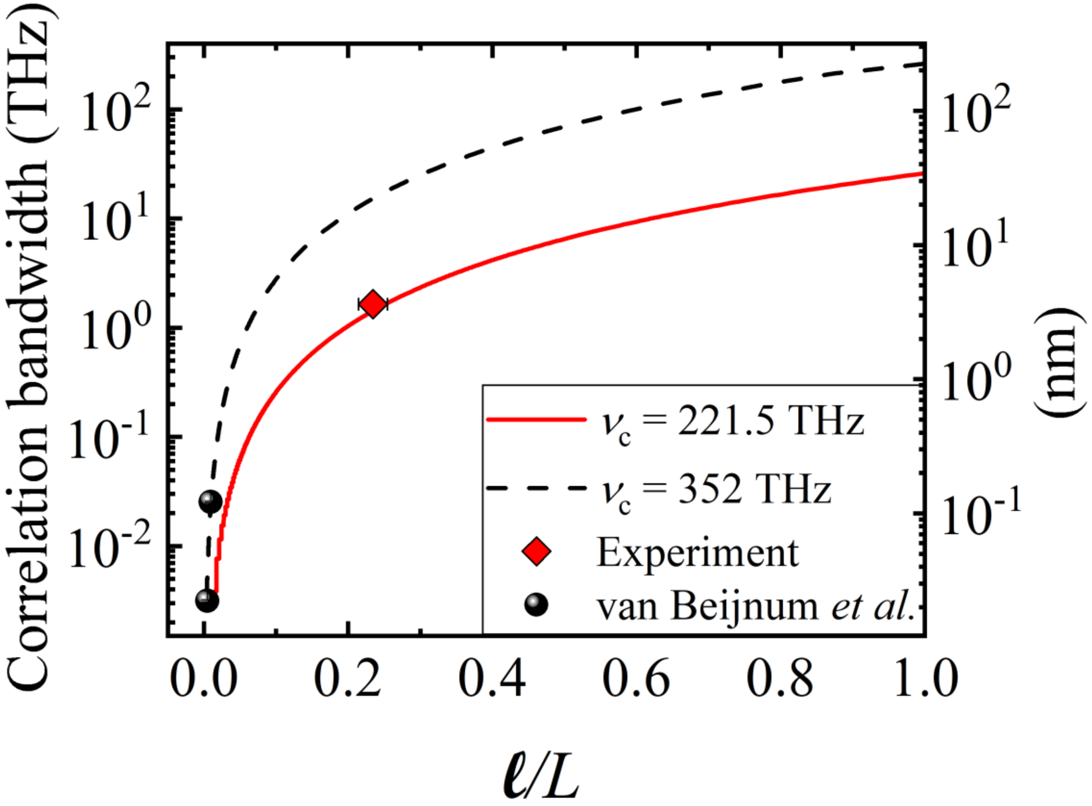


Exploring the freq. width of WFS



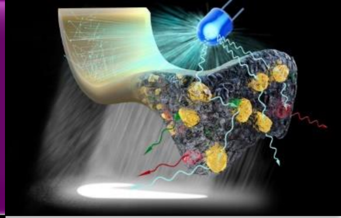
Bandwidth tuning by changing the sample thickness within multiple scattering limit





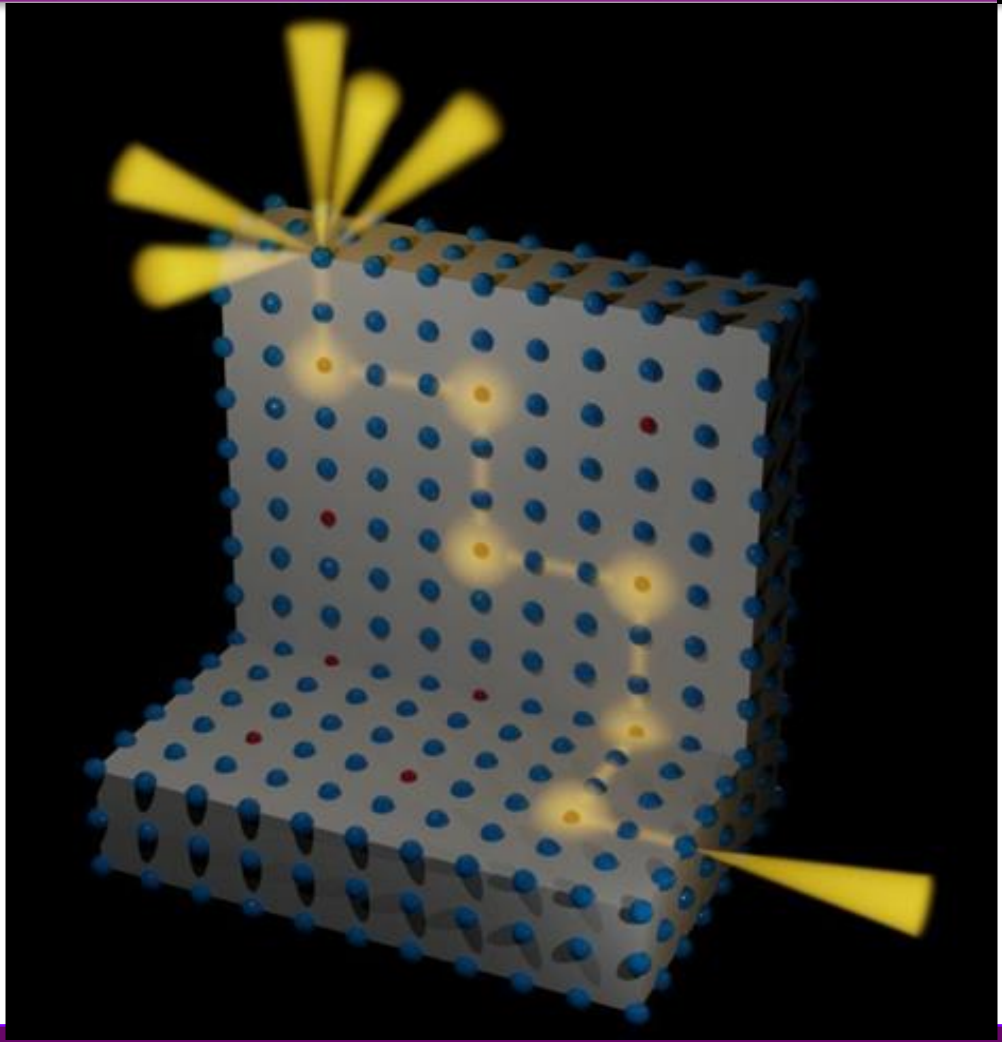
Adhikary, PhD thesis (2021)
Beijnum *et al.*, Opt. Lett. **36** (2011).

Coupled cavities in 3D

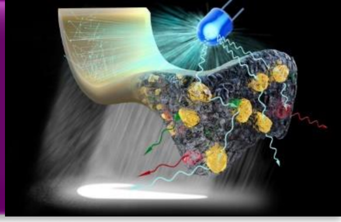


Coupled cavities shielded in a 3D band gap.

Unconventional light propagation in a few high-symmetry (x,y,z) directions.

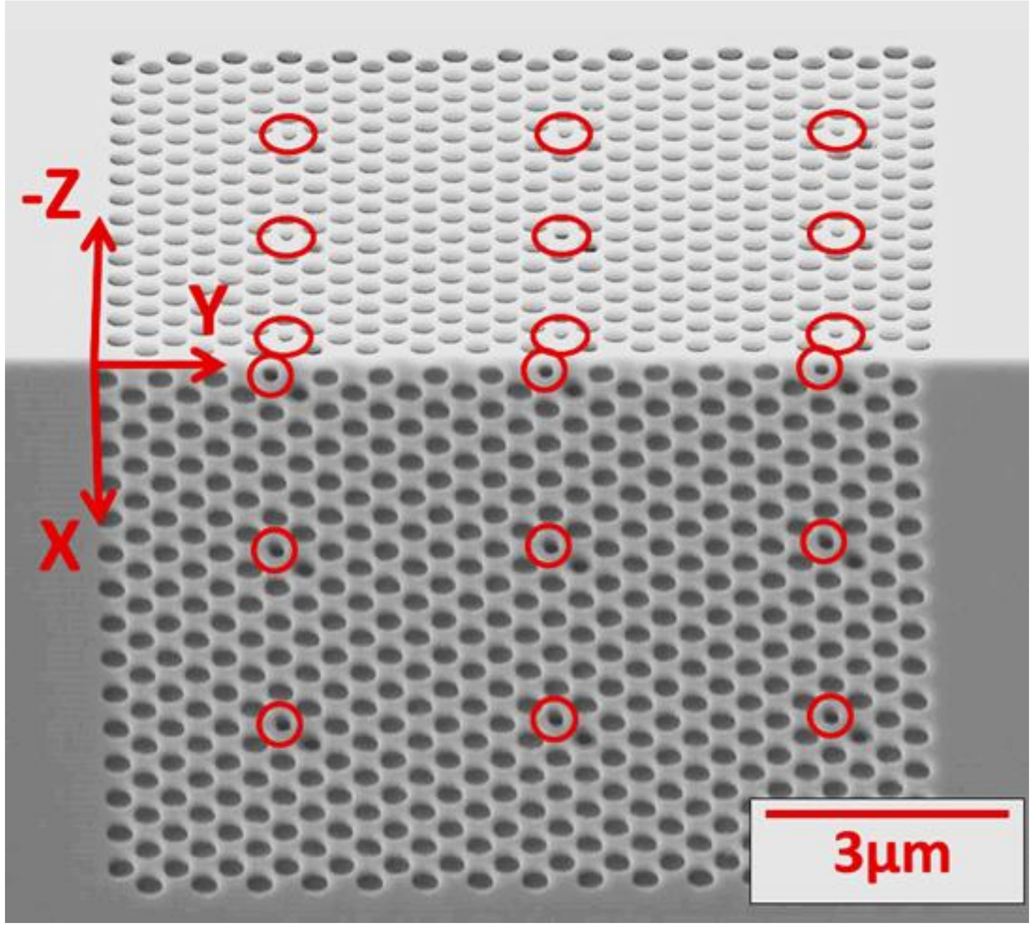


Coupled cavities in 3D



A 3D inverse woodpile crystal made of Si, doped with point defects – cavities.

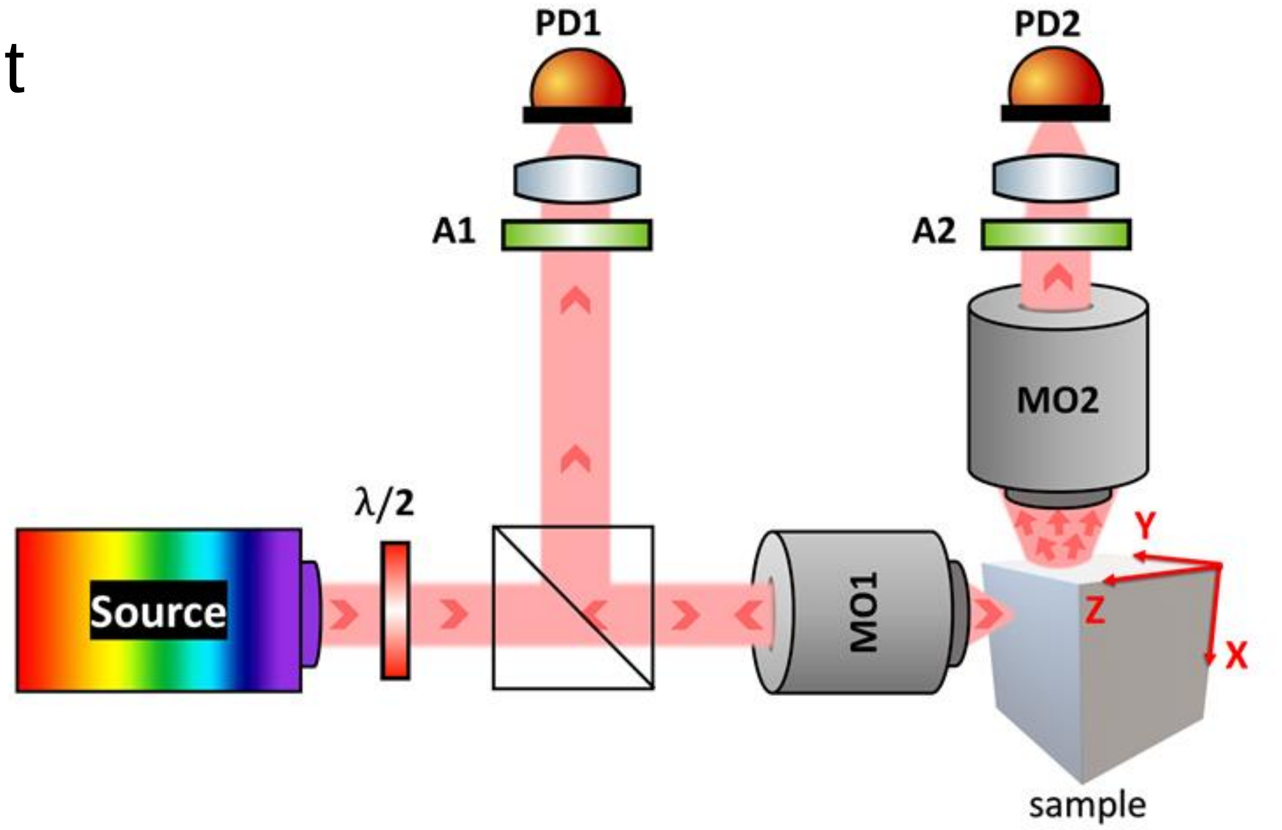
The cavities are periodically repeated in 3D in the crystal forming the 3D cavity superlattice.



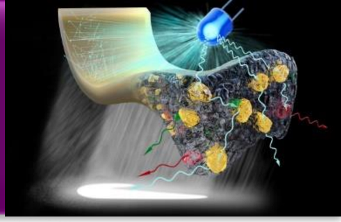
Woldering, Mosk, and Vos, Phys. Rev. B, **90**, 115140: 1-9 (2014)

Measurement of cavity superlattice

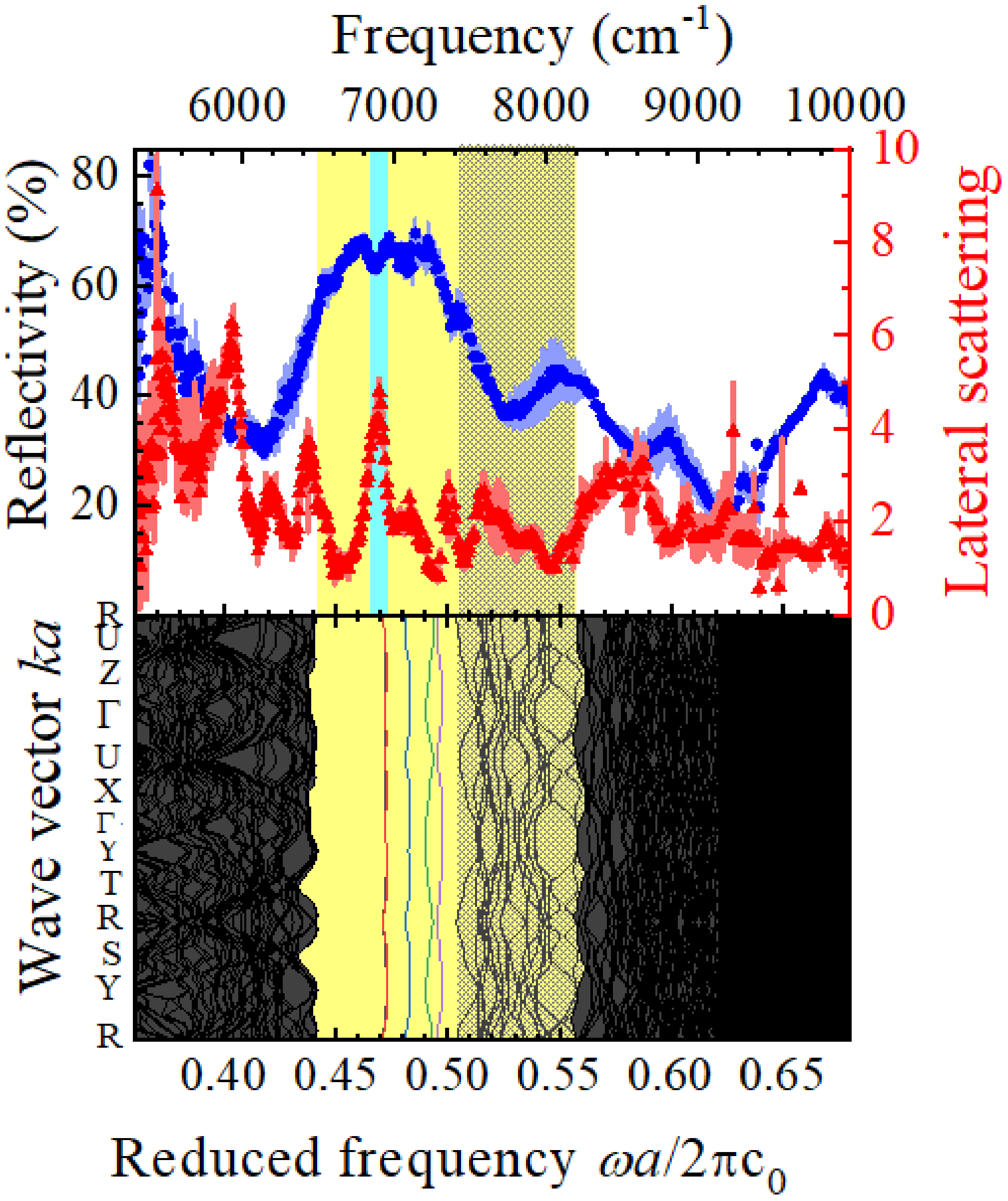
Spectroscopic measurement of reflectivity and scattering



Measurement of cavity superlattice

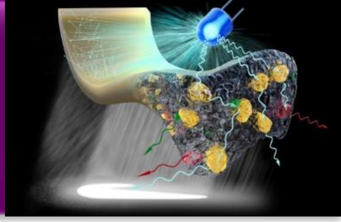


1. Narrowed band gap from high frequency side
2. Troughs inside the reflectivity peak
3. Narrow scattering peak at frequency corresponding to a reflectivity trough within bandgap

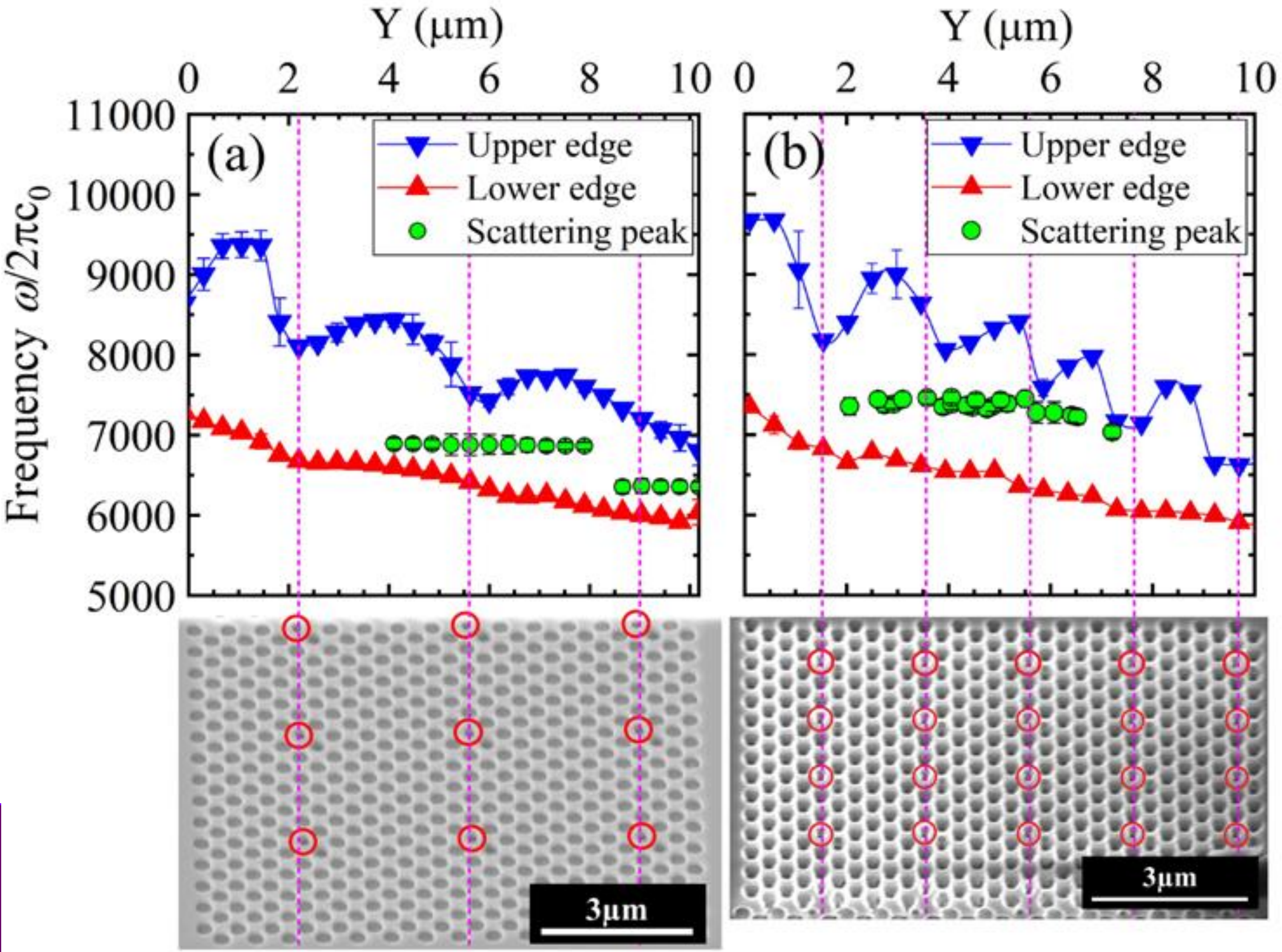


Adhikary, PhD thesis (2021)

Coupled cavities



Cavities are coupled in the Y direction when they are closely spaced.



Adhikary, PhD thesis (2021)

Minh Duy Truong

Sensing the position of a single scatterer in opaque media using Mutual Extinction and Transparency

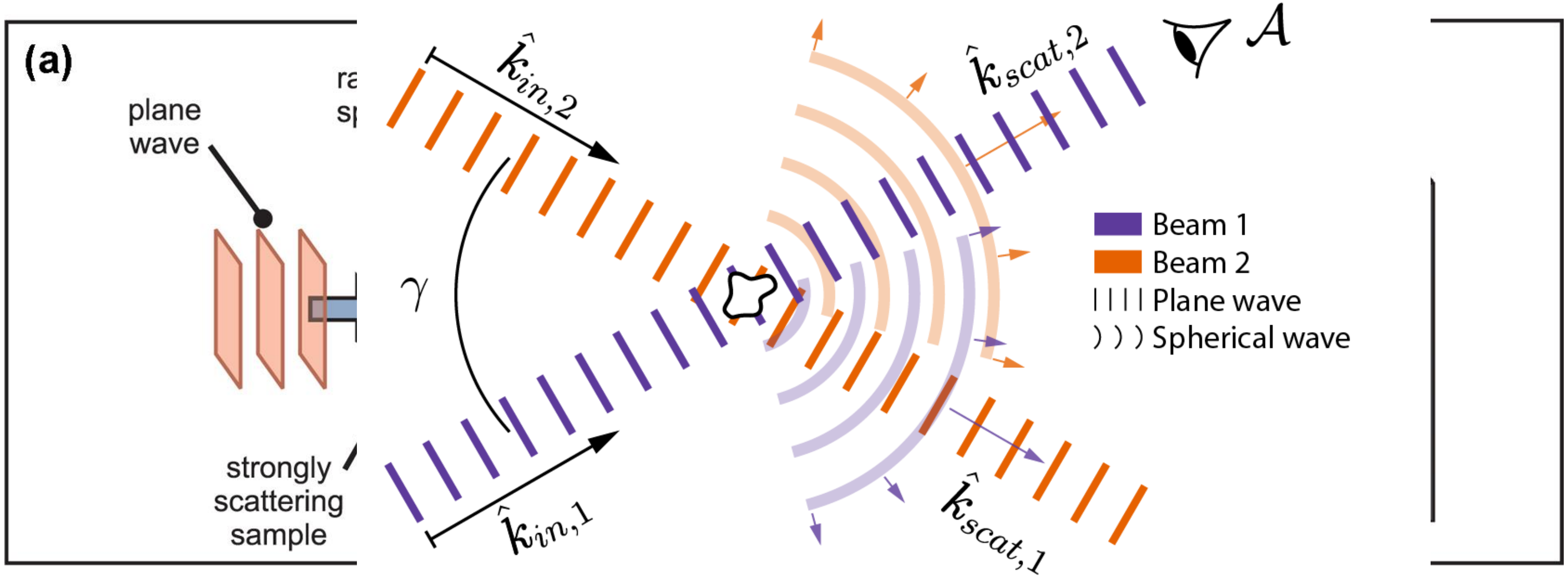
"NEEDLE IN A HAYSTACK"

MINH DUY TRUONG

Free-form Scattering Optics program meeting

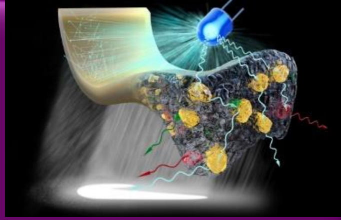
1st November, 2021

Wavefront Shaping → Mutual Extinction and Transparency



Phys. Rev. A 104, 043515 (2021)

Applications of Mutual Extinction & Transparency



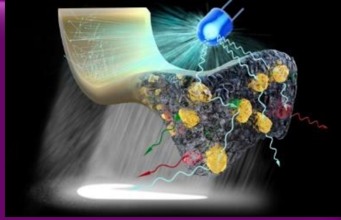
cross-interference
of multiple beams

$\vee$

1-beam
scattering methods

- ❖ Determine the shape (nano-scale)
- ❖ Sense a scatterer in opaque media (needle in a haystack)
- ❖ Detect concentration of matter in the air/liquid

Why Mutual Extinction & Transparency?



- Conventional methods: 1 beam

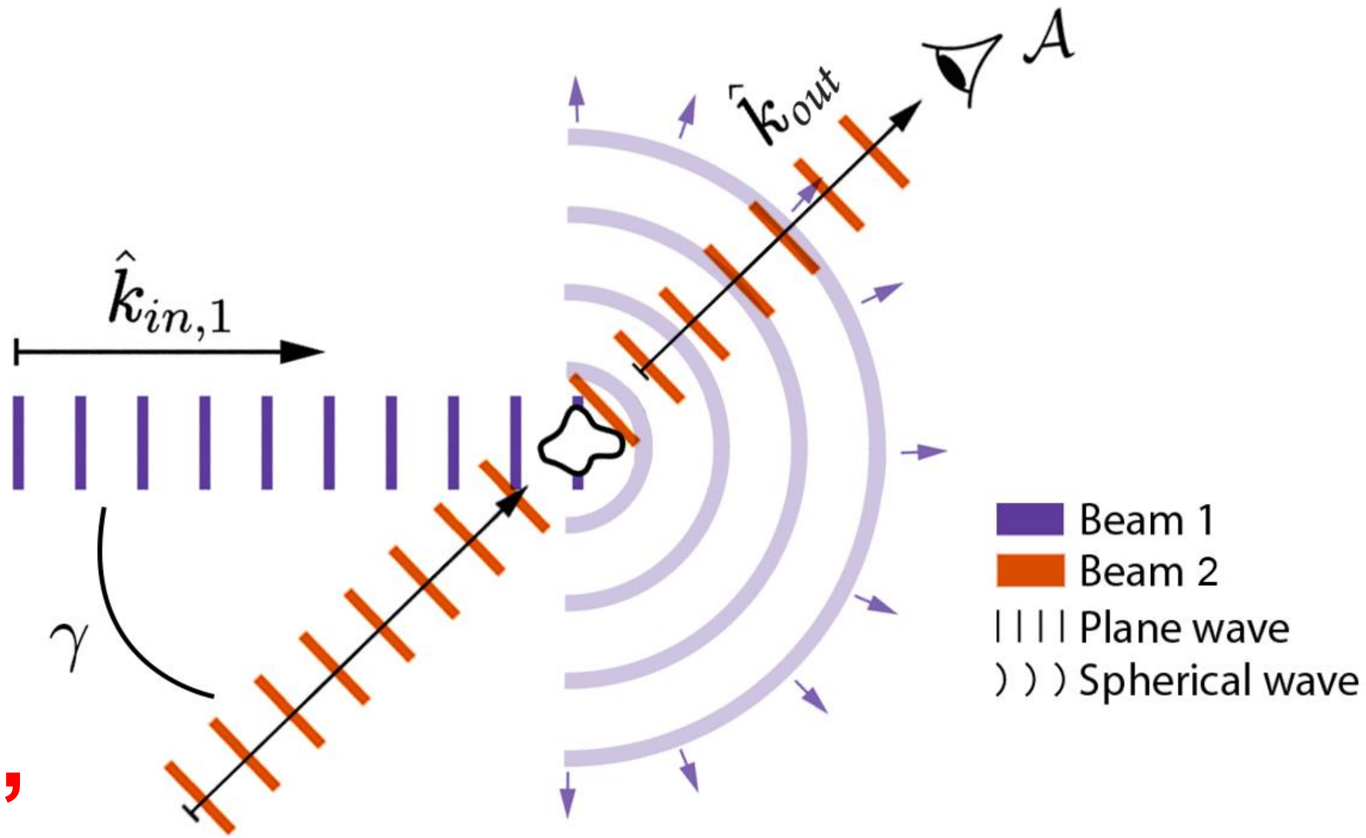
$$I_1 \propto |\psi_{\text{scat},1}|^2 = \psi^*_{\text{scat},1}\psi_{\text{scat},1}$$
$$\propto |f(\mathbf{k}_{\text{out}}, \mathbf{k}_{\text{in}})|^2$$

f: scattering amplitude

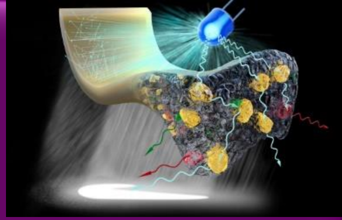
- Mutual Extinction: 2 beams

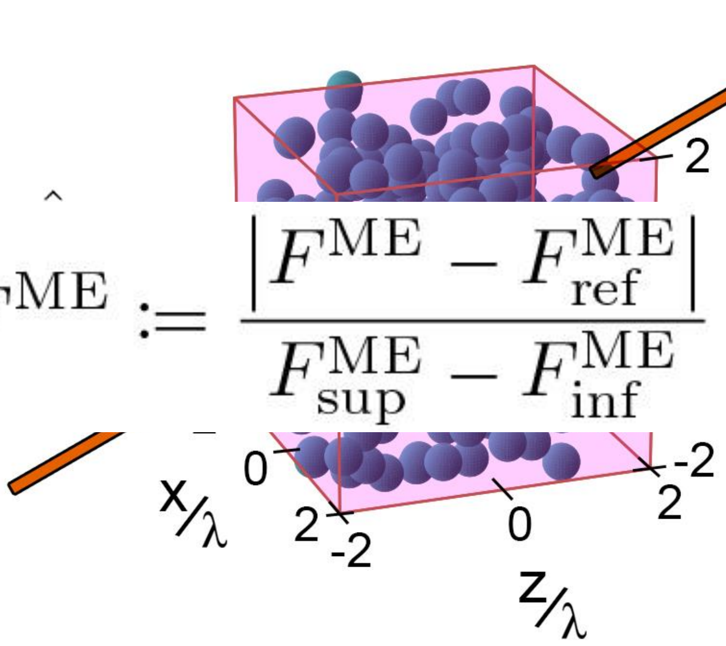
$$I_2 \propto \psi^*_{\text{in},2}\psi_{\text{scat},1} \propto f(\mathbf{k}_{\text{out}}, \mathbf{k}_{\text{in}})$$

"Amplitude vs Intensity"

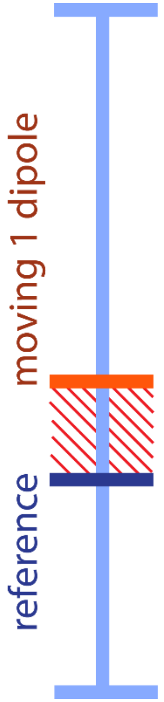


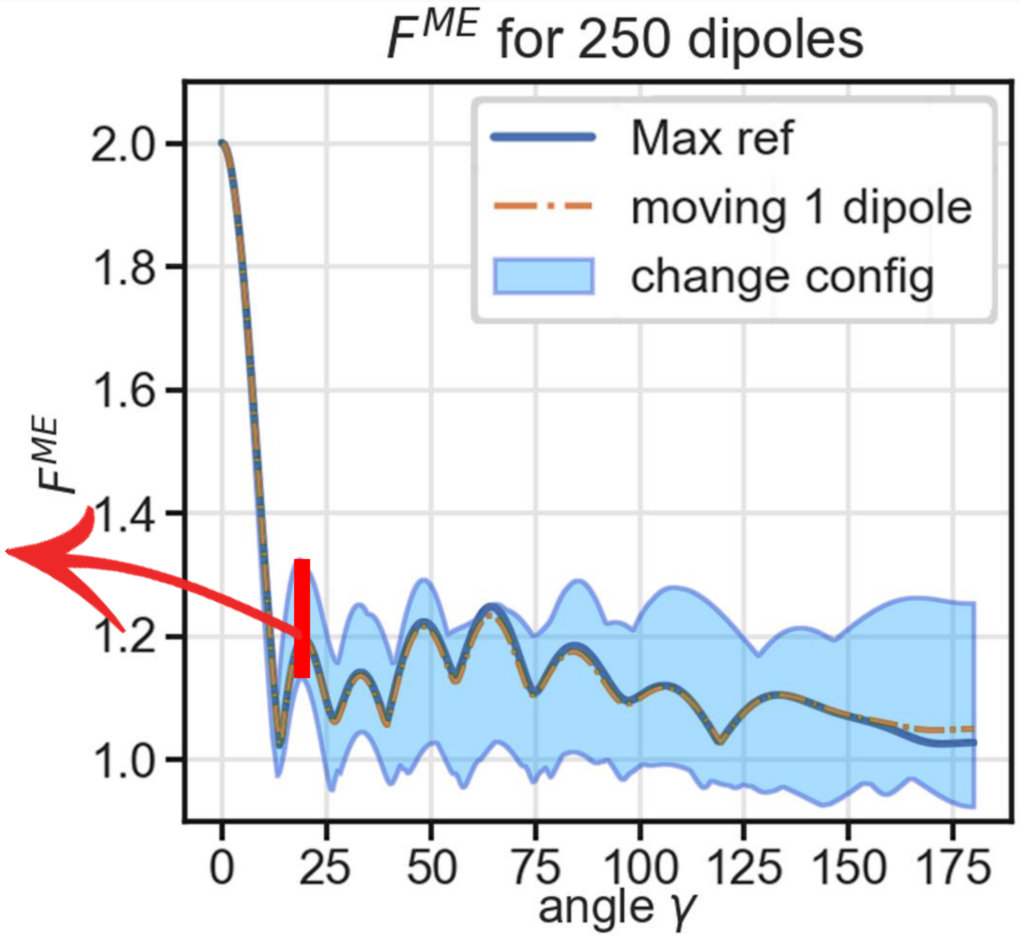
Sensitivity of MET - needle in a haystack





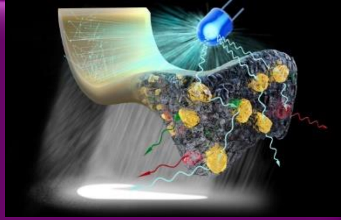
$$\tilde{\delta} F^{\mathrm{ME}} := \frac{\left| F^{\mathrm{ME}} - F^{\mathrm{ME}}_{\mathrm{ref}} \right|}{F^{\mathrm{ME}}_{\mathrm{sup}} - F^{\mathrm{ME}}_{\mathrm{inf}}} > \frac{1}{N_{\mathrm{dipole}}}$$

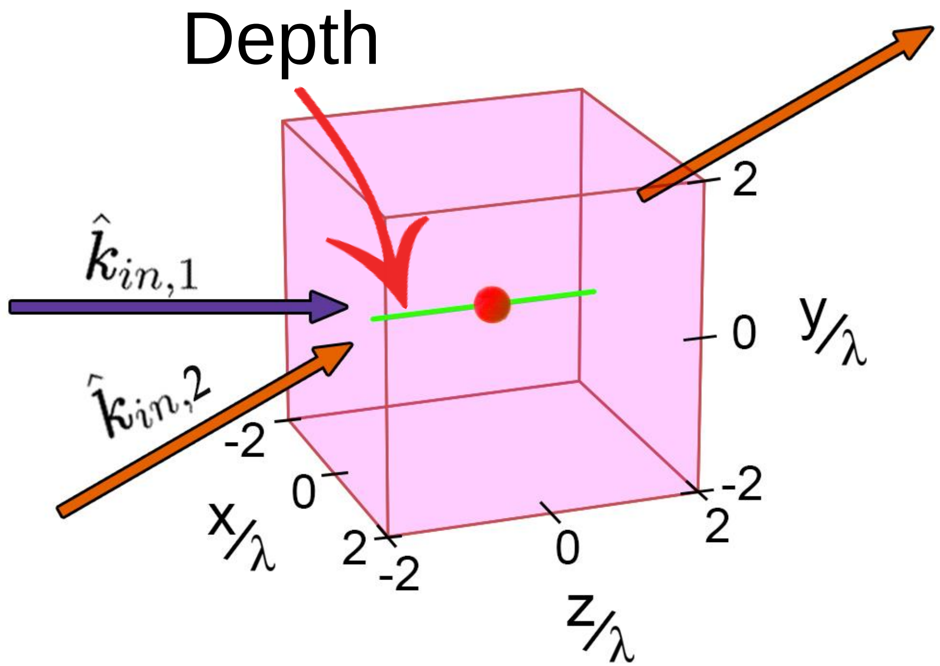


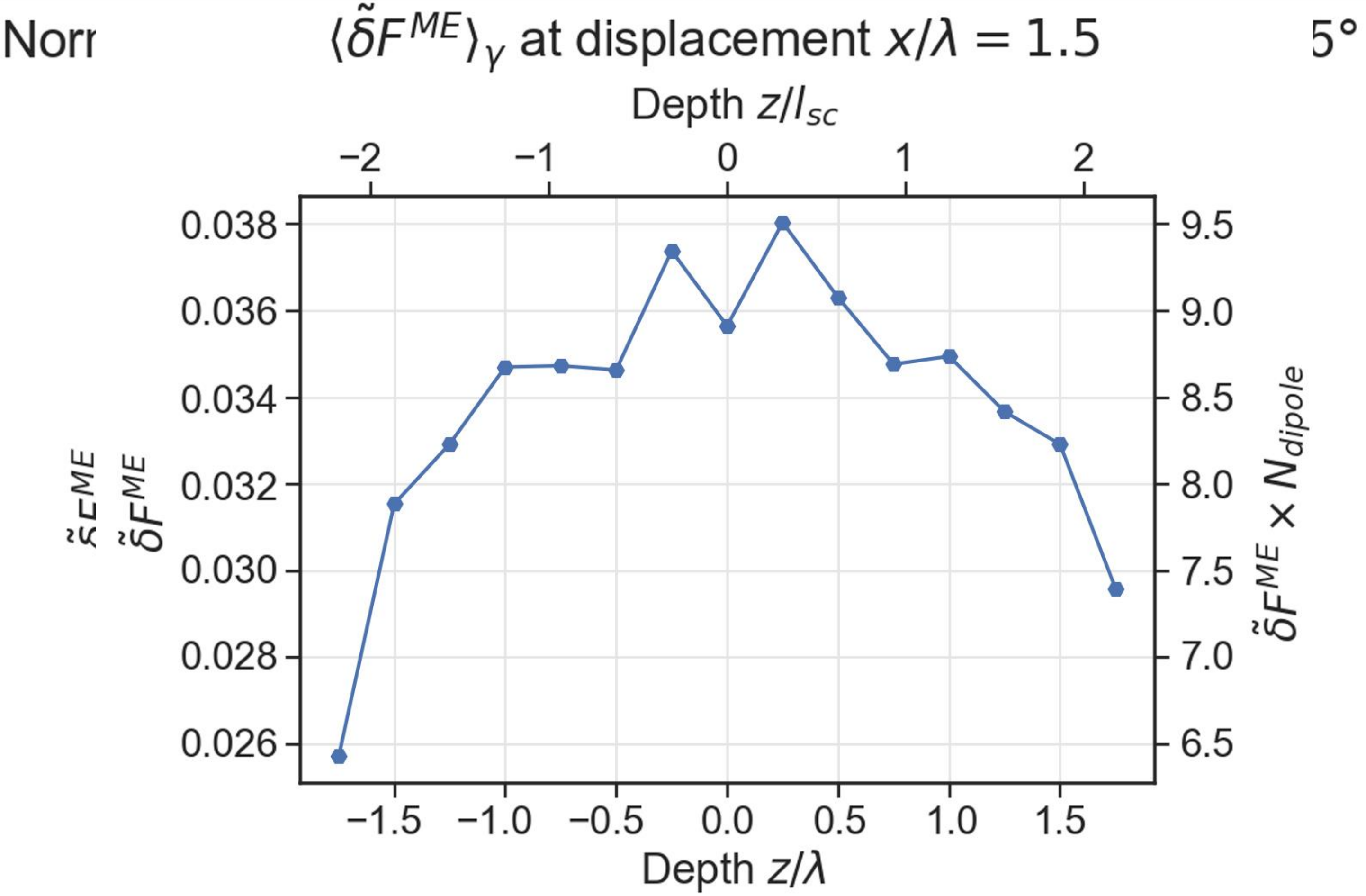


- ❖ Move 1 scatterer
- ❖ Change all the configuration (N scatterers)

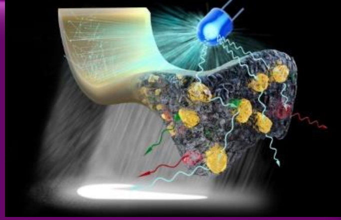
Sensitivity of MET - location of a moving scatterer







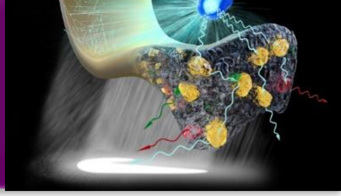
Summary



- ❖Mutual Extinction and Transparency (MET)
- ❖Why MET from multiple beams better than conventional 1 beam methods
- ❖Sensitivity of MET in sensing a scatterer in opaque media

Summarizing & action points (Willem)

Time plan realization



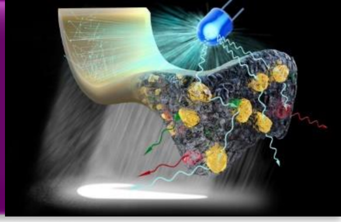
Work package		2017				2018				2019				2020				2021			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
D1 Anisotropic surface scattering	PhD #9					Build algorithm for structured scattering surface computation						Guest @UT (C2)	Finalise algorithm		Fabrication of S3 Surface				Application Luminaire (internship)		Thesis
D2 Directing shaped waves th. absorp. & conv.	PhD #10					WFS on hidden target						Internship marks (ASML)		"Needles in haystack"						Lumil. intern-ship	Thesis
D3 Controlled functional speckle	PhD #6			Set up method & techniques, employ ceramic samples					Intern @Schott	Stabilize speckle, advanced ceramics				Internship speckle (TNO)		Analysis, modeling			Thesis		

Table 6. Planning and deliverables of project D and corresponding work packages.

Science is being executed quite close to plan (yoopee!)

Due to delay early on (legal wrangling…), FFSO delayed by Δt=2 yrs, so 2017 $\rightarrow$ 2019, 2018 $\rightarrow$ 2020. And then corona started (…) , so internships at User facilities hampered $\Rightarrow$ Revise plans with Users

Deliverables status

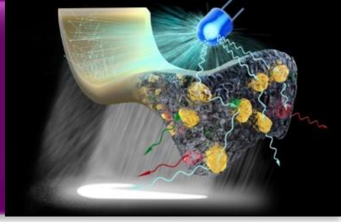


Well underway:
D1.1-3
D2.1 (part)
D2.2
D3.1

Project deliverables:
D1.1: Design strategy for homogeneous illumination optics with diffuse gratings.
D1.2: Easy-to-use software based on Matlab to our users.
D1.3: Fabrication of a S^3 for a test case.
D2.1: Demonstrate exact localization of known markers through thin scattering layers.
D2.2: 'Needle in a haystack': detect microscopic markers embedded in scattering media.
D3.1: Theoretical framework for combined effect of perturbations (in position, wavelength) on speckle patterns.
D3.2: New optical methods for on- and off-board calibration of satellite-detectors.
D3.3: Design efficient homogenization of laser source for industrial illumination.

Delayed:
D3.2 & D3.3
→ Consult with Users if still relevant, or if new ones more urgent?

Summarizing

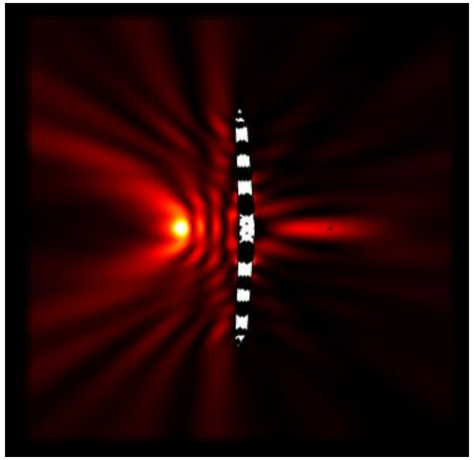


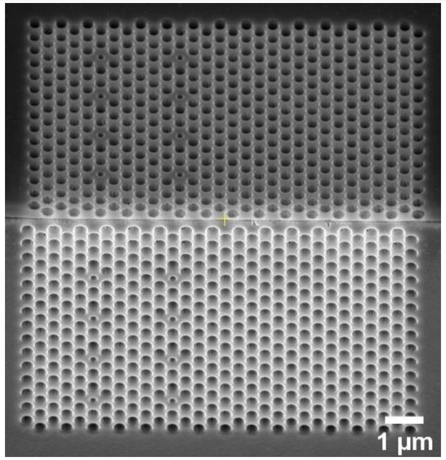
Exciting results obtained in Work Package D (like in packages A-C) on several aspects of wave shaping

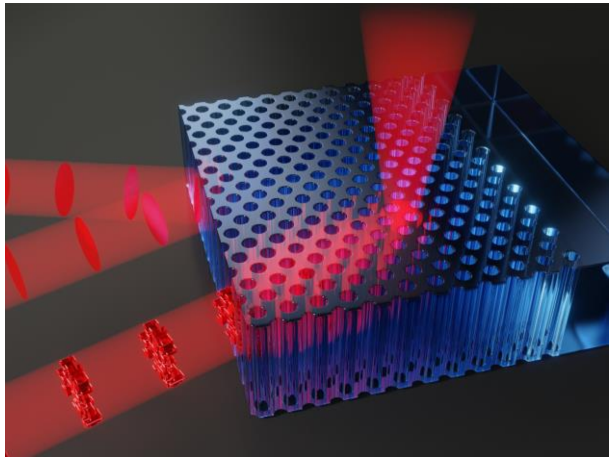
1st PhD graduated (Manashee)

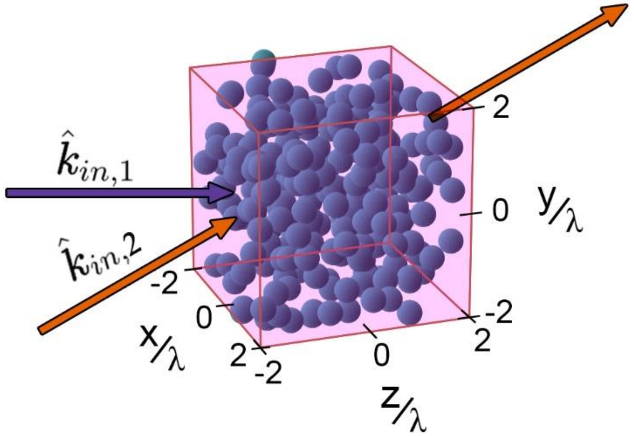
Time plan & deliverables well underway

A few adjustments are welcome, consultations with Users sought

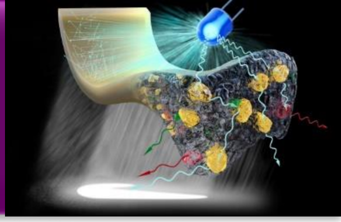


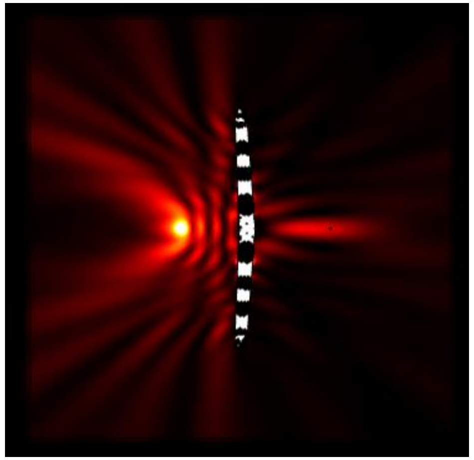


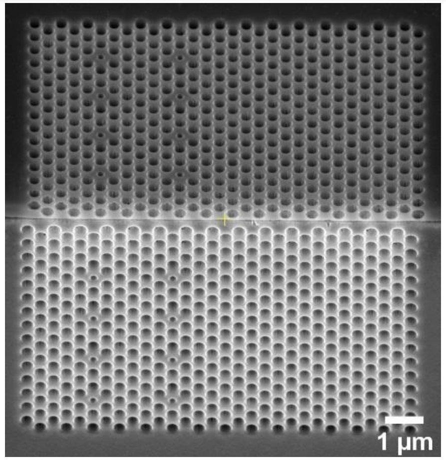




Thank you for your attention!







Thank you very much!