Tunable Optical Metasurfaces with Amplitude and Phase Reconfigurability

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Australian Government
Australian Research Council

Acknowledgments

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Tunable Optical Metasurfaces with Amplitude and Phase Reconfigurability

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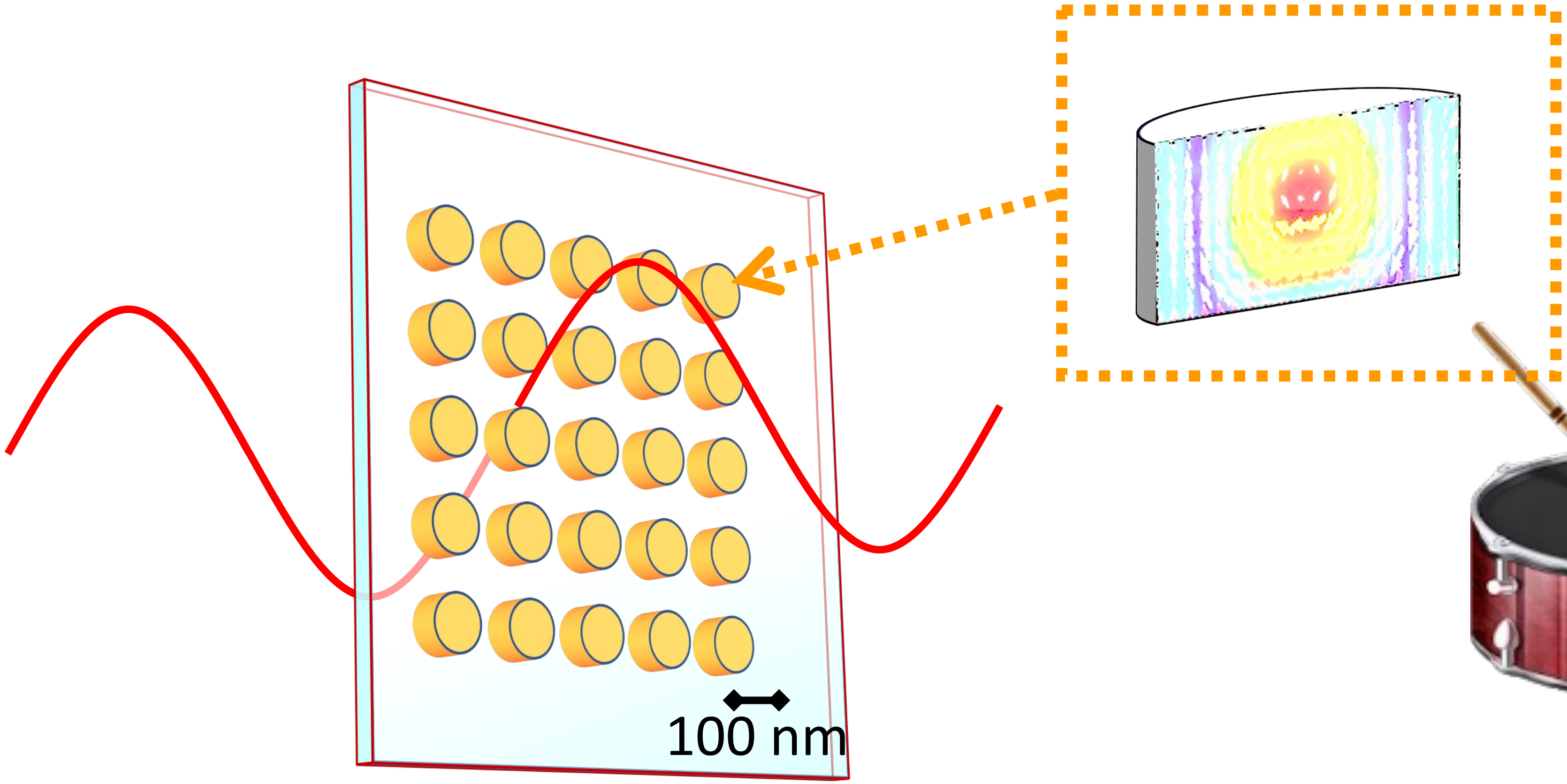
ANFF

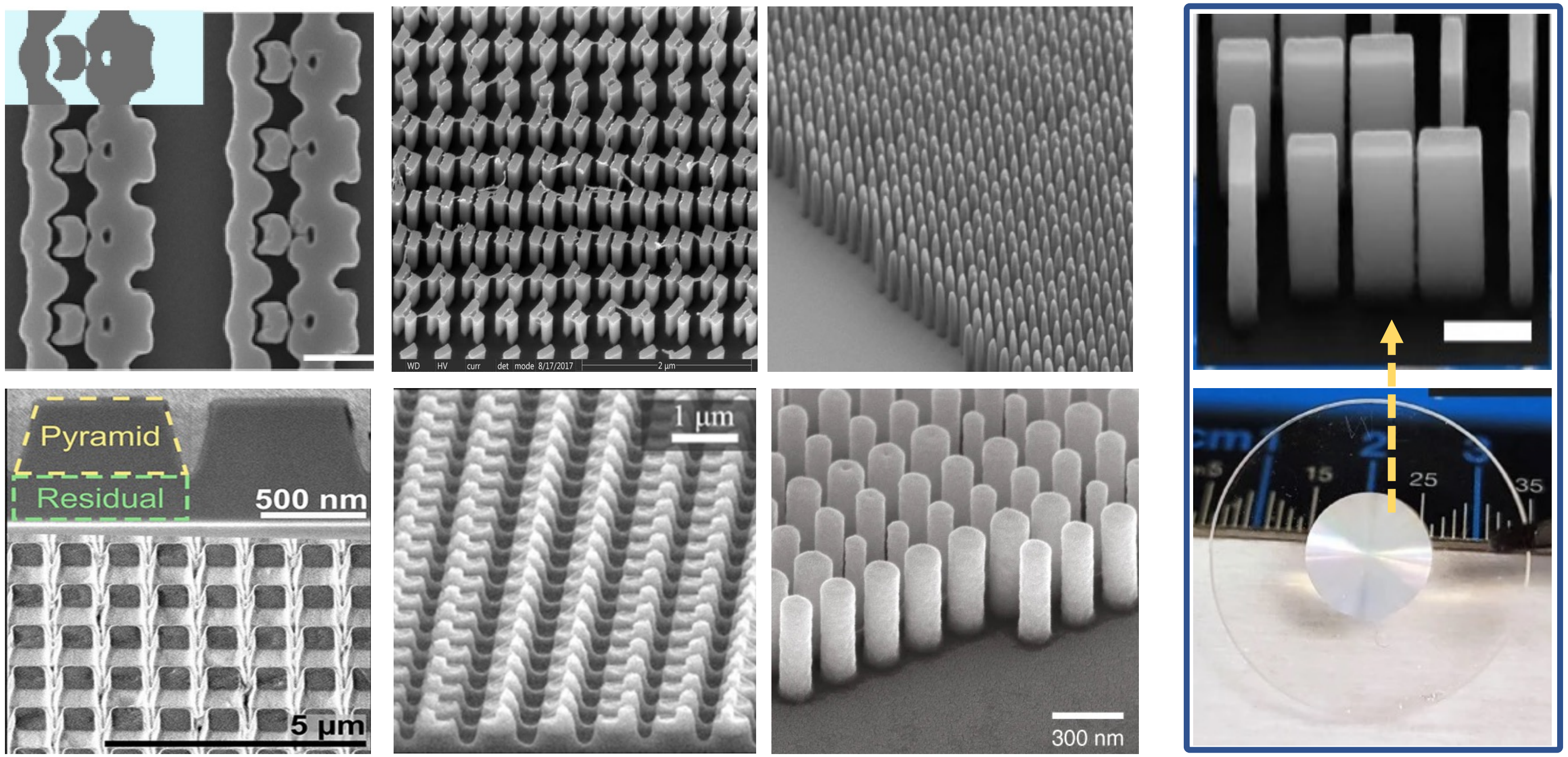
Australian National Fabrication Facility

Driven by resonances

Metasurfaces are subwavelength arrays of nano-scale optical elements



Meta-optical elements

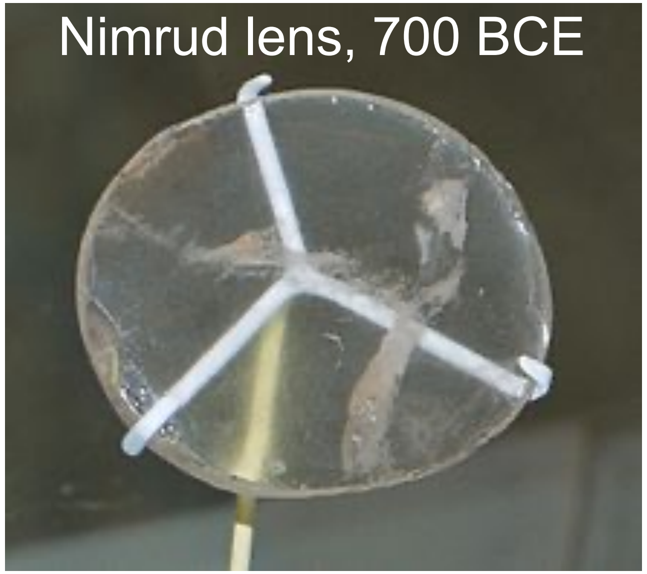


$LiNbO_3$ GaAs HfO TiO_2

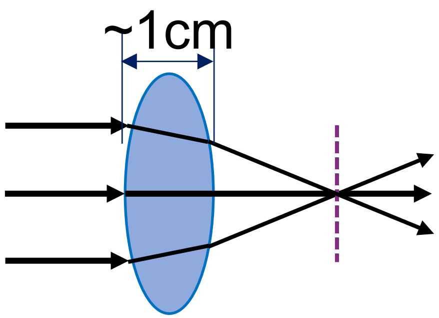
Metasurfaces of different geometries and different materials

From realism to sur-realism and different materials

Replacing bulky glass optical elements



The same concept



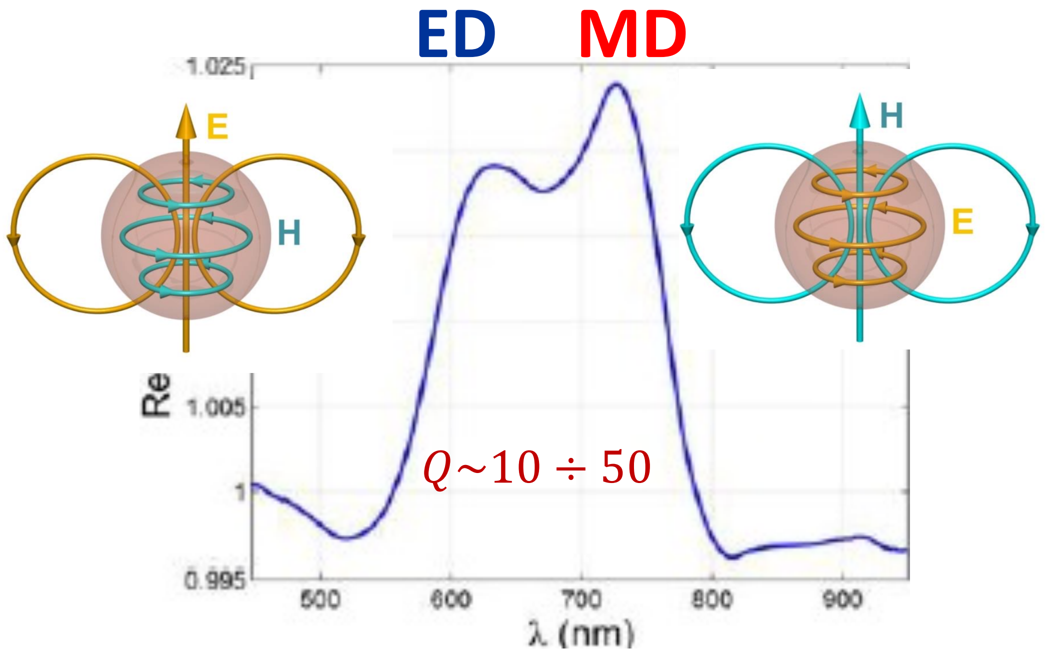
- The lens limits the thickness of OSs
- The number of lenses is limited

Metasurfaces can miniaturise optical components while adding new functionalities

Resonances in metasurfaces

Mie-type resonances

localised resonances

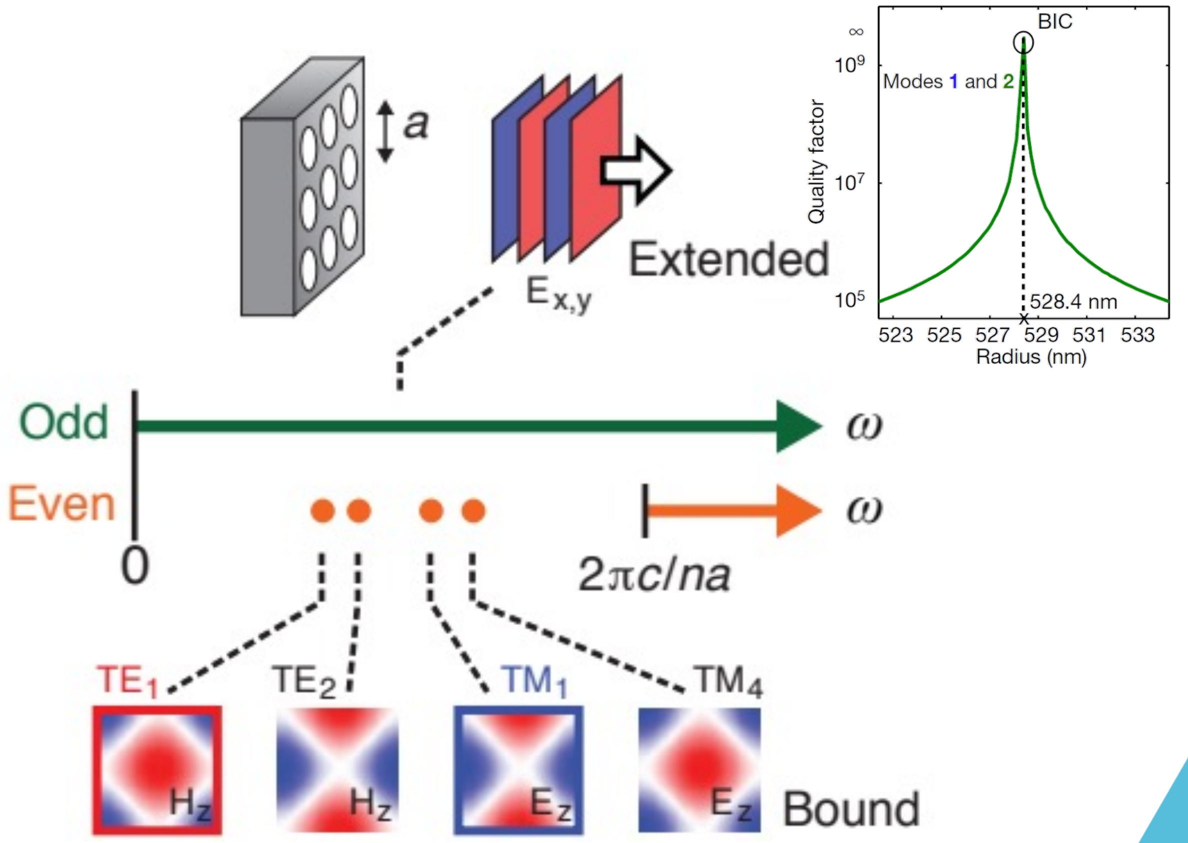


Evlyukhin *et al.*, *Nano Lett.* **12**, 3749 (2012)
Kuznetsov *et al.*, Sci. Rep. **2**, 492 (2012)

Bound state in the continuum (BIC)

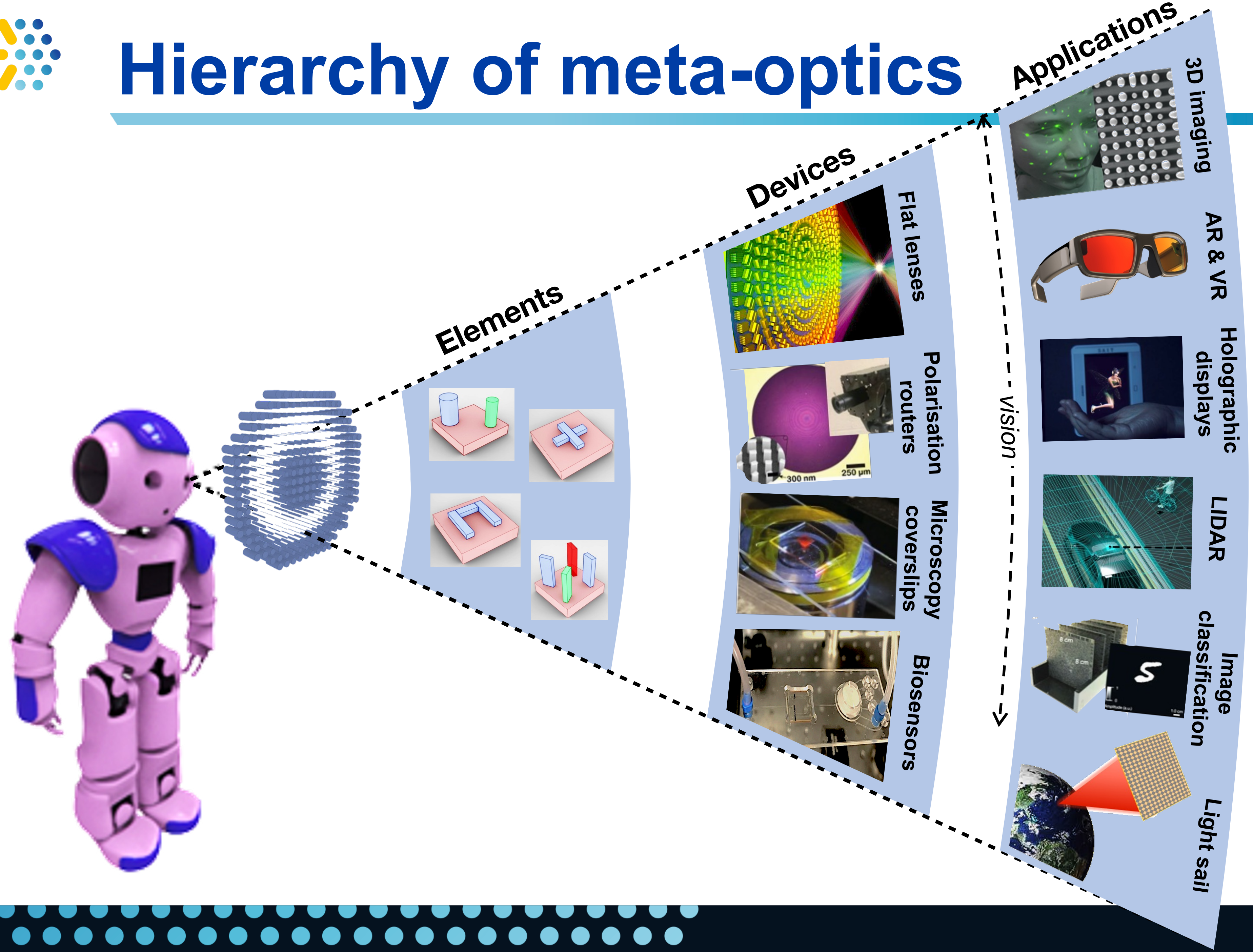
lattice resonances

$Q \sim 100 \div 10{,}000$



Hsu, *et al.*, *Nat. Rev. Mat.*, **1**, 16048, (2016)

Hierarchy of meta-optics



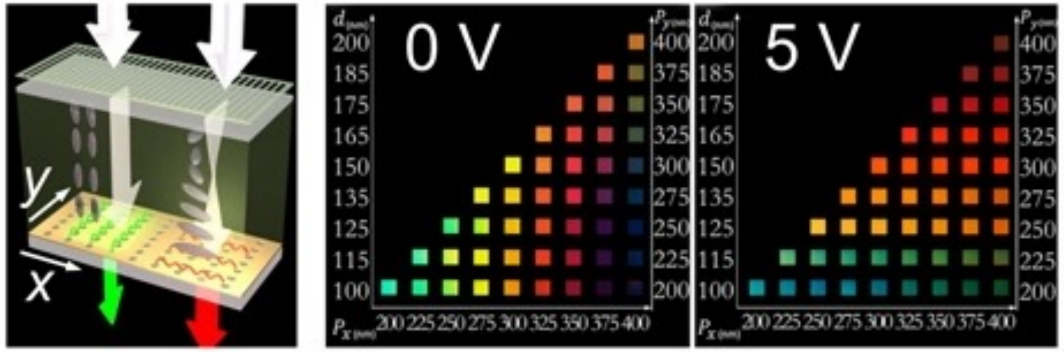
Industrial applications are emerging

Many of them require dynamic tunability of the functionality

Why tunable metasurfaces

Amplitude tuning

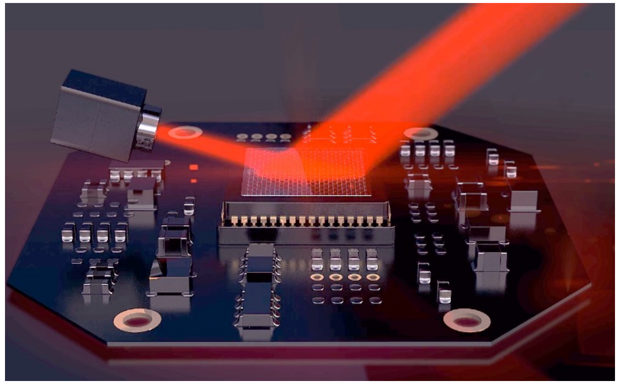
Adaptive colour displays



Neubrech, et al., Science Advances **6**, eabc2709 (2020)

Phase tuning

Dynamic beam steering (LIDAR)

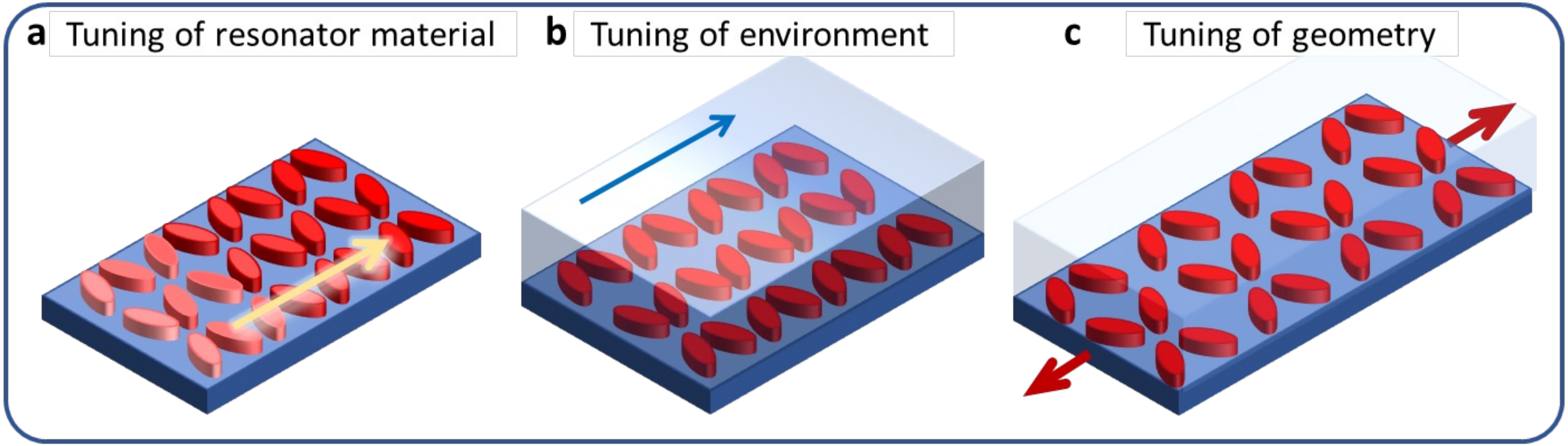


Berini,
ACS Photon. (2022)

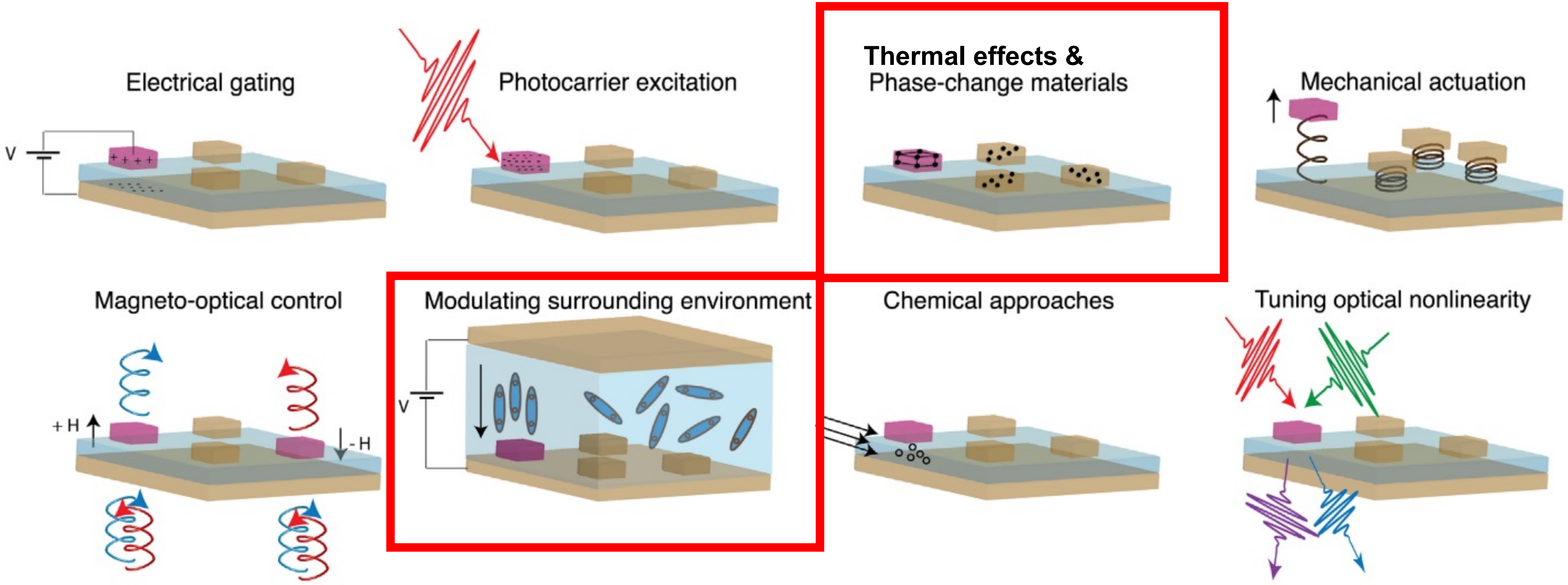
Holographic displays and spatial light modulators

Ultimate goal: Fully programmable optical functionalities

How to tune optical metasurfaces



Tuning mechanisms

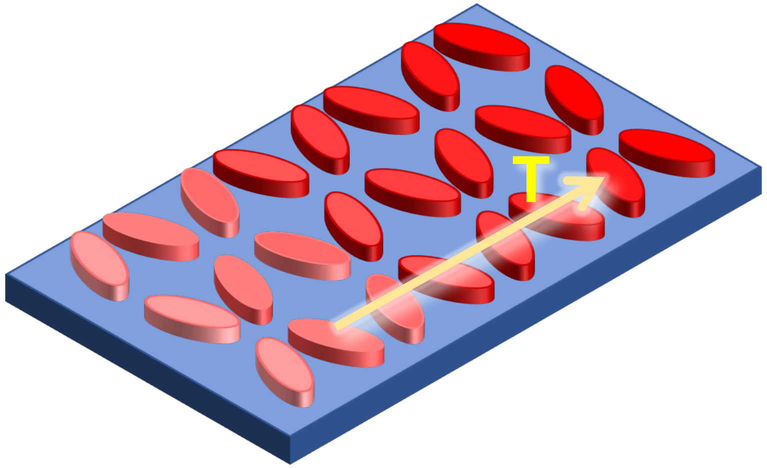


The choice of mechanism will likely depend on the application

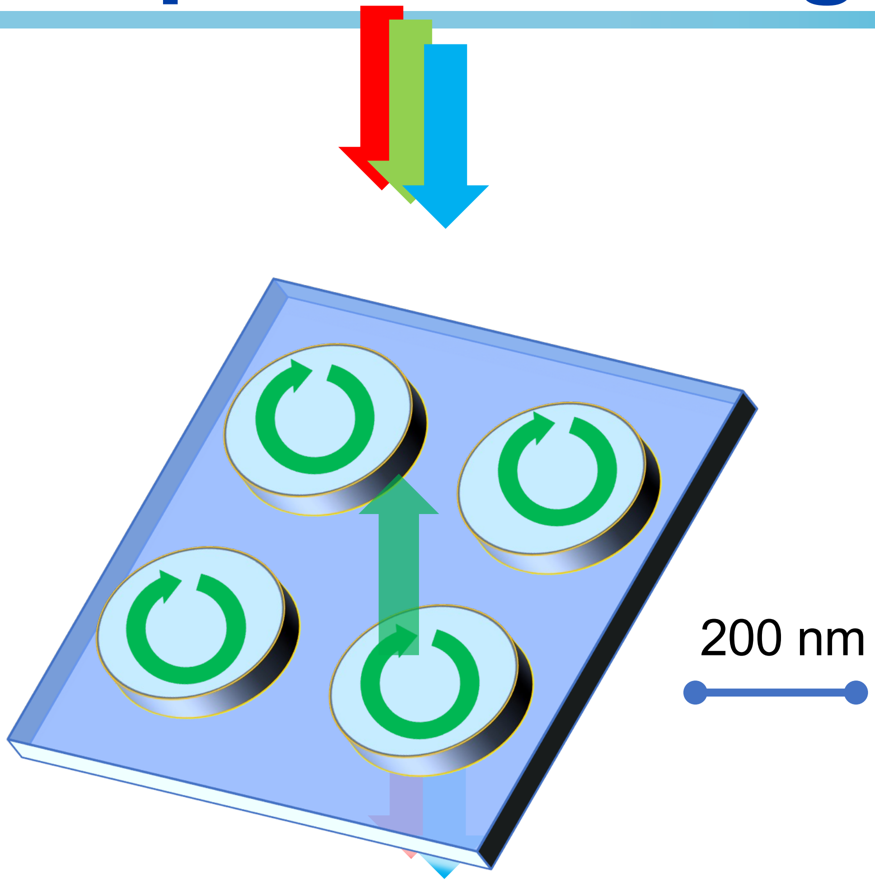
Outline

- Amplitude tuning with programmable functionalities
- Phase only tuning of dielectric metasurfaces
    - Reflection operation
    - Transmission operation
- Conclusion

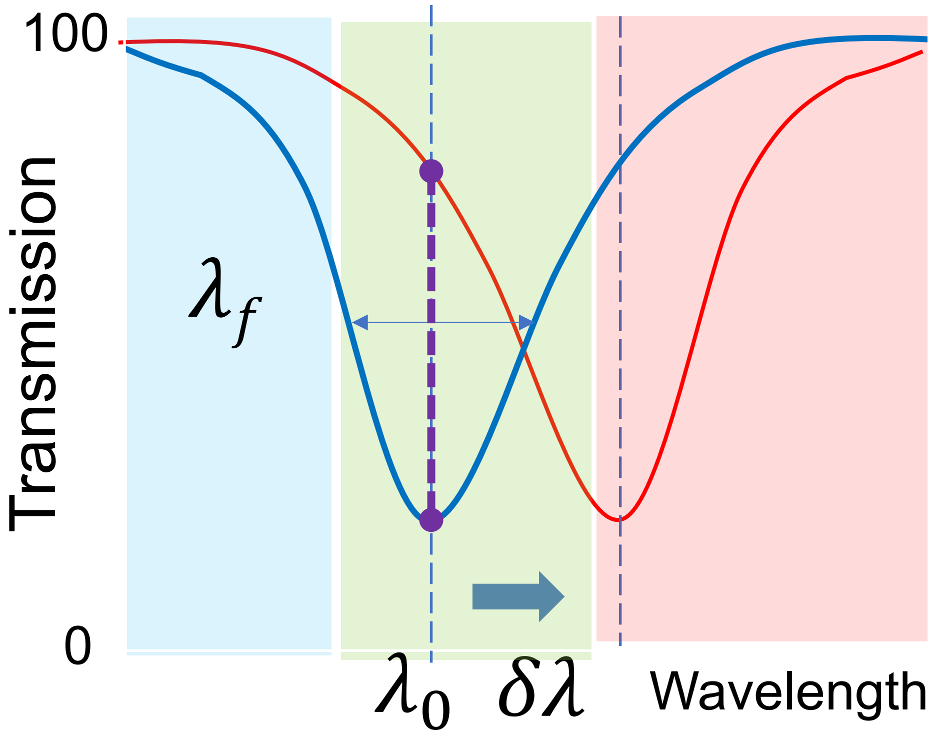
Amplitude tuning
of transmission
by thermo-optic effect



Amplitude tuning of MSs

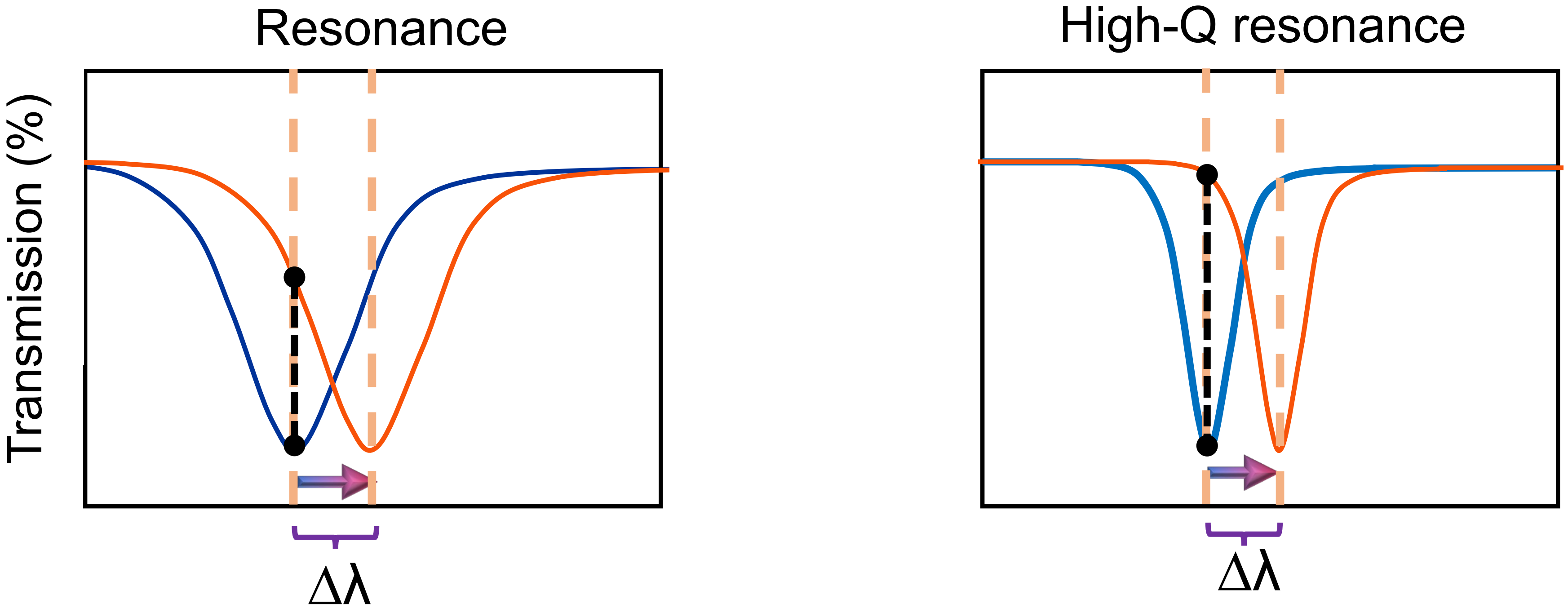


Transmission geometry



Only one resonance needed

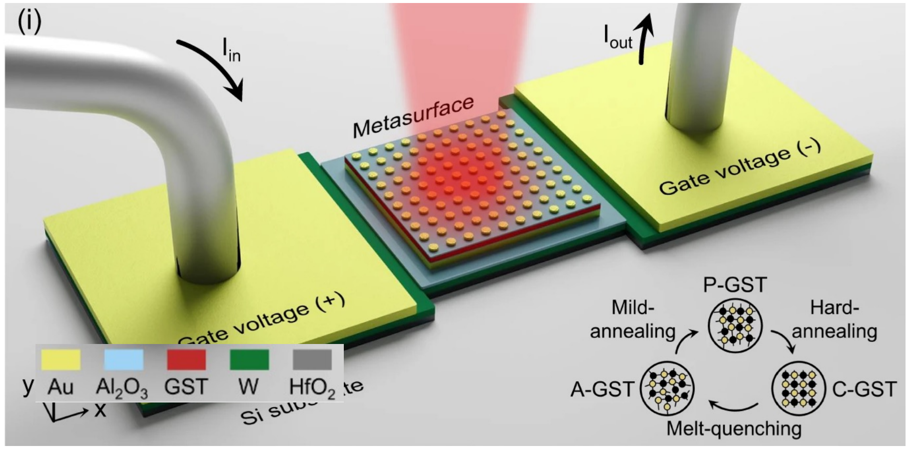
Resonance spectral shift

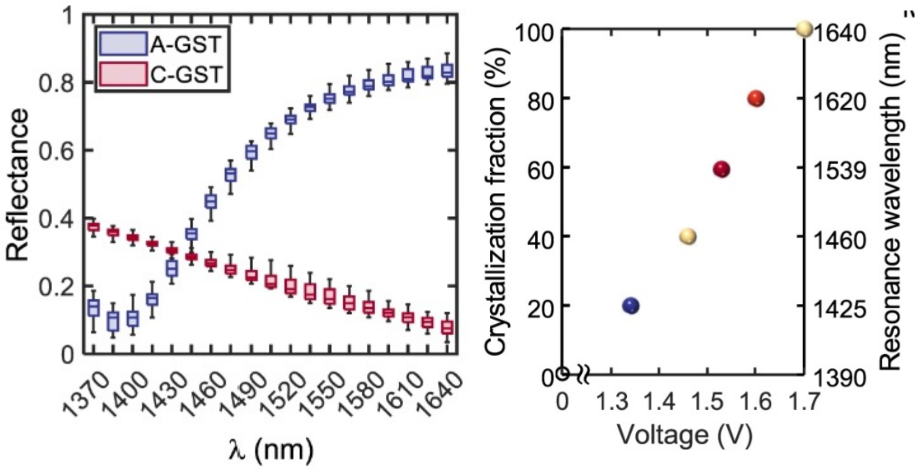


For high-Q resonances, the modulation is significantly stronger!

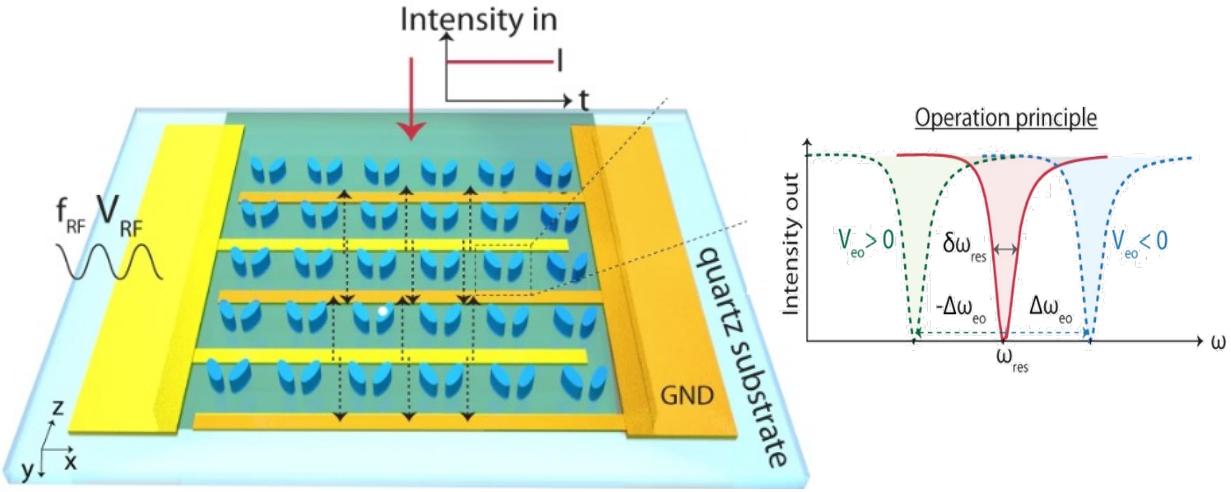
Electrically-driven tunable metasurfaces

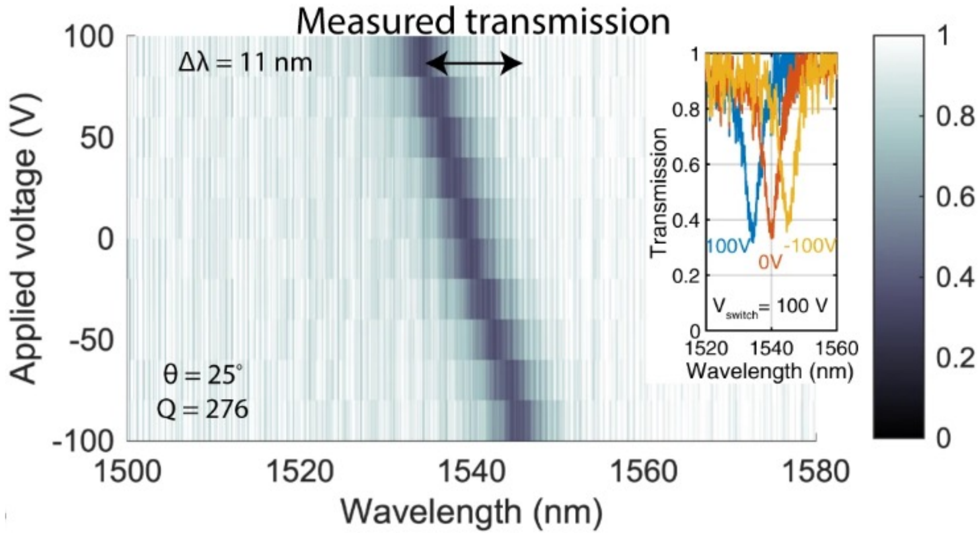
Electrically driven reprogrammable phase-change metasurface





Electro-optic spatial light modulator EO organic layer



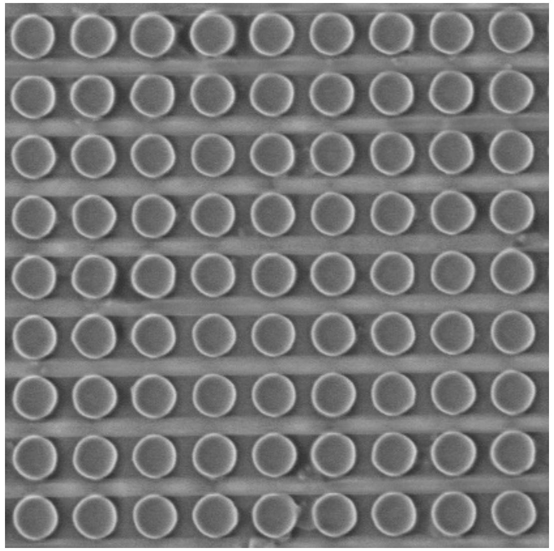


Abdollahramezani *et al.*, Nature Commun. 13, 1696 (2022)

I.-C. Benea-Chelmus *et al.*, Nature Commun. 13, 3170 (2022)

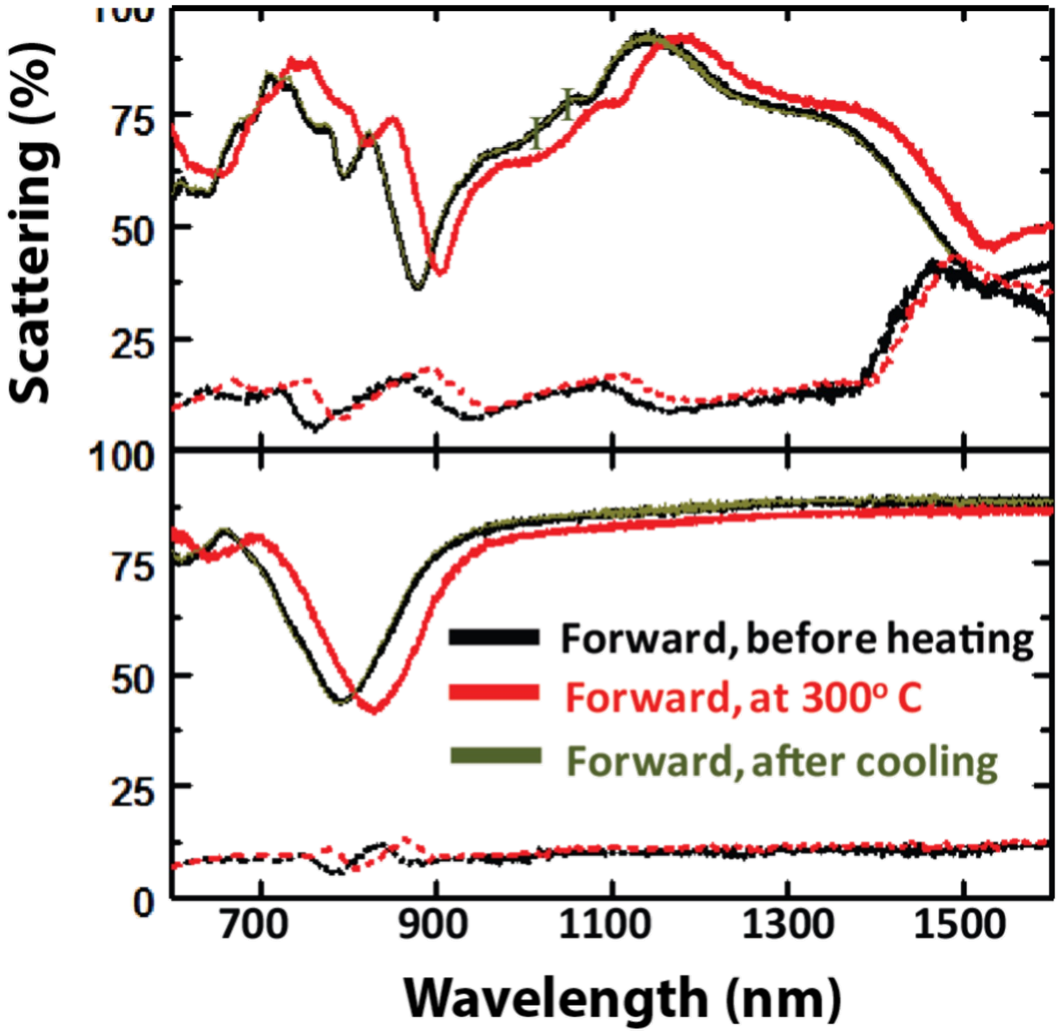
Thermal tuning of Mie-resonant MSs

Si disks Mie-resonant metasurface



Electrical heating to 300° C

Reversible spectral shift of 30 nm

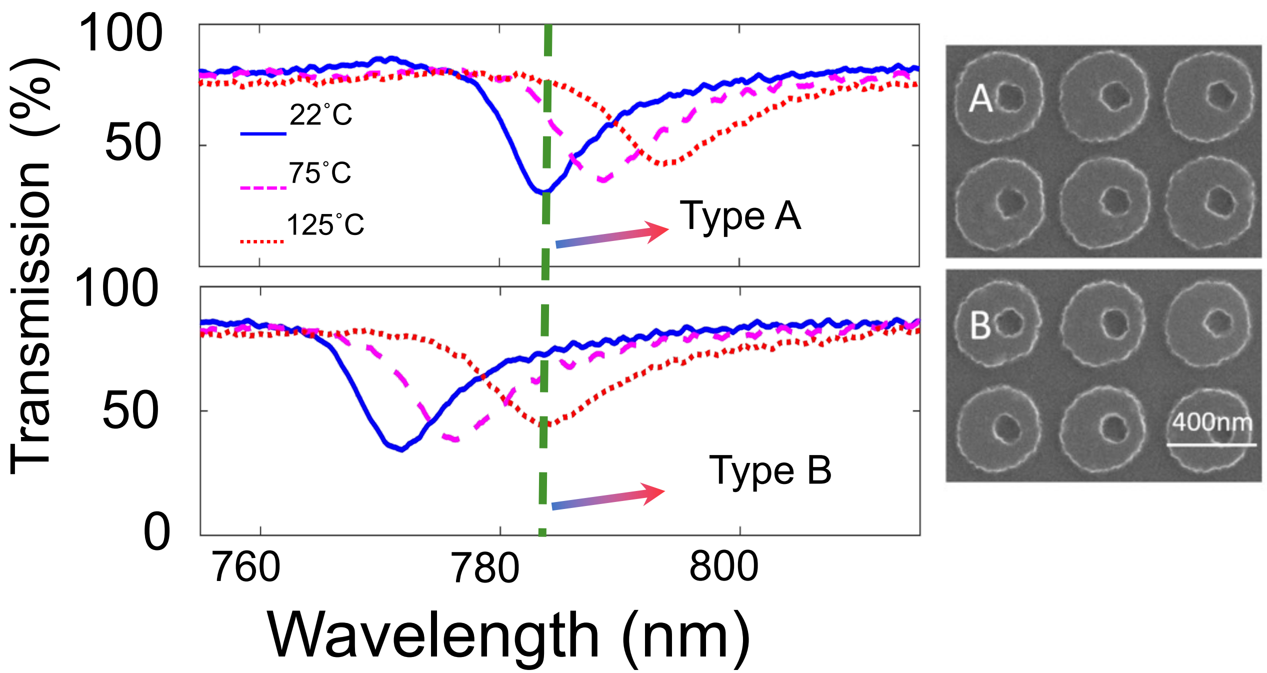


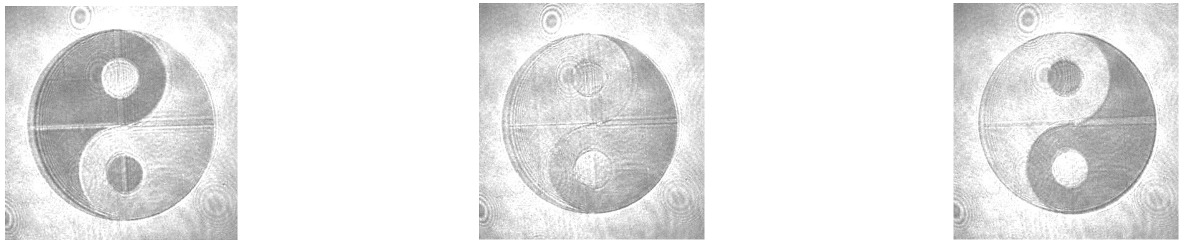
Disks diameter *d*=470 nm

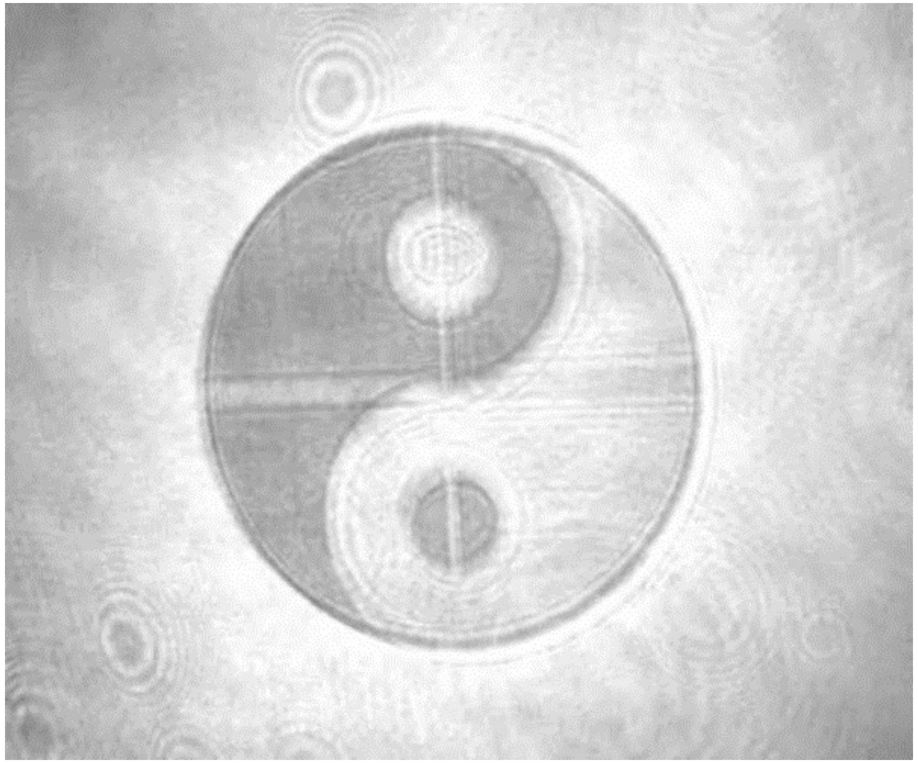
d=170 nm

Rahmani *et al*., Adv. Func. Mat. **27**, 1700580 (2017)

Thermal tuning of high-Q metasurfaces

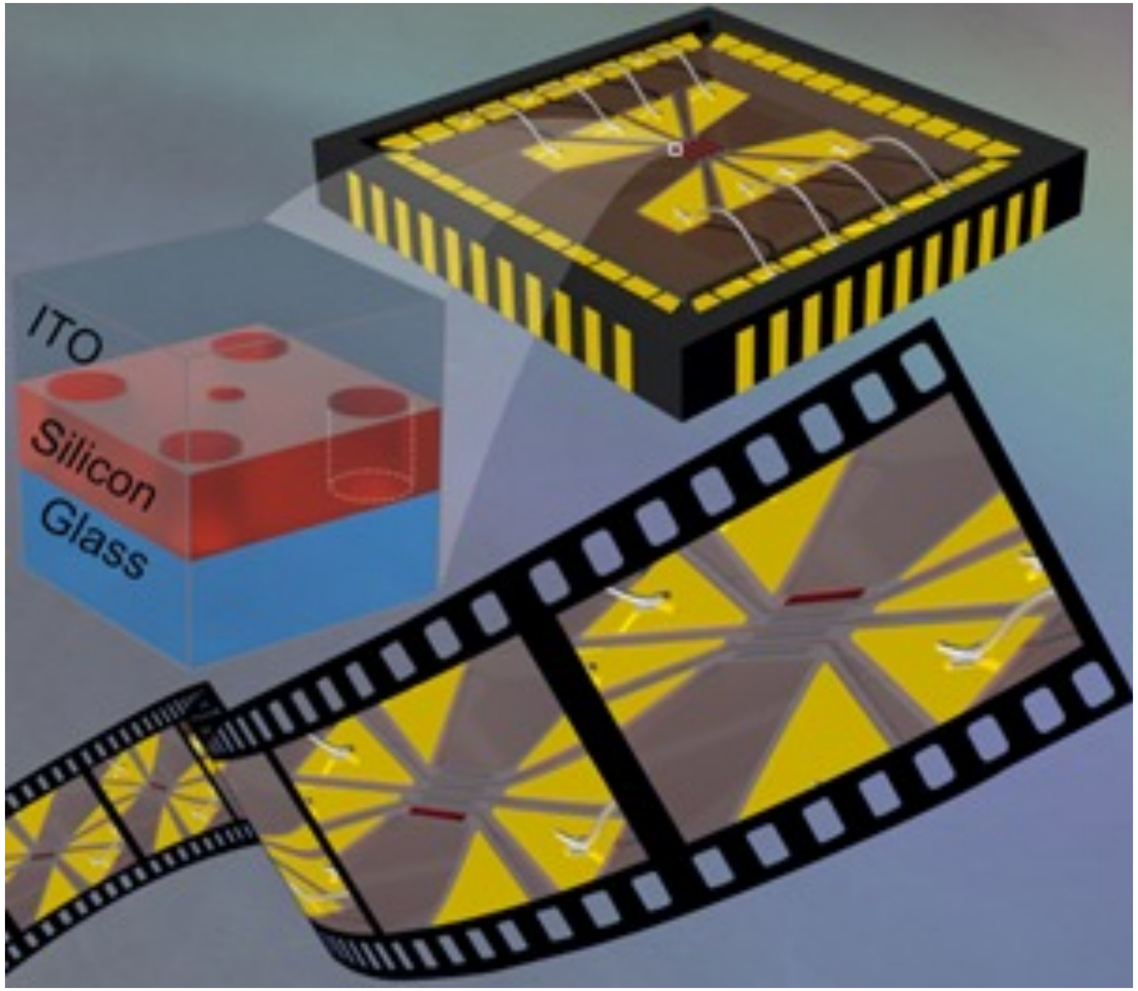




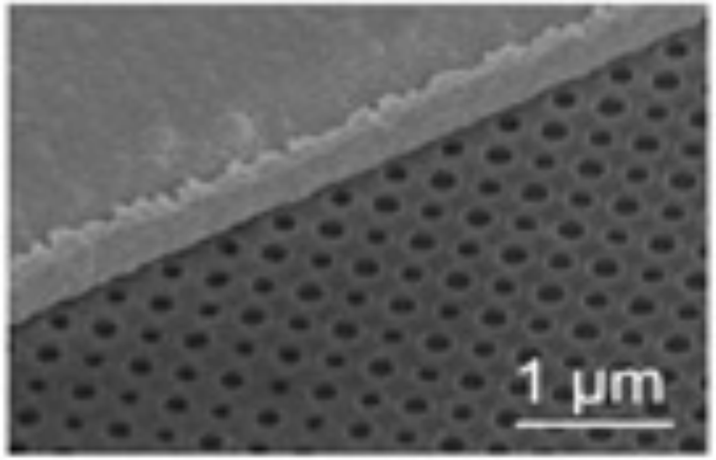


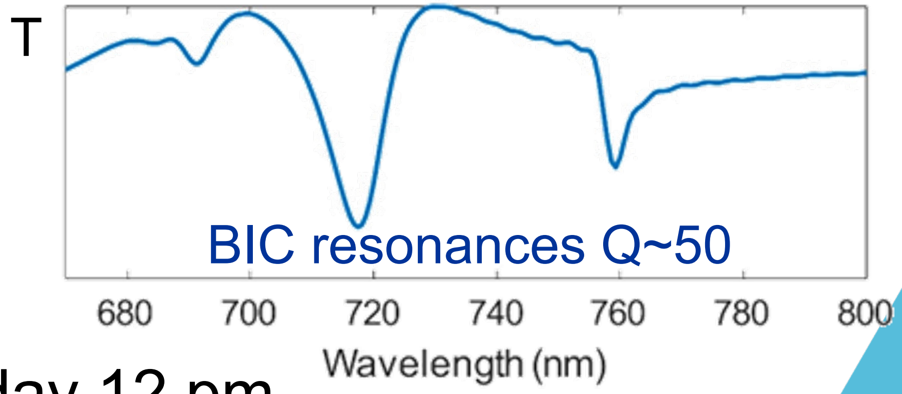
λ = 784 nm

Multi-pixel programmable MSs



Membrane metasurface



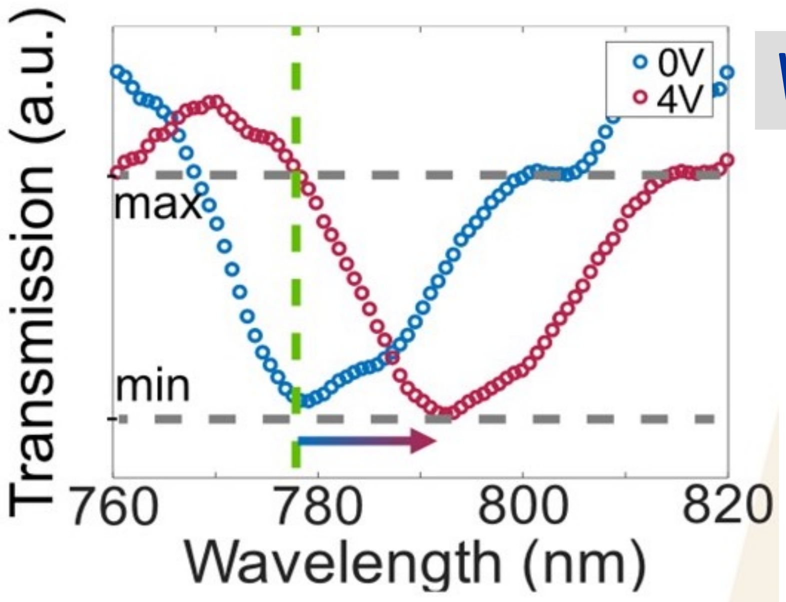


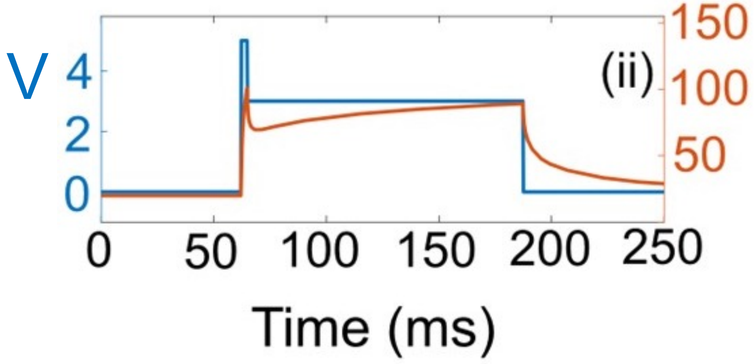
Presentation by K. Zangeneh Kamali, Tuesday 12 pm

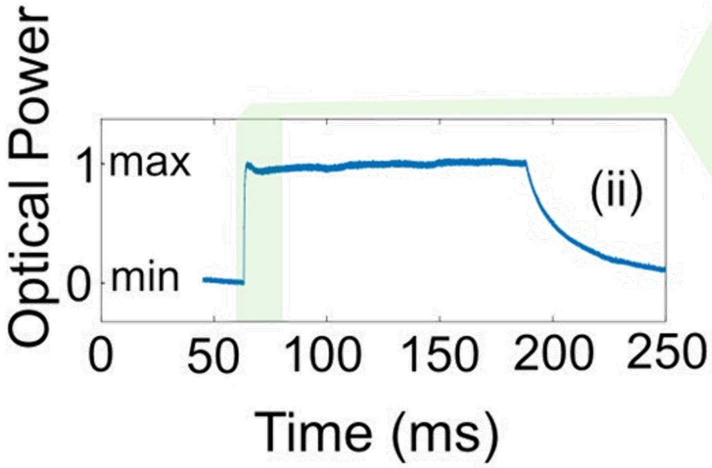
Speed of amplitude tuning

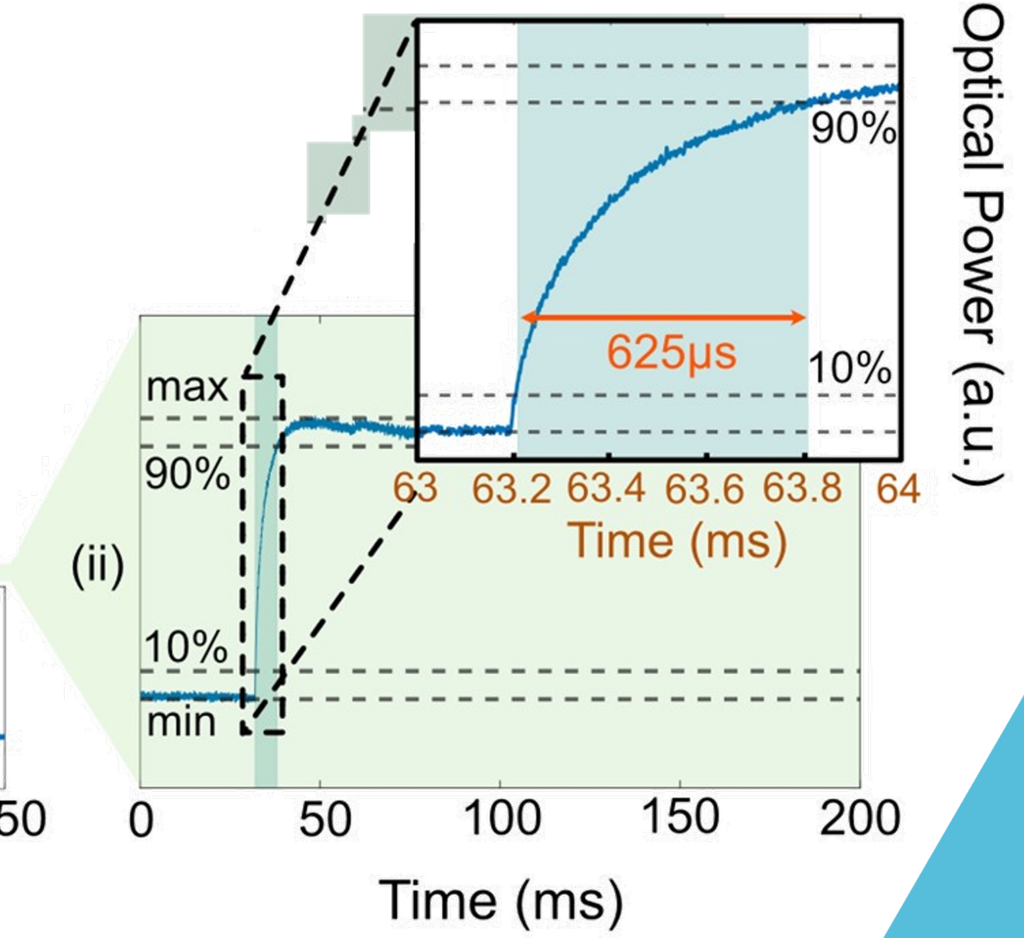
Reversible spectral shift of 12 nm

Video rate tuning, 90% modulation



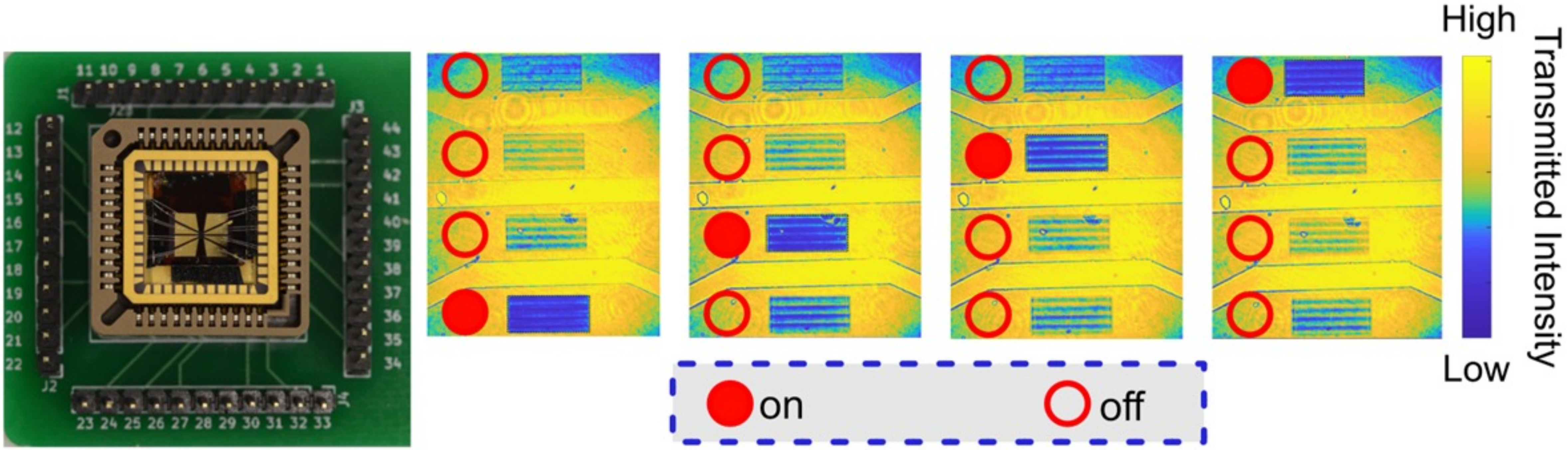






Zangeneh Kamali *et al.*, submitted (2022)

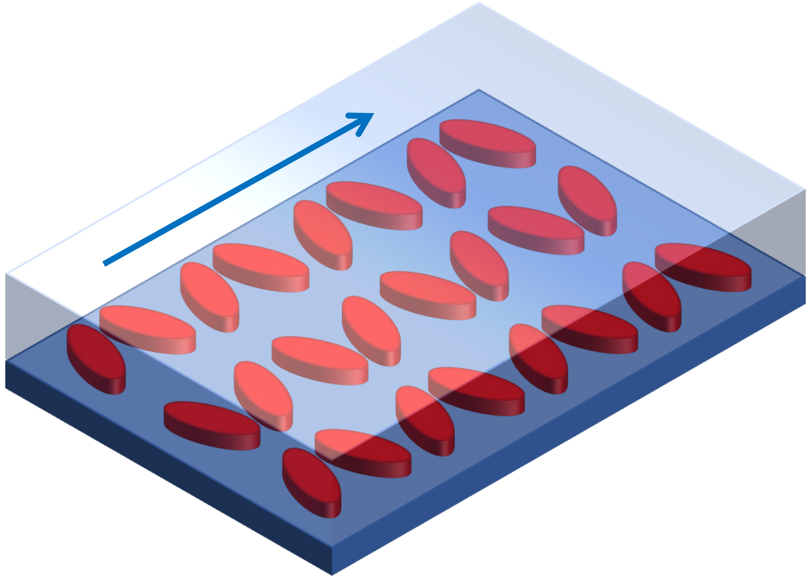
Spatially selective pixel tuning

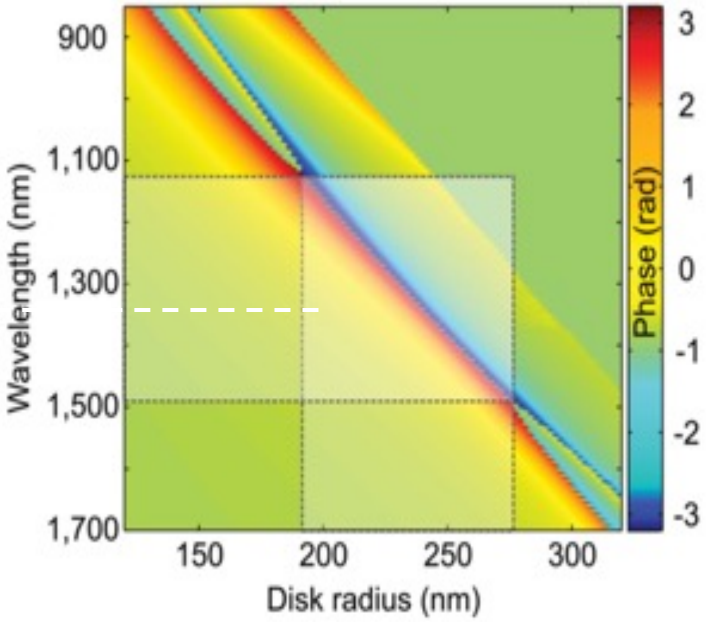


Multi-pixel control compatible with user-electronic devices

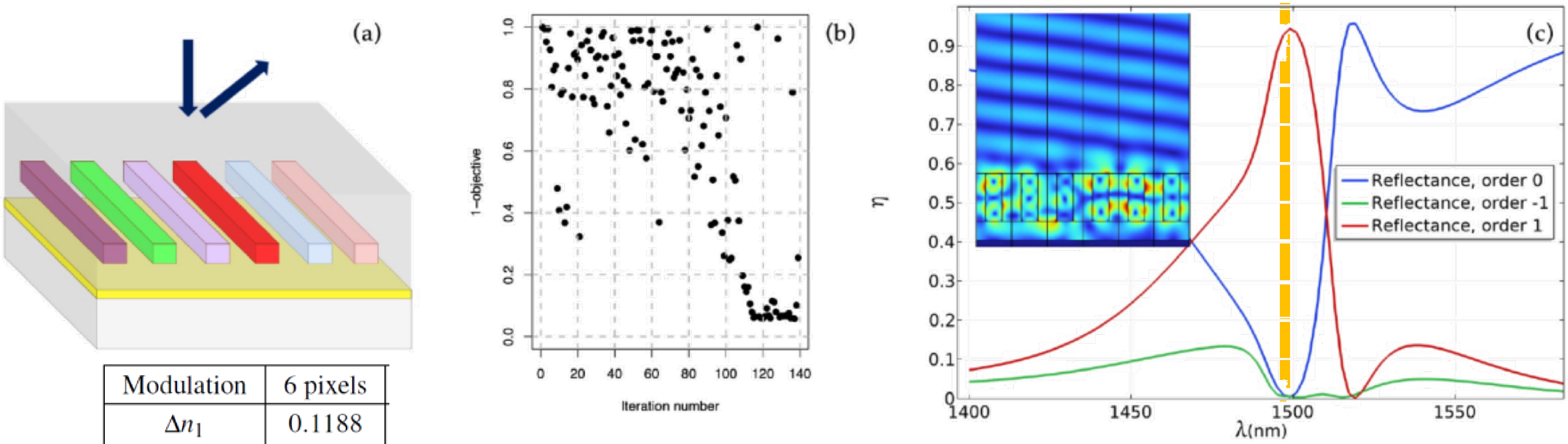
Zangeneh Kamali *et al.*, submitted (2022)

Phase tuning





Thermal phase tuning of reflective MSs



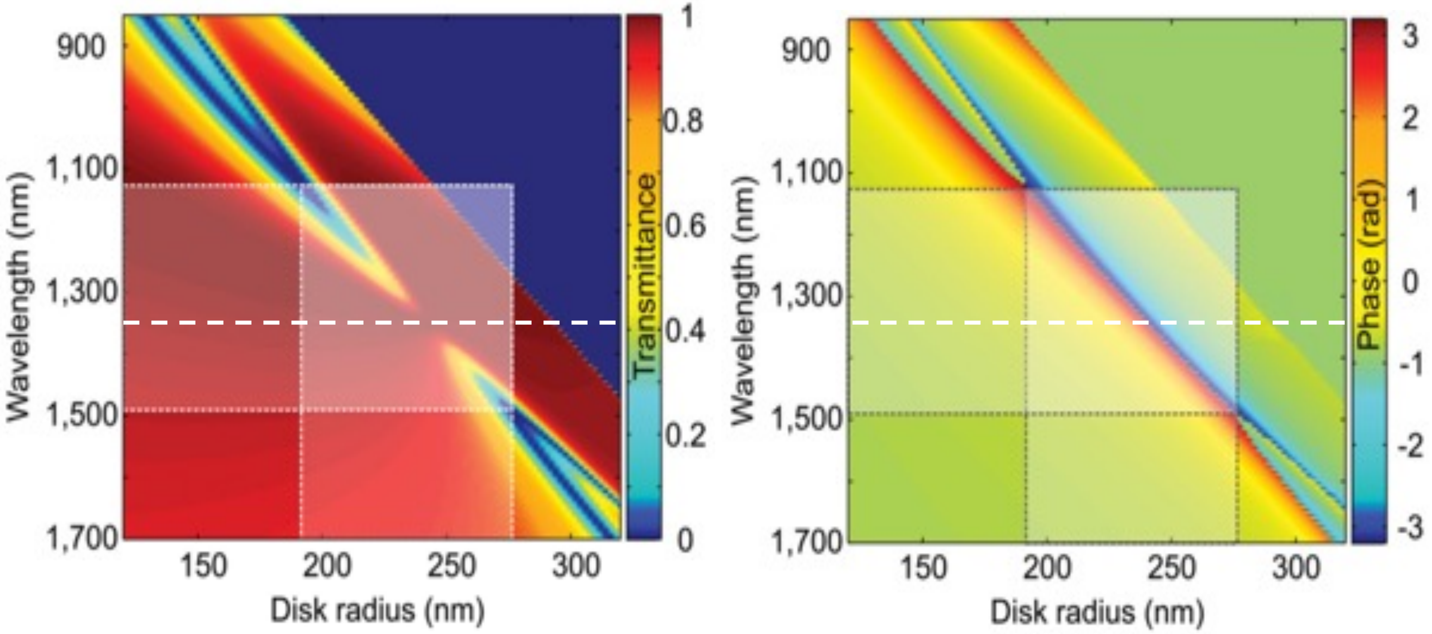
Modulation	6 pixels
Δn_1	0.1188
Δn_2	0.1621
Δn_3	0.250
Δn_4	0.0068
Δn_5	0.020
Δn_6	0.0541

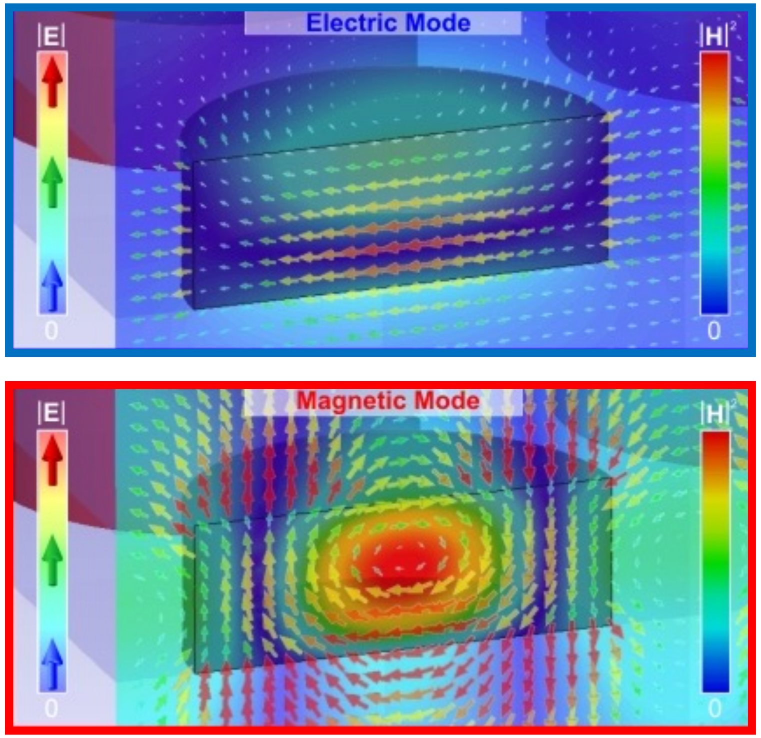
non-monotonous variation of the refractive index along the pixels

Elsawy *et al*., submitted (2022)

Phase tuning of transmissive MSs

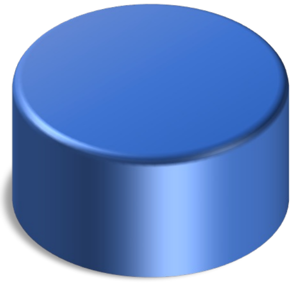
Two resonances in Huygens condition





Overlap of two resonances needed.

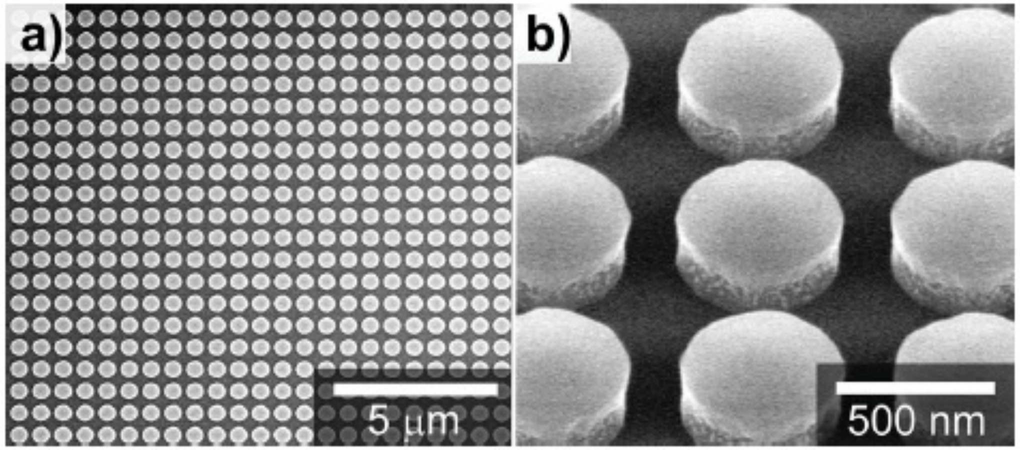
Resonance control by geometry

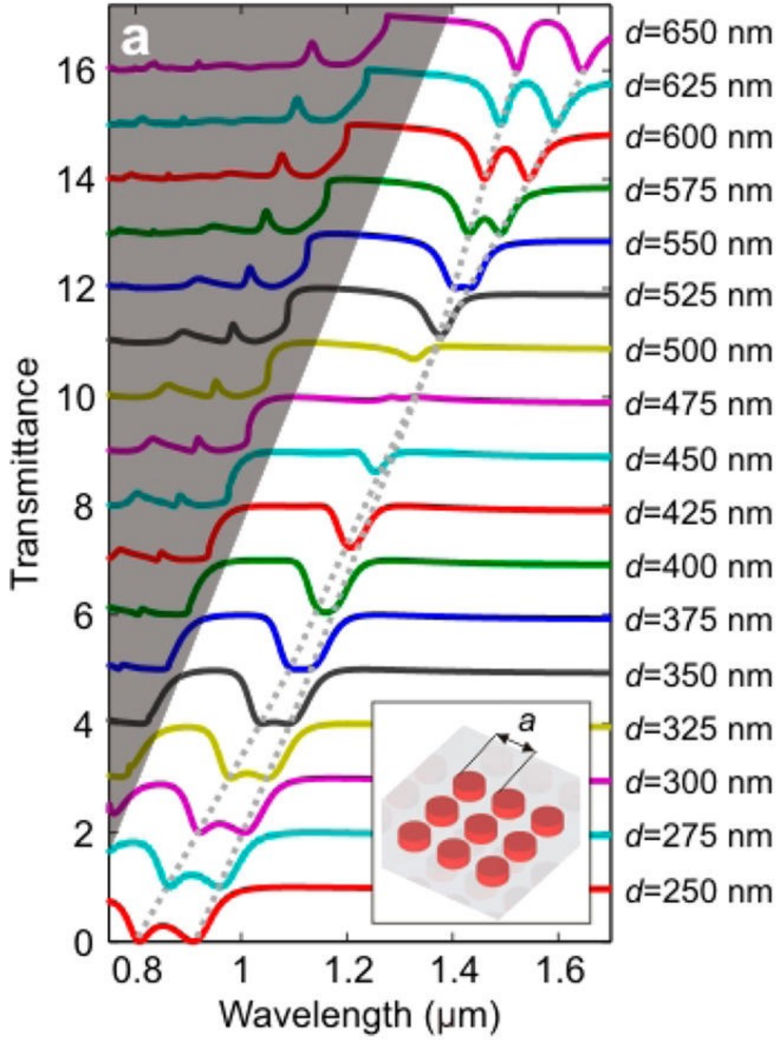


Silicon disks:
diameter,
height

Evlyukhin *et al.*, PRB **84**, 235429 (2011)

Fabrication: SoI technology

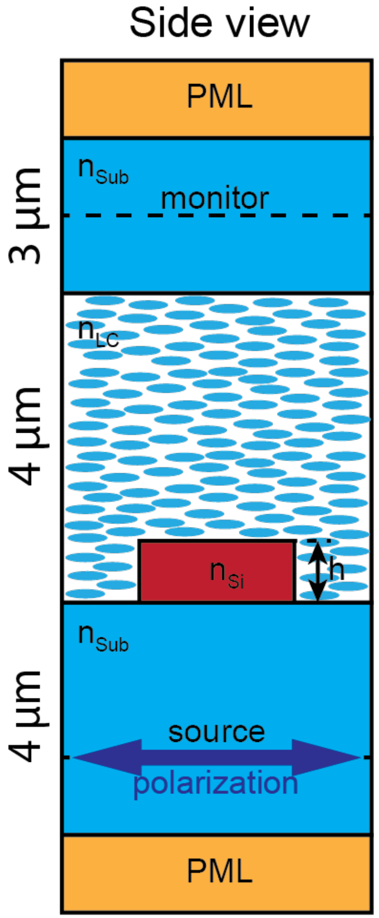


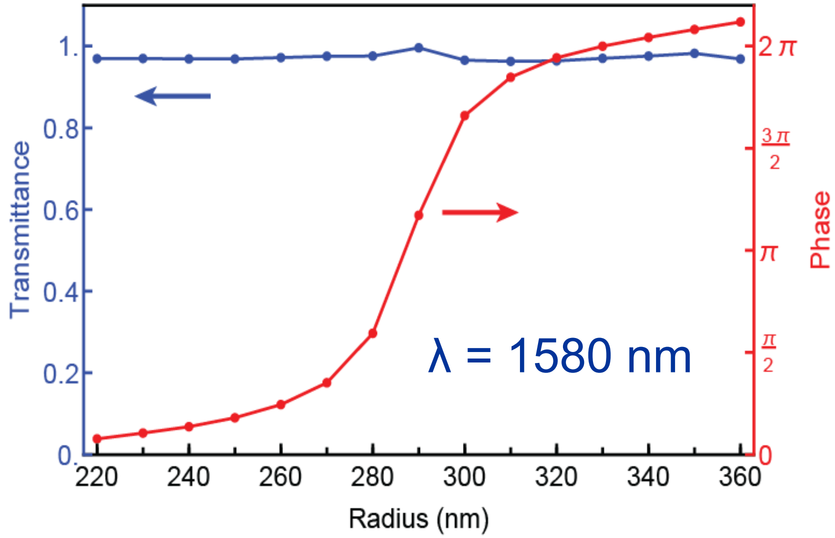


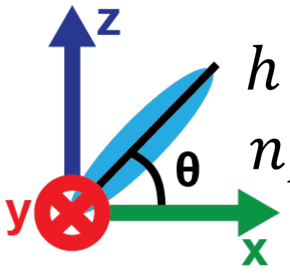
Staude *et al.*, *ACS nano* **7**, 7824 (2013)

Tuning of the surrounding environment

Huygens' regime: for disks' radius $r = 290\ nm$

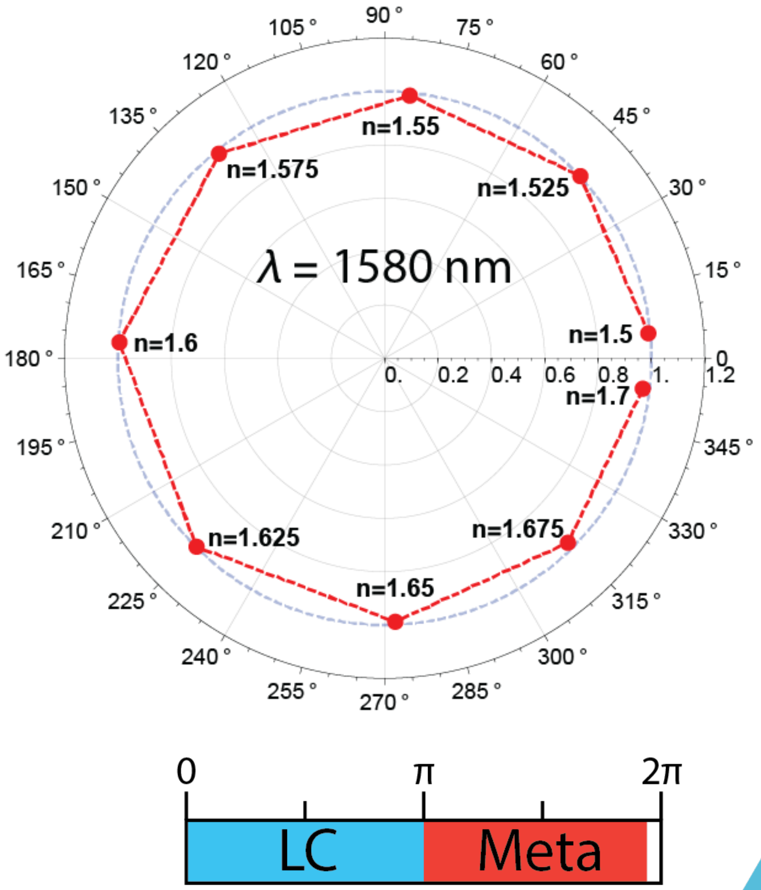




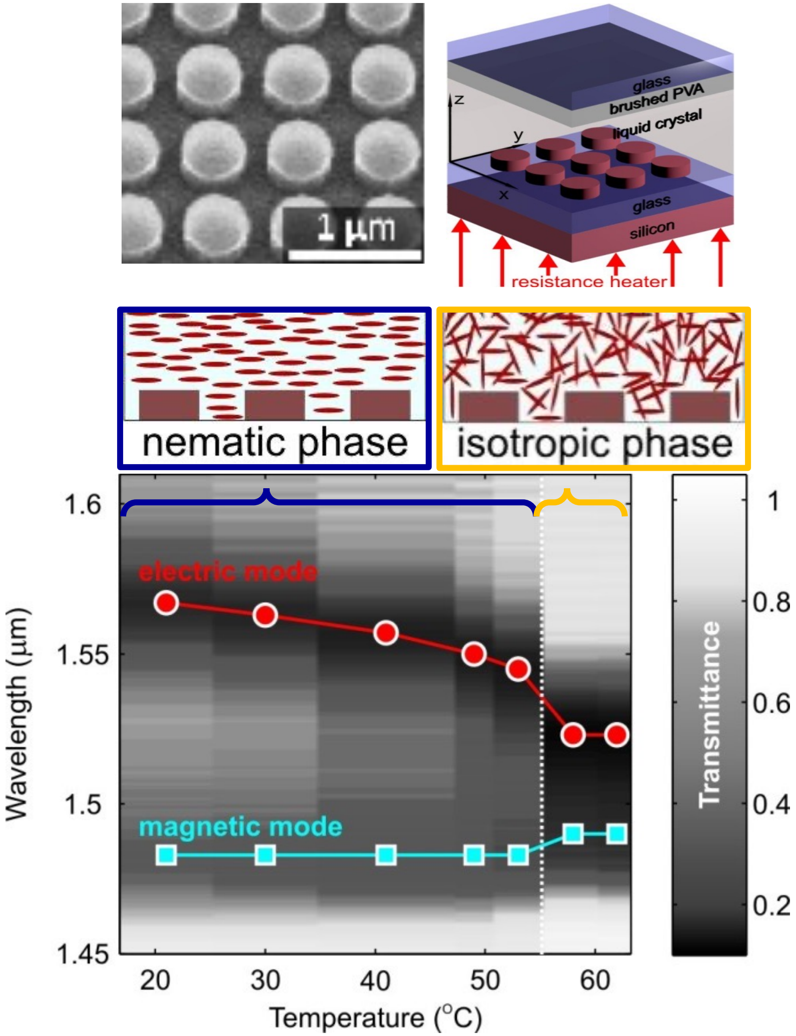


$$h = dist = 260\ nm$$

$$n_{LC} = 1.6$$

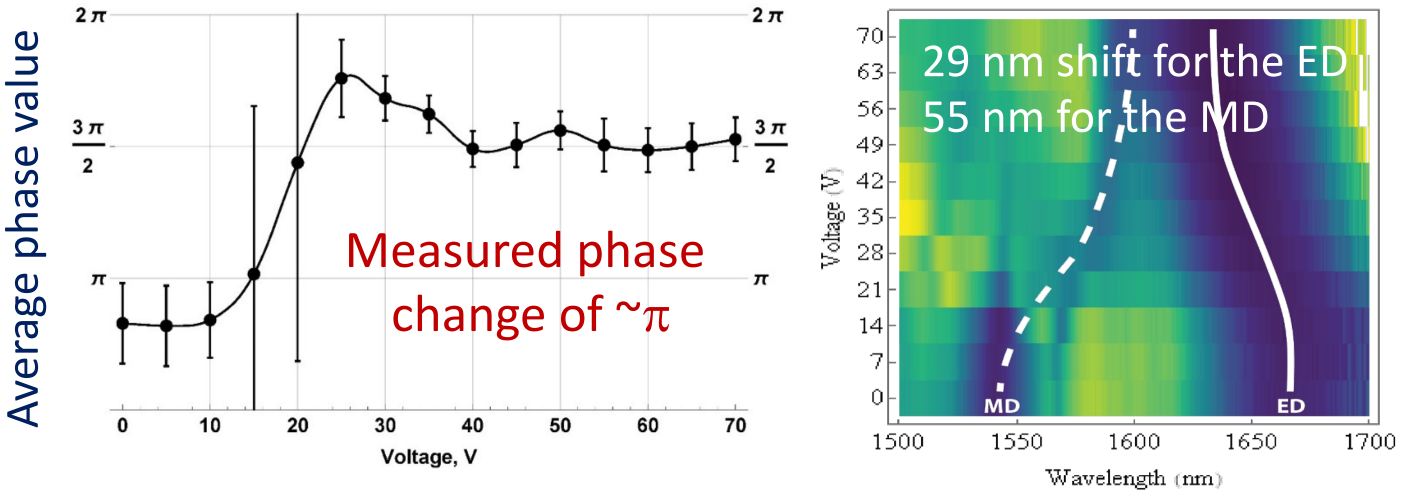


Tunable liquid crystal metasurfaces

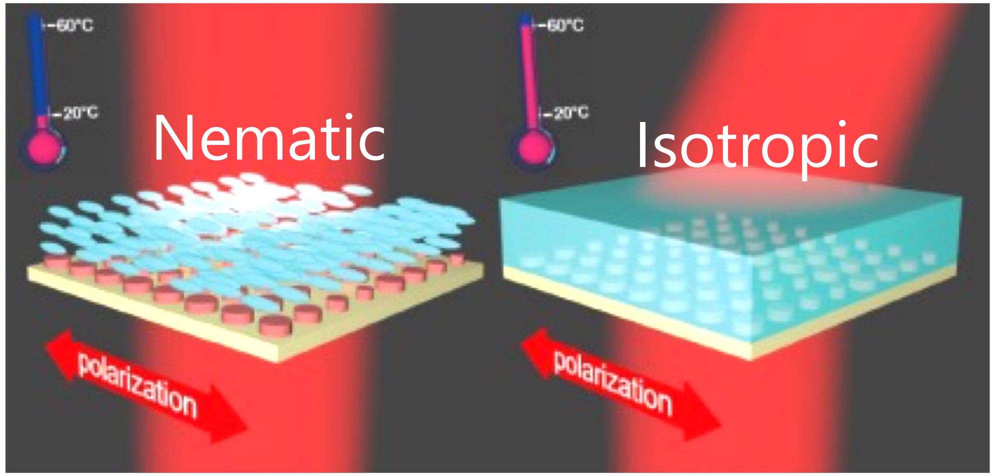


Sautter *et al*., ACS Nano **9**, 4308 (2015)

Tuning of phase

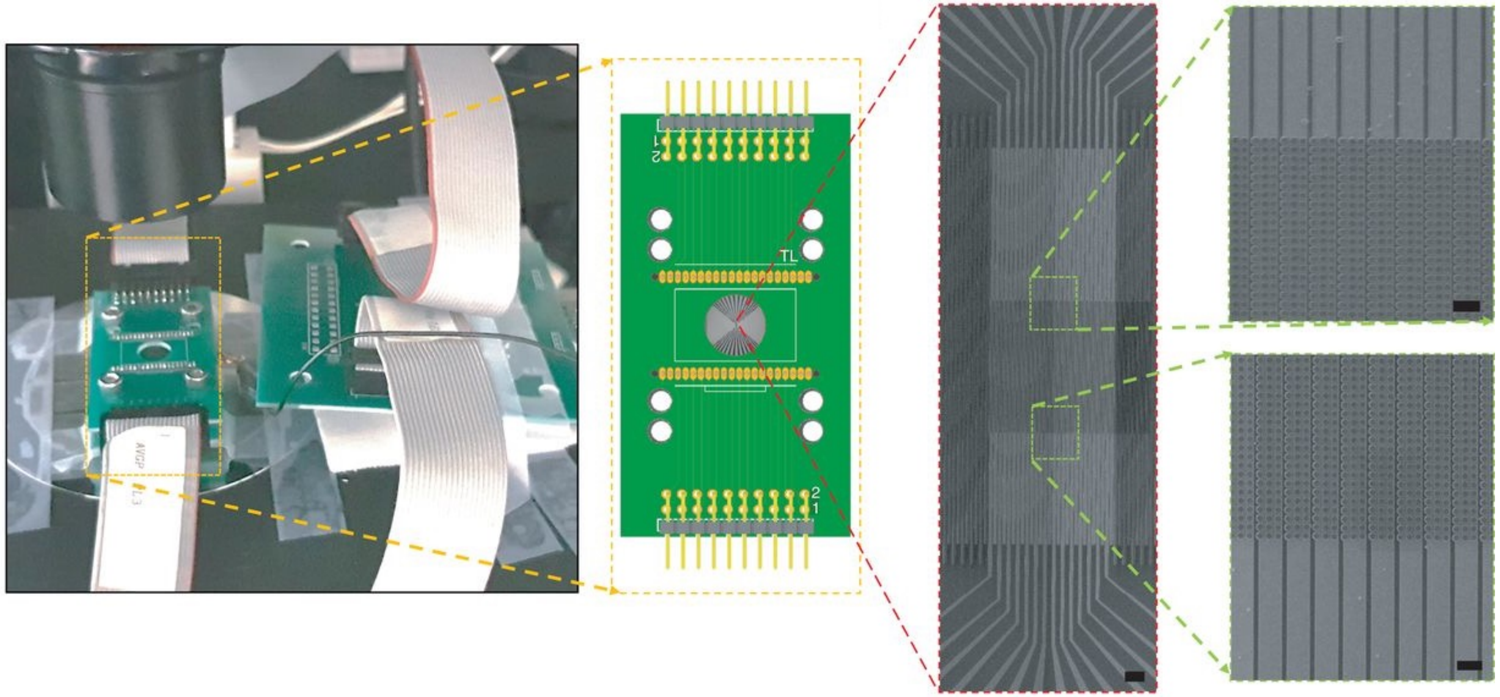


Komar *et al*., *Appl. Phys. Lett.* **110**, 71109 (2017)

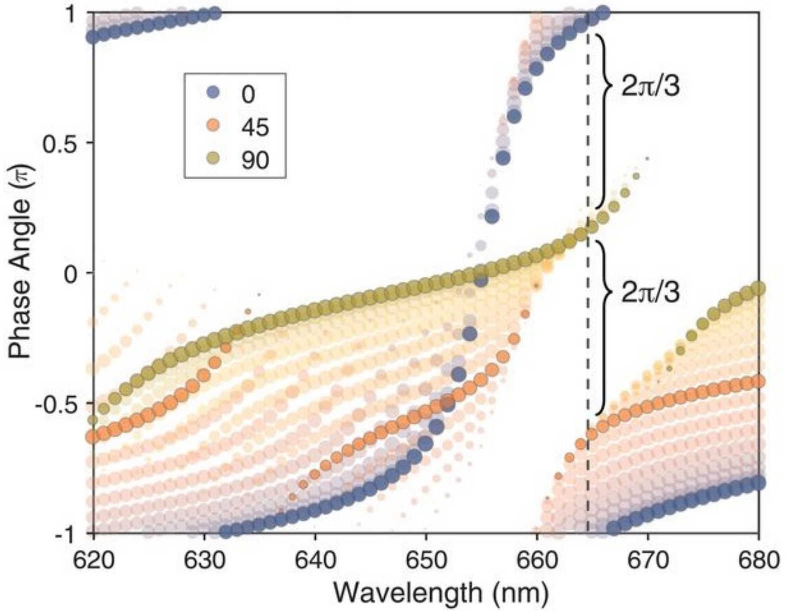


Komar *et al*., *ACS Photonics* 5, 1742 (2018)

Spatial light modulator based on tunable dielectric MSs



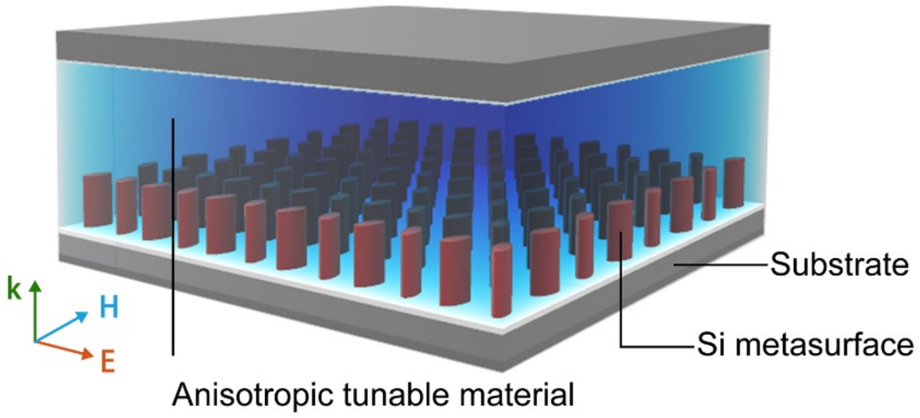
Three phase modulator



S.-Q. Li, et al., Science 364, 1087-1090 (2019)

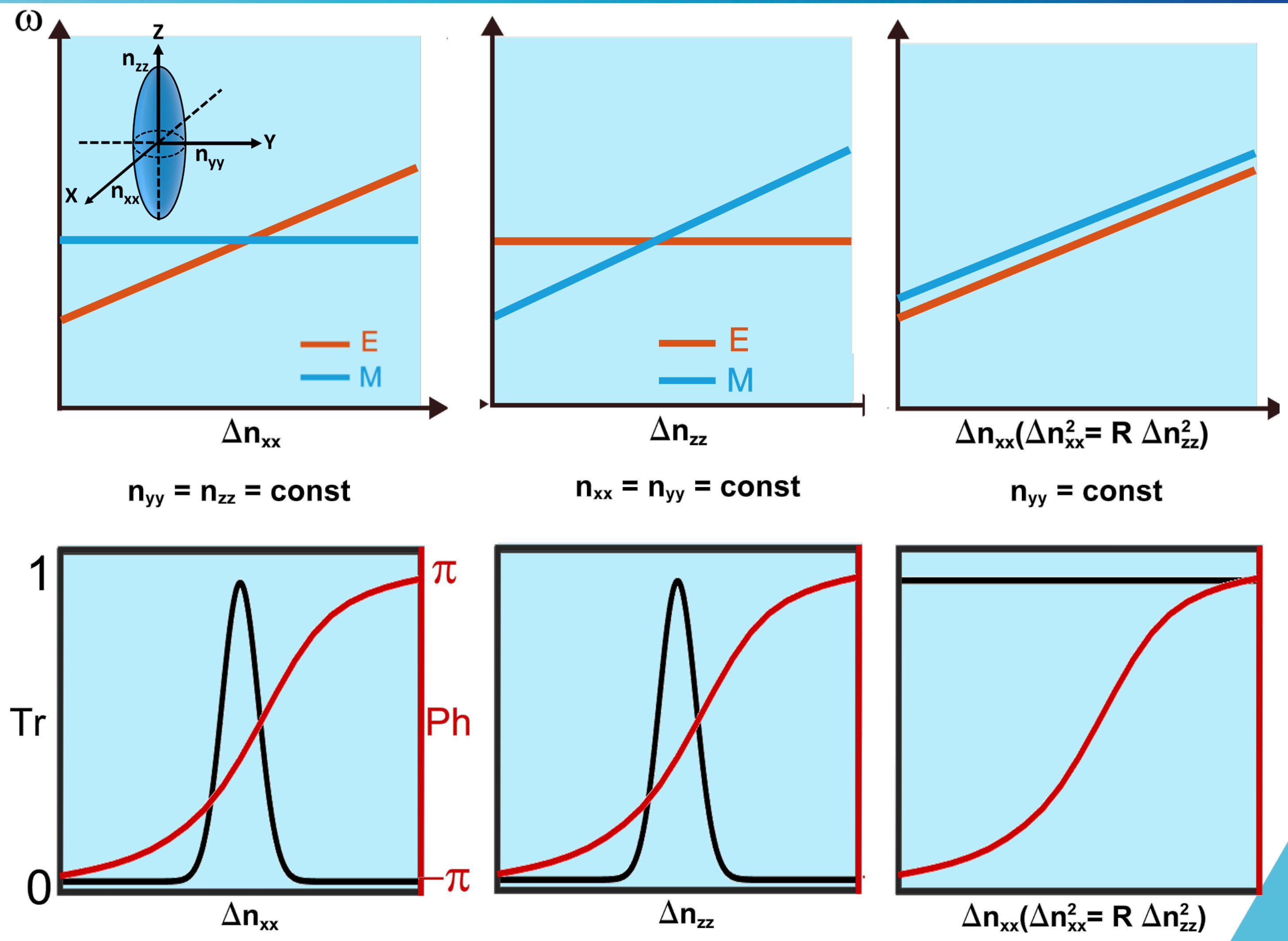
Mechanism of optical anisotropic tuning

LC is an anisotropic material

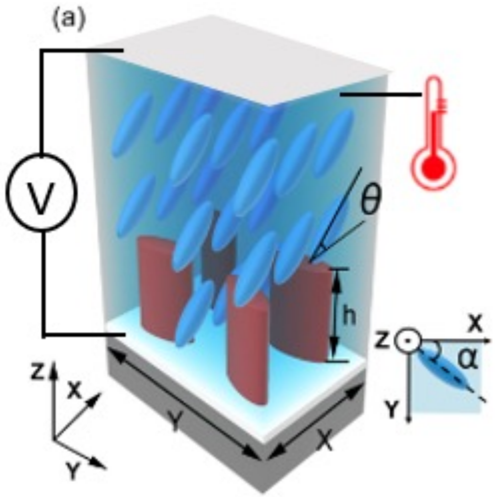


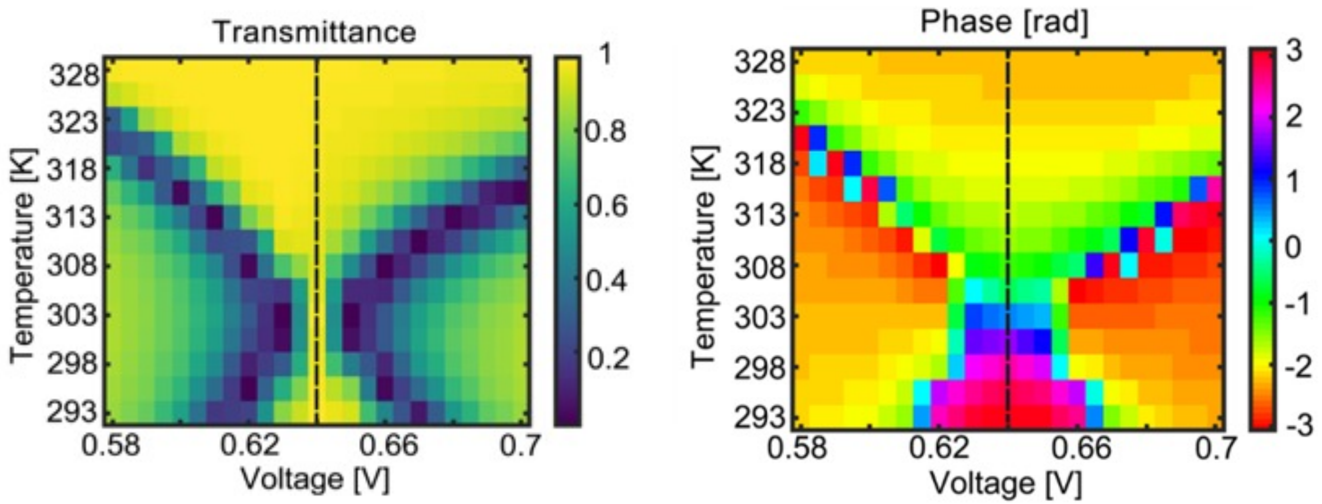
Metasurface infiltrated with anisotropic material

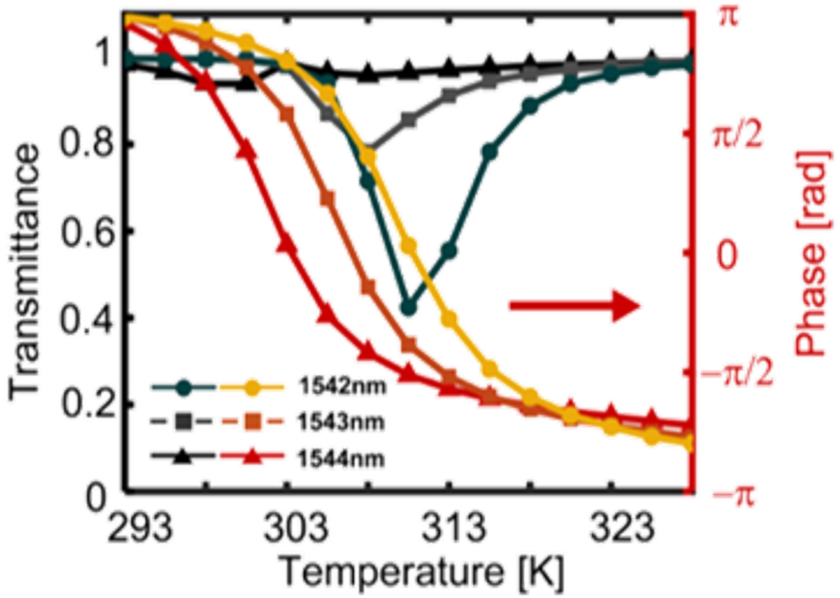
$$\hat{\boldsymbol{n}} = \begin{bmatrix} n_{xx} & 0 & 0 \\ 0 & n_{xx} & 0 \\ 0 & 0 & n_{zz} \end{bmatrix}$$



LC tunable extreme Huygens metasurfaces







- Temperature and voltage to control both resonances
- Huygens regime at 0.64 V, bandwidth = 3.5nm
- The two resonances shift at the same rate

Pure phase tuning in the full 2π range with unitary efficiency

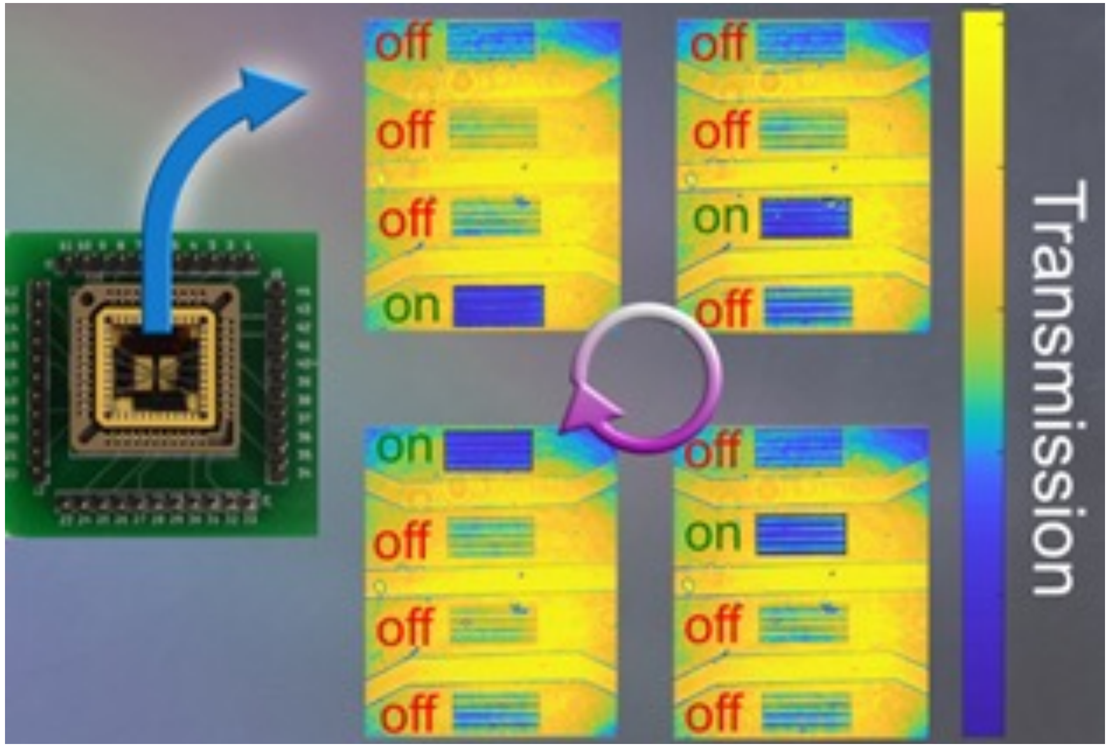
Yang *et al.*, *Adv. Opt. Mat.* **10**, 2101893 (2022)

Conclusions

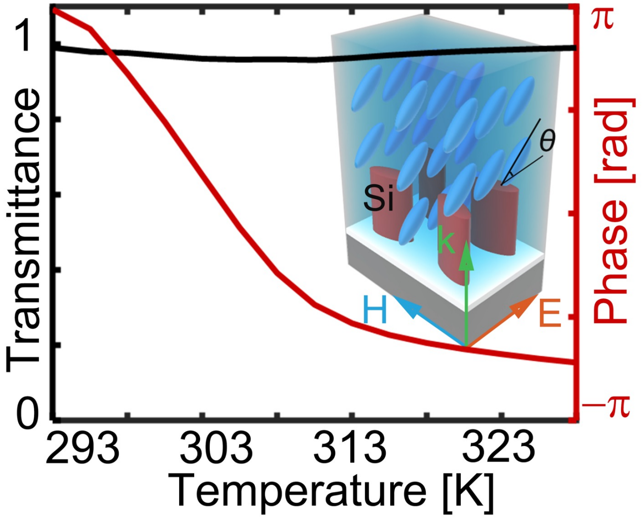
Thank you!

Amplitude tuning

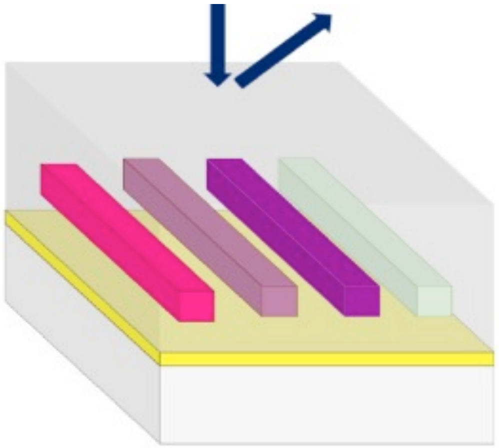
Programmable metasurfaces



Phase tuning



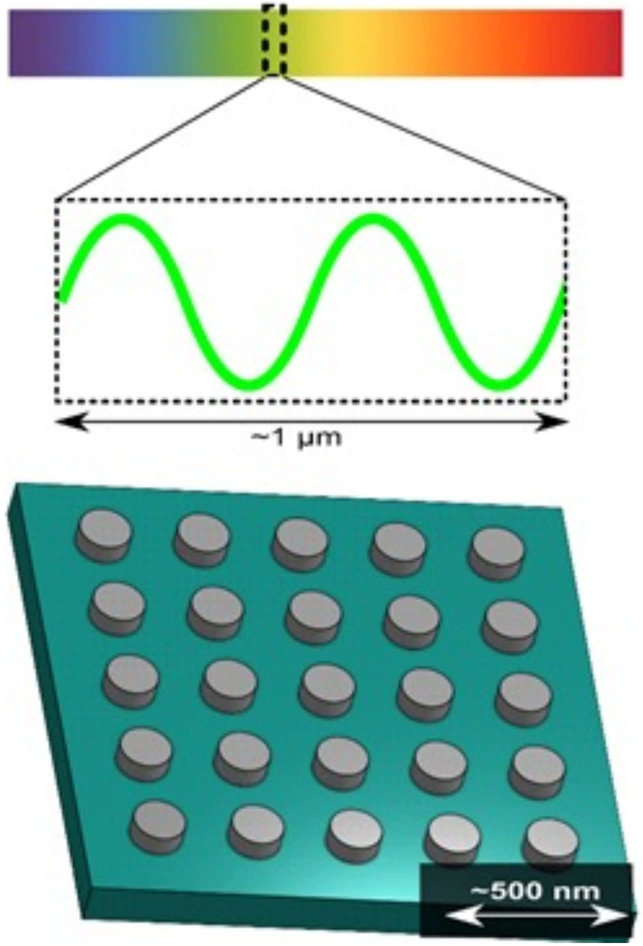
Anisotropy tuning

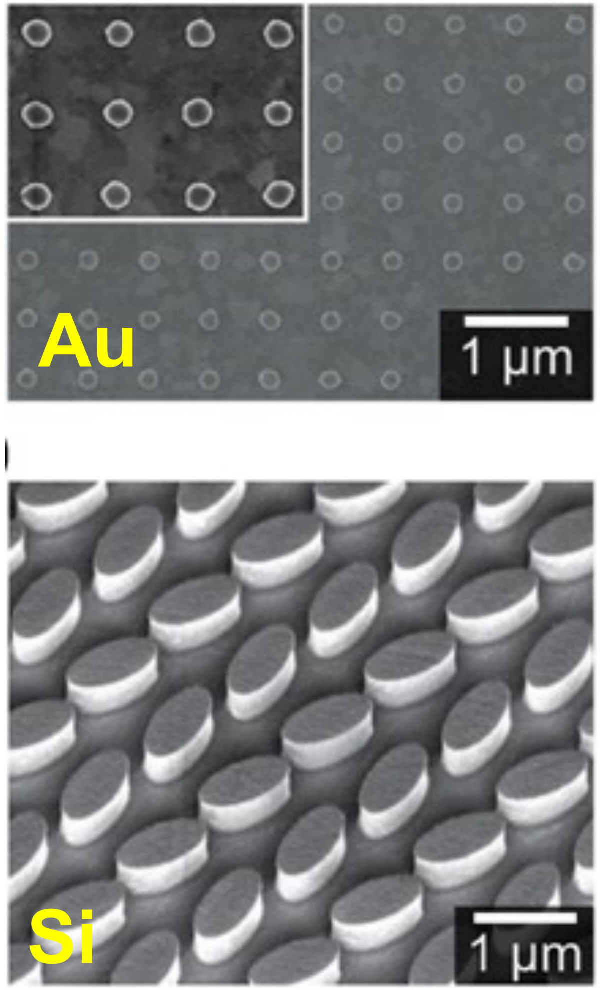


Non-monotonous variation

Optical metasurfaces

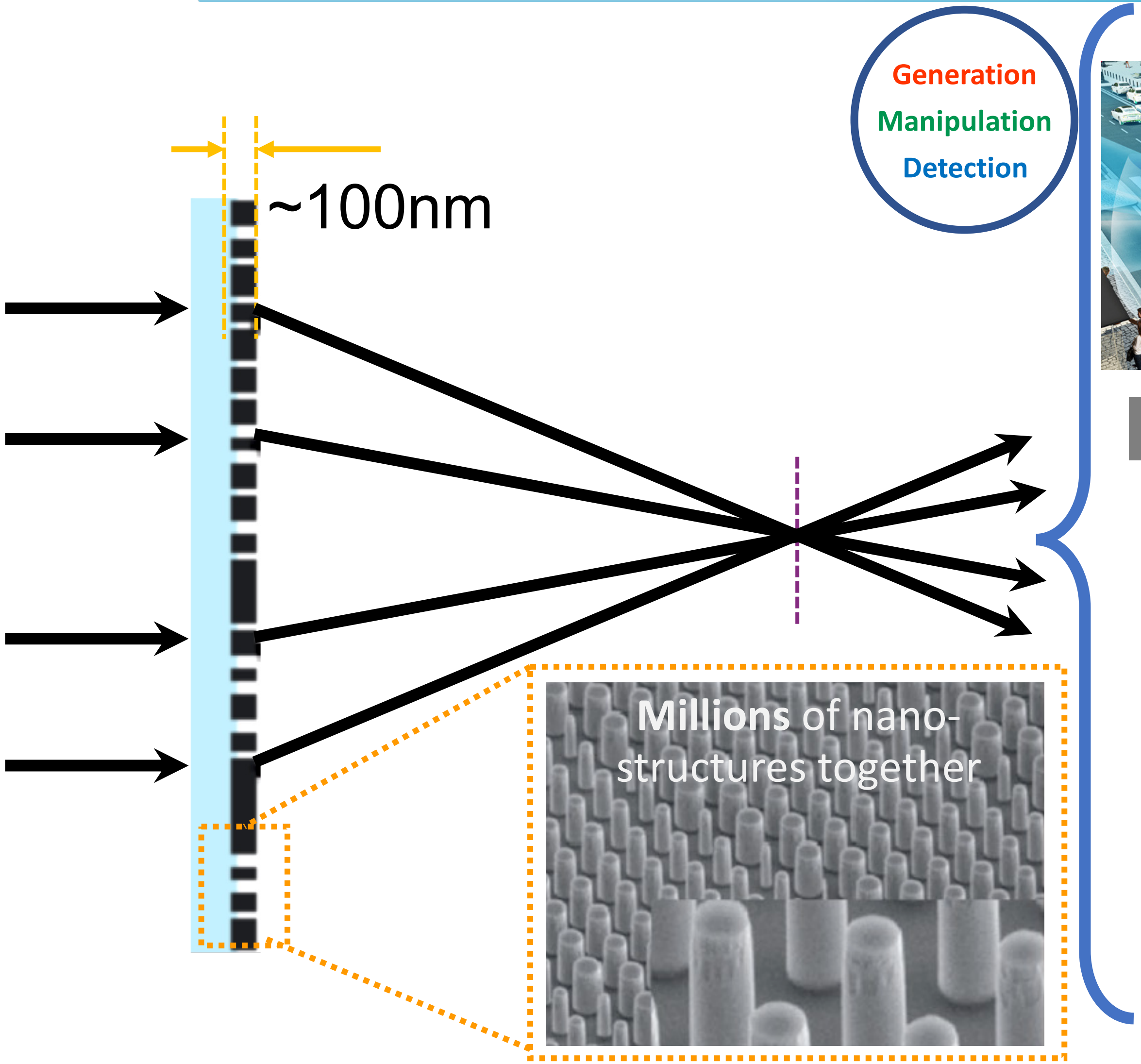
Metasurfaces are subwavelength arrays of nano-scale optical elements



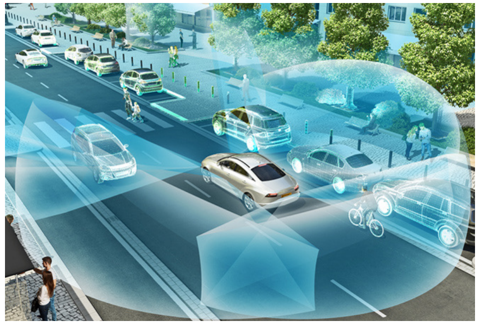


Strong light confinement;
Light is re-emitted with required phase, polarisation and colour

Meta-optics impact



Transport



LIDAR technologies

Health

Wearable optical sensors

Defence

Night vision technologies

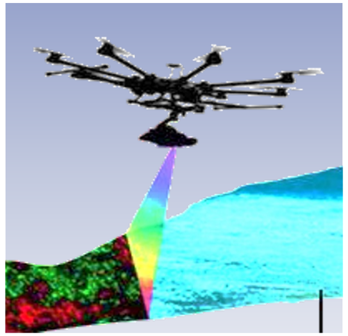
Education

Holographic displays
Augmented reality

Communications

Li-Fi technologies

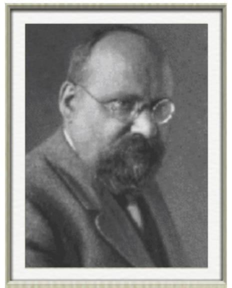
Agriculture



Remote sensing:
infrared & quantum

Mie resonances in dielectric MSs

Light scattering by nanoparticles


Gustav Mie

G. Mie, Ann. Phys. **25**, 377 (1908)

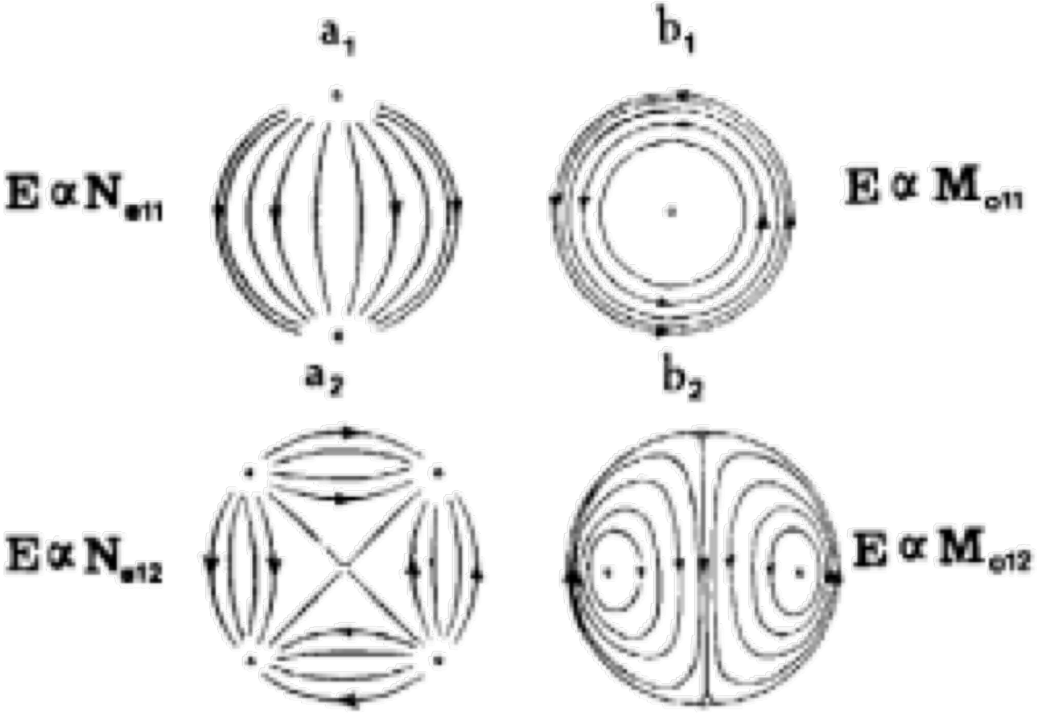
$$Q_{sca} = \frac{2}{x^2}\sum_{n=1}^{\infty}(2n+1)(|a_n|^2+|b_n|^2)$$

$$Q_{ext} = \frac{2}{x^2}\sum_{n=1}^{\infty}(2n+1)Re(a_n+b_n)$$

$$a_n = \frac{m^2 j_n(mx)[xj_n(x)]' - j_n(x)[mxj_n(mx)]'}{m^2 j_n(mx)[xh_n^{(1)}(x)]' - h_n^{(1)}(x)[mxj_n(mx)]'};$$

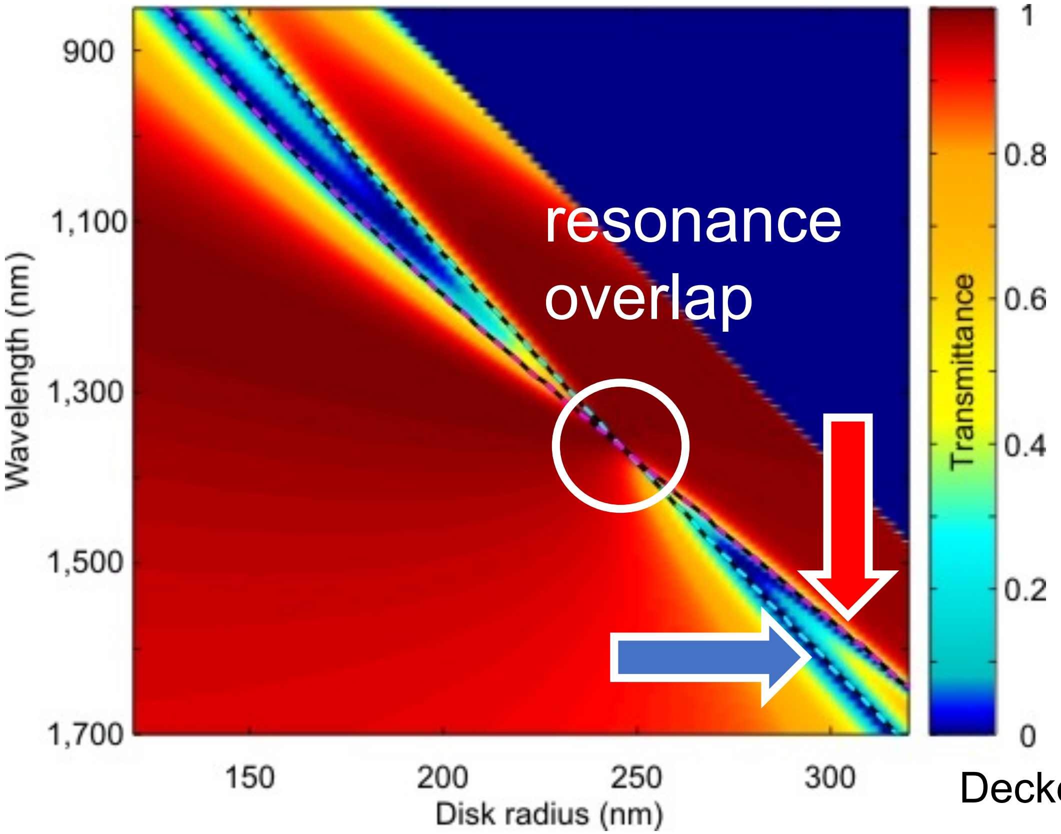
$$b_n = \frac{j_n(mx)[xj_n(x)]' - j_n(x)[mxj_n(mx)]'}{j_n(mx)[xh_n^{(1)}(x)]' - h_n^{(1)}(x)[mxj_n(mx)]'}$$

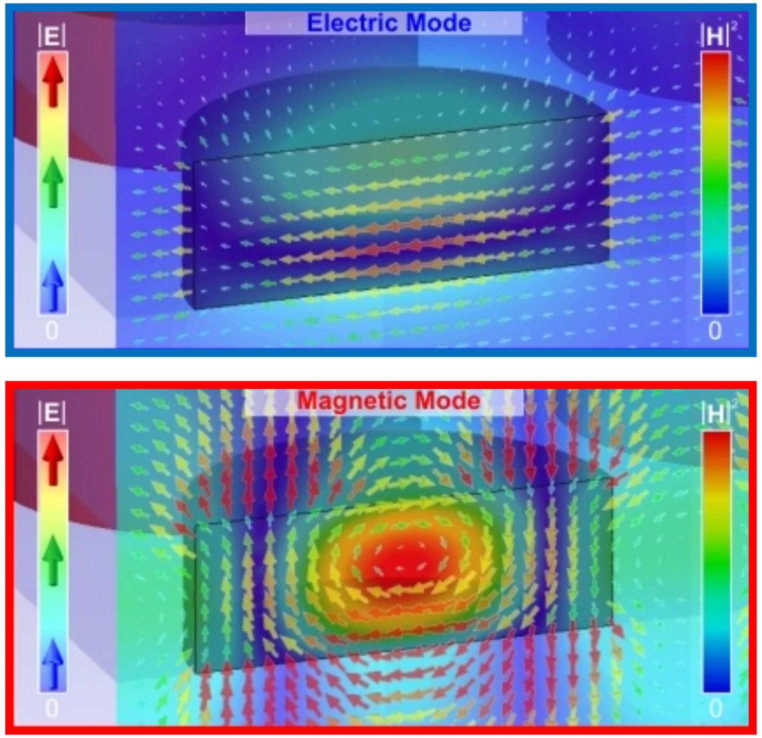
Electric type Magnetic type



E&M resonances in dielectric MSs

Silicon nanodisk metasurface (h = 220 nm, variable radius) in n = 1.66 medium.



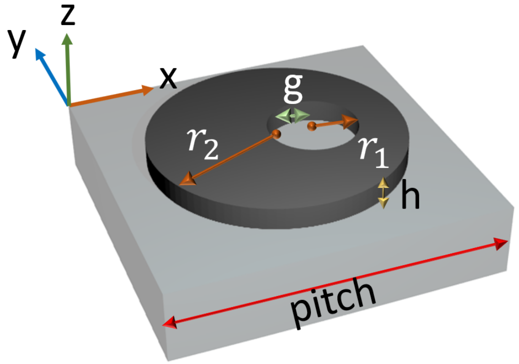


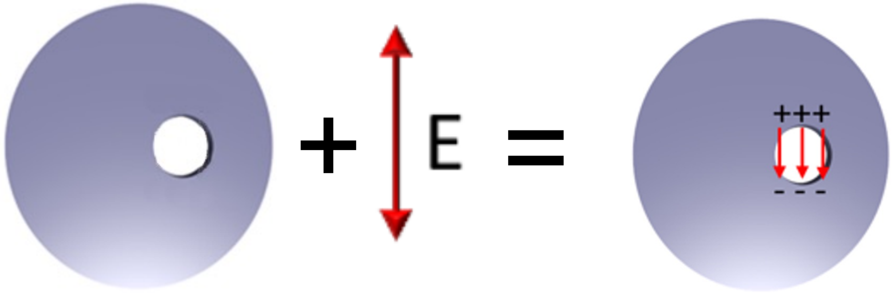
Decker *et al.*, Adv Opt Mat **13**, 813-820 (2015)

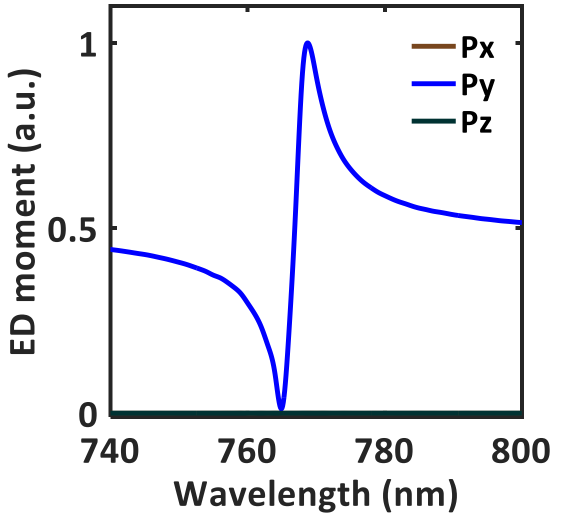
- Complete crossing of electric and magnetic resonances is achieved (dual particles or Kerker condition)
- Transmittance becomes unity for resonance overlap

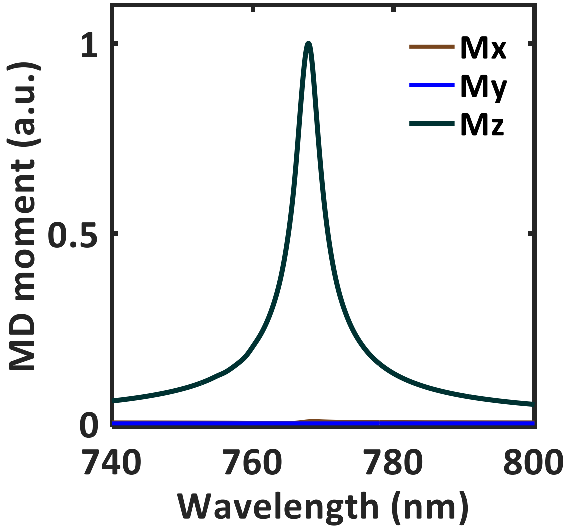
High-Q resonant metasurfaces

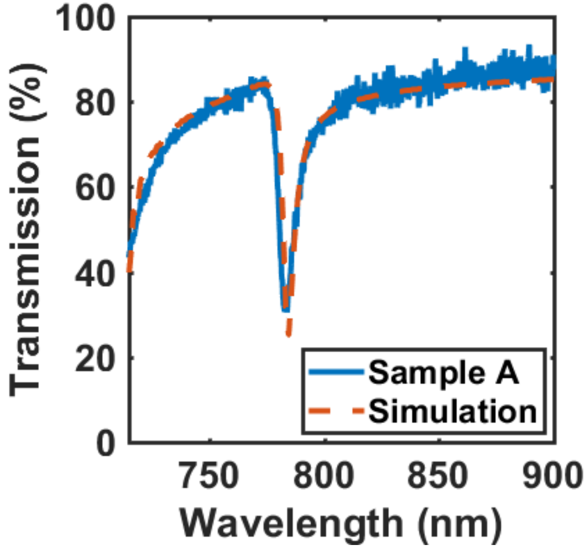
Design: Silicon disk–hole structure – quasi-BIC mode







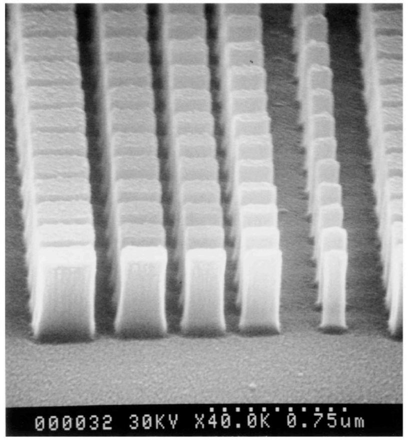




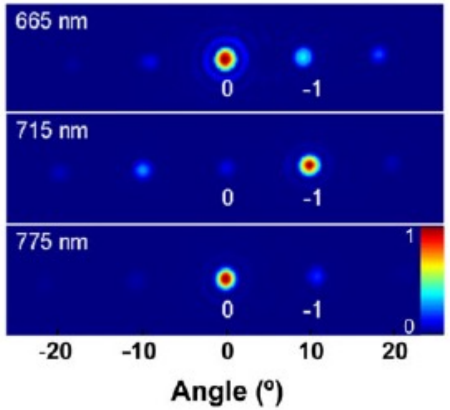
h = 30 nm
r_1 = 60 nm,
r_2 = 190 nm
g = 50 nm
Q ~ 100

Zangeneh Kamali *et al.*, Small 15, 1805142 (2019)

Beam steering

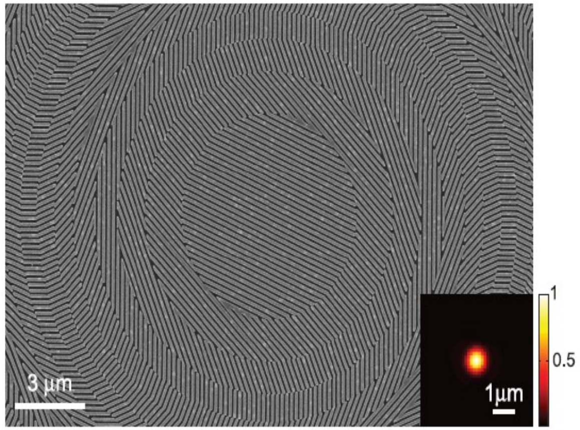


Lalanne *et al.*, OL **23**, 1081 (1998)

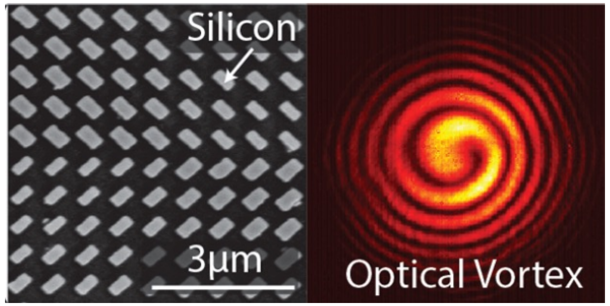


Yu *et al.*, LPR 9, 412 (2015)

Beam shaping

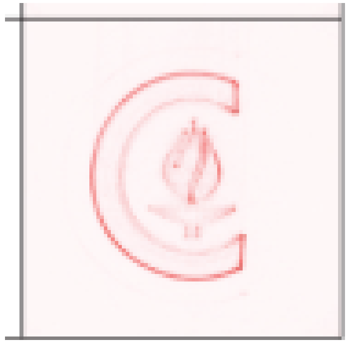


Lin *et al.*, Science **345**, 298 (2014)



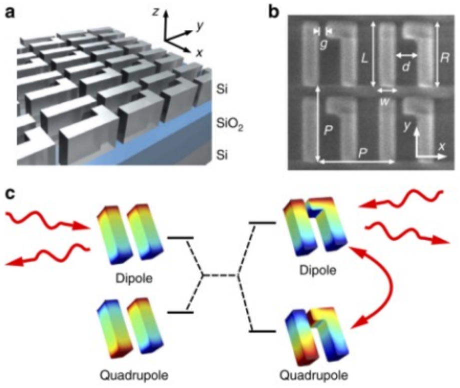
Yang *et al.* NL **14**, 1394 (2014)

Holography



Arbabi *et al.*
Nat. Nano. **10**, 937 (2015)

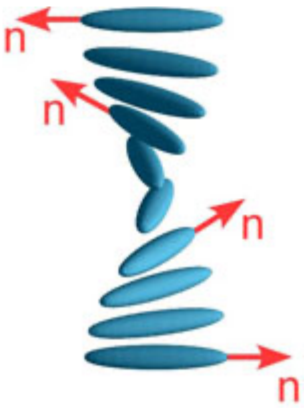
Sensing



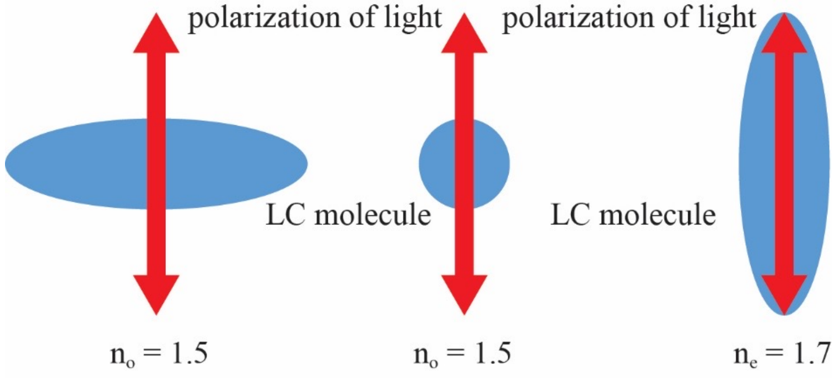
C. Wu, *et al.*
Nat. Comm. **5**, 3892 (2014)

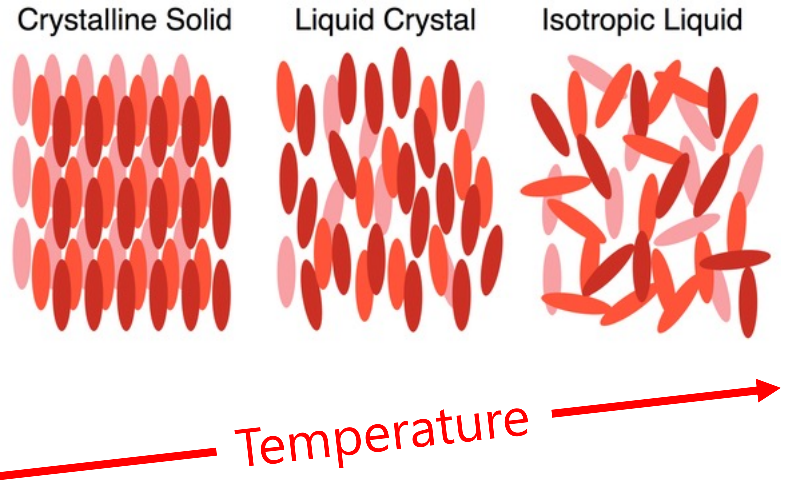
Fundamental of Liquid Crystals (LCs)

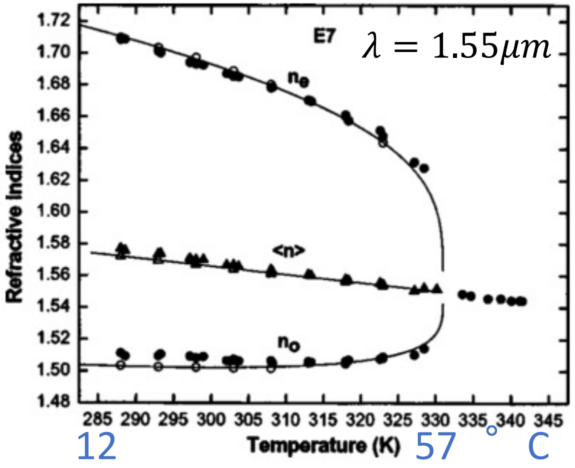
Director axis $\hat{n}(\vec{r})$



Positive nematic liquid crystal

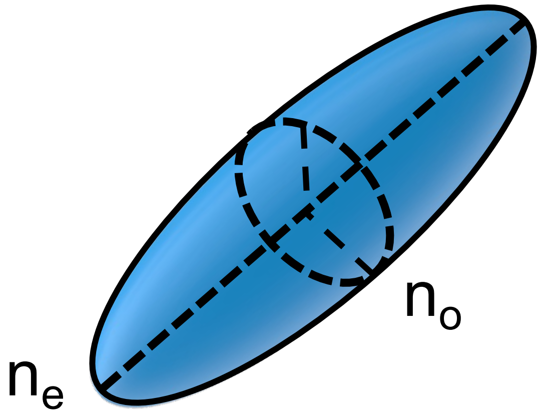


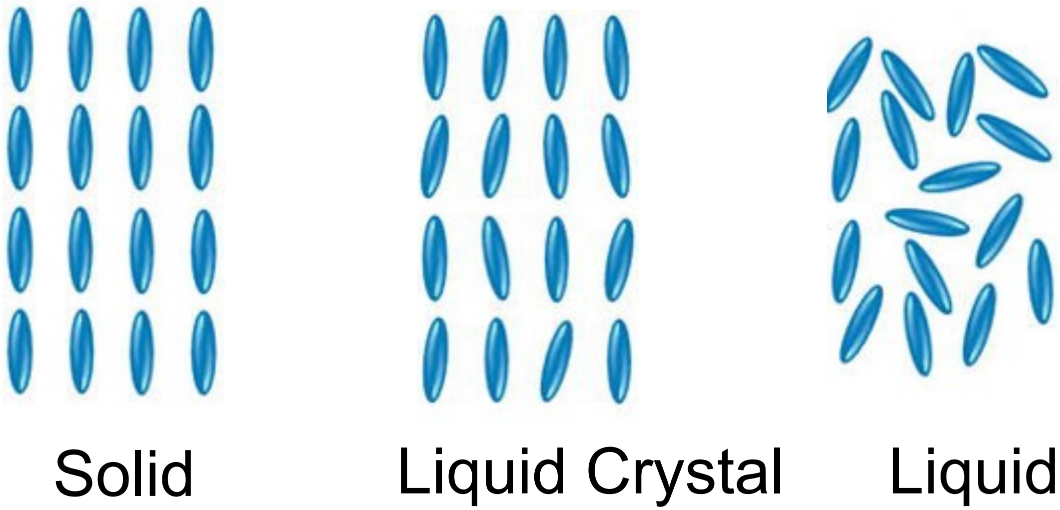


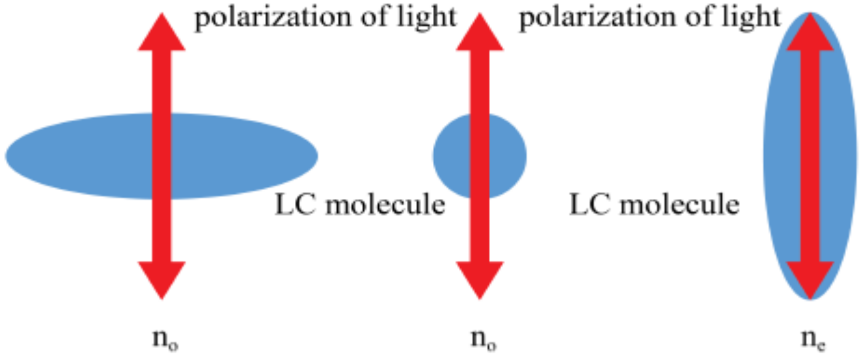


Fundamental of Liquid Crystal (LC)

Liquid Crystal molecule

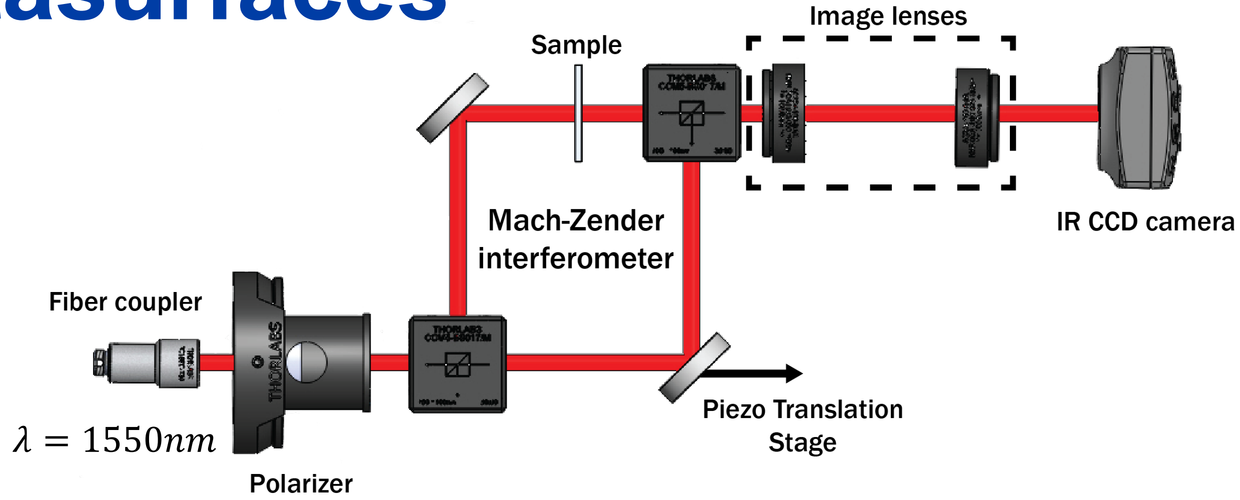


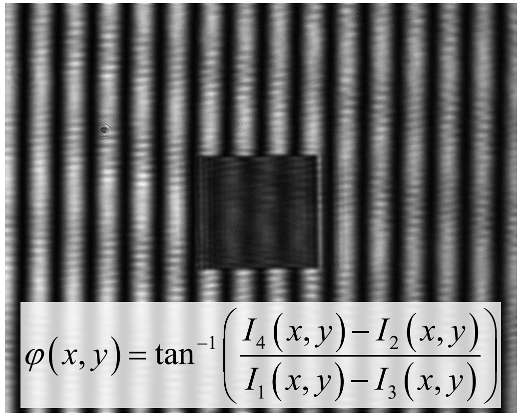




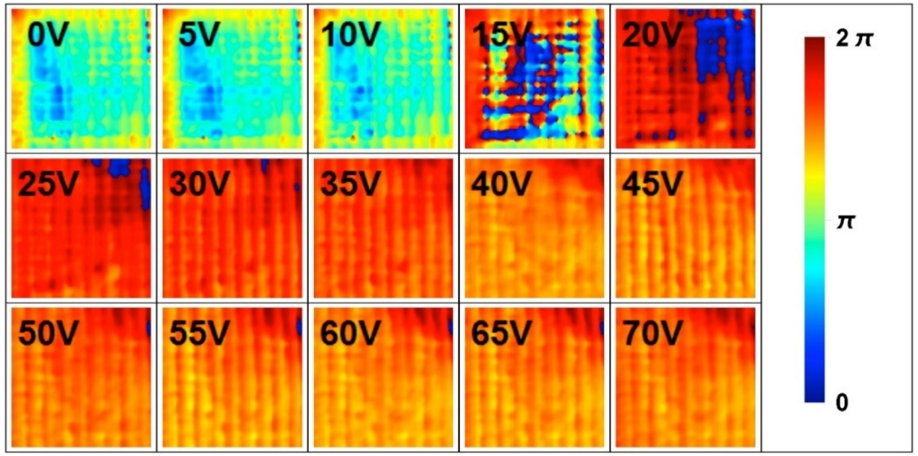
Refractive index depends on mutual orientation of molecules and light polarization.

Phase tuning of LC infiltrated metasurfaces

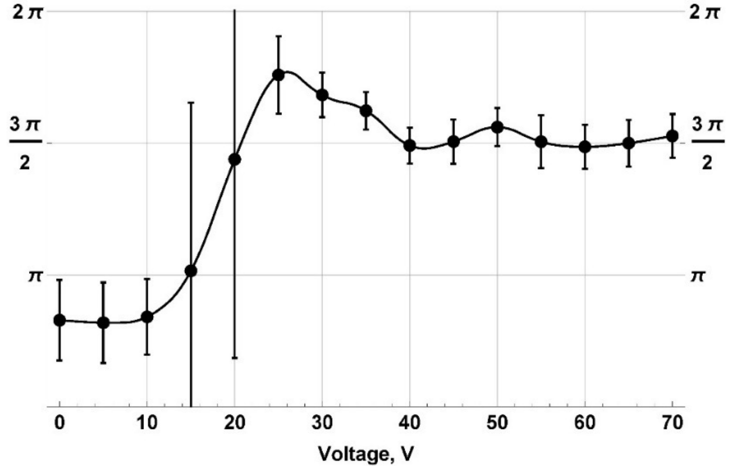




Experimental images



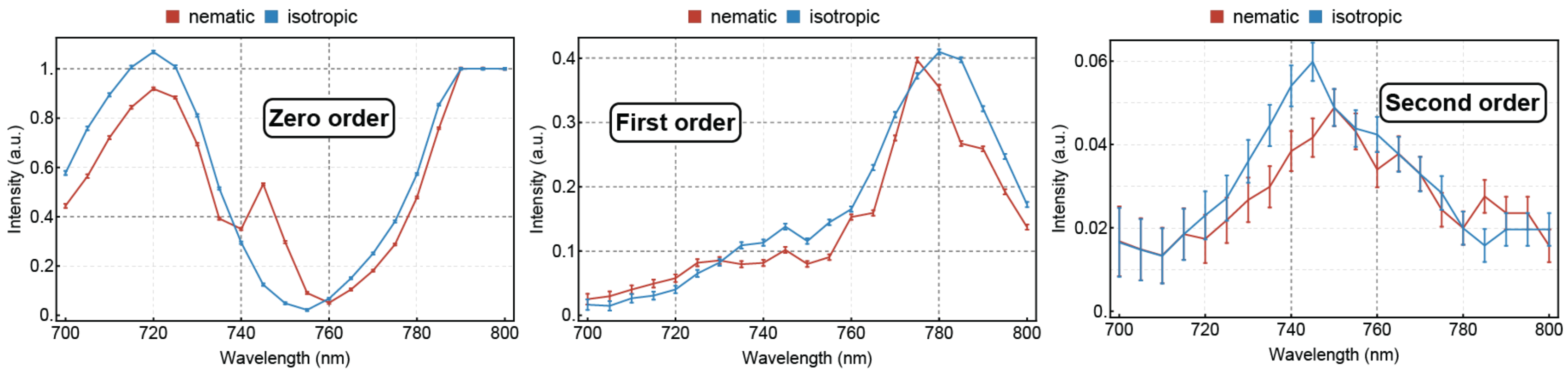
Average phase value for every voltage



Measured phase change of ~π

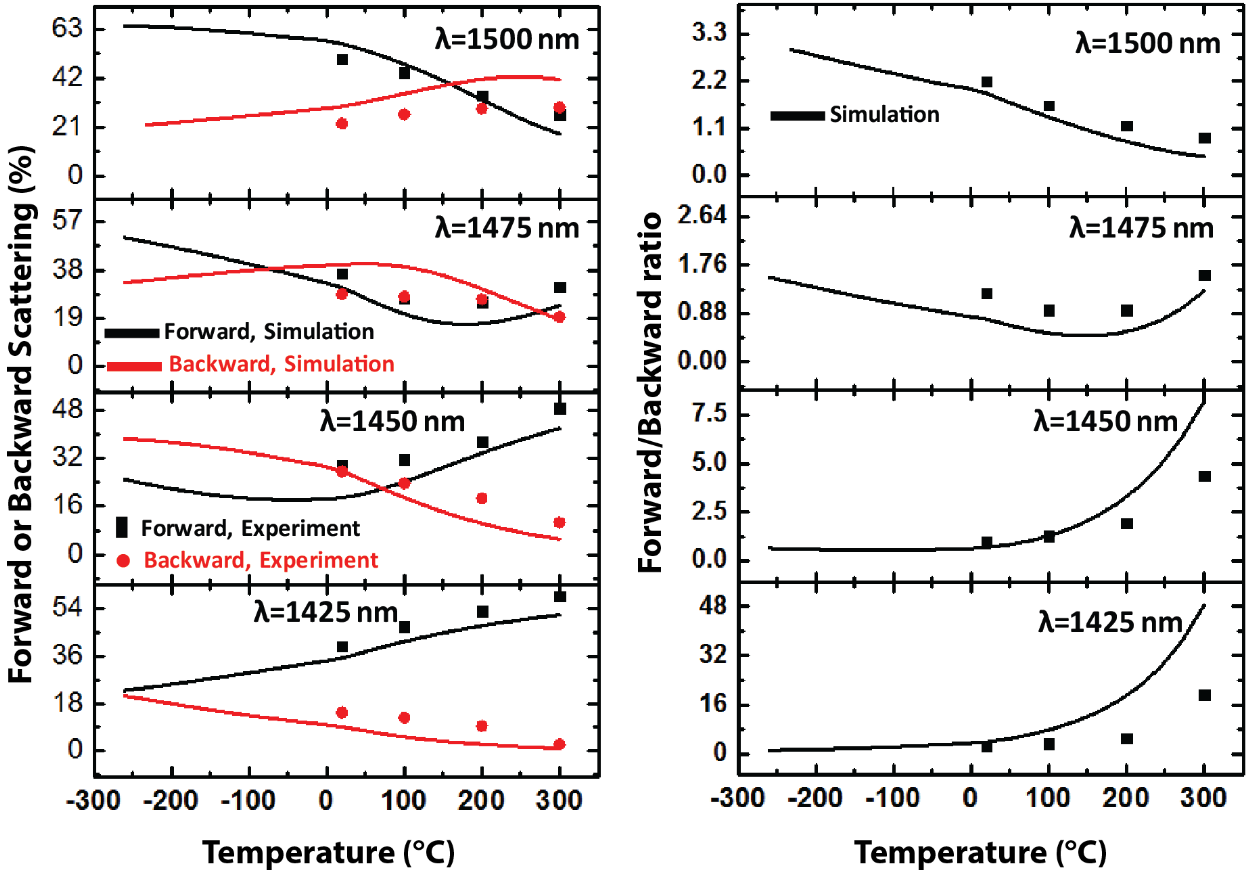
Komar et al., *Appl. Phys. Lett.* **110**, 071109 (2017)

The highest beam deflection observes at wavelength 745 nm



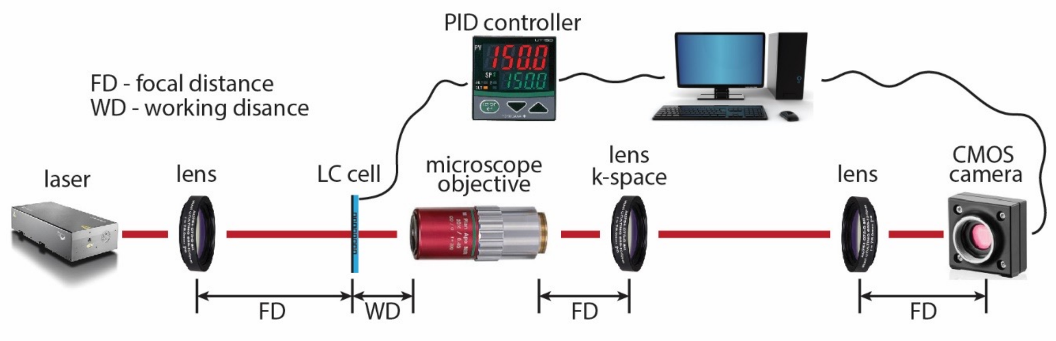
Heating process results in a jump in the forward to backward ratio from 1 to 50 times

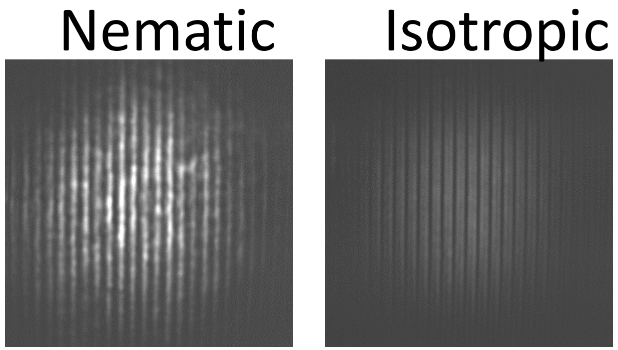
Disks diameter $d = 770\ nm$

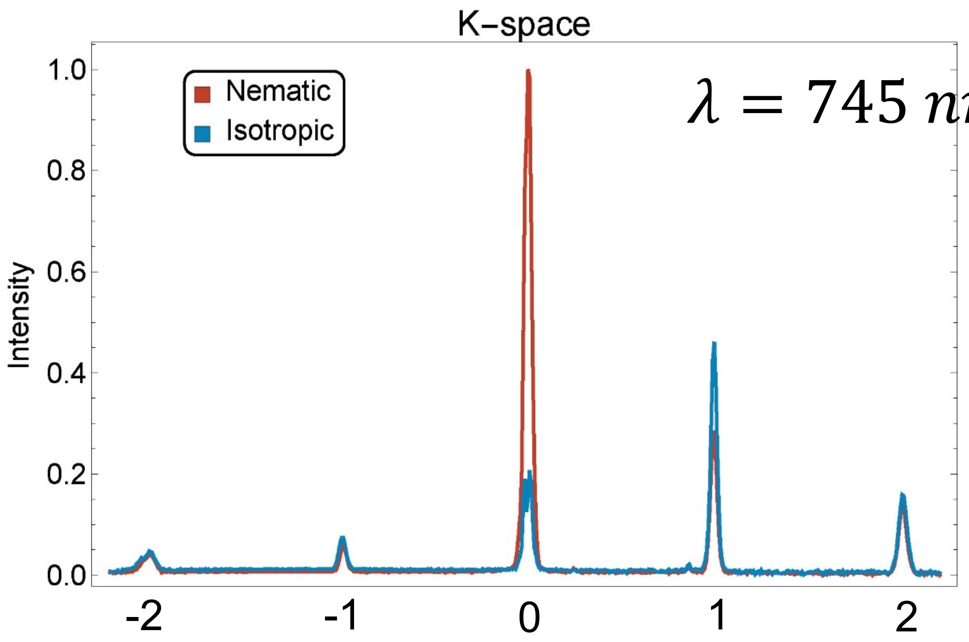


M. Rahmani, A. Komar *et al.*, *Adv. Funct. Mater.* **27**, 1700580 (2017)

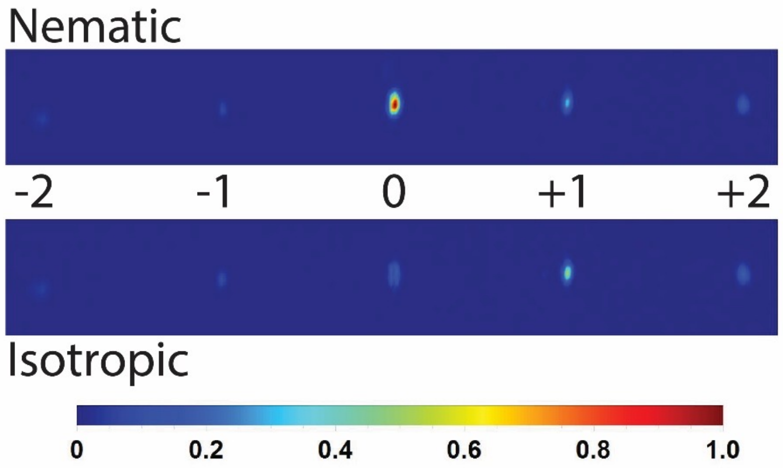
The switching of intensity from 0 to 1 order is experimentally observed





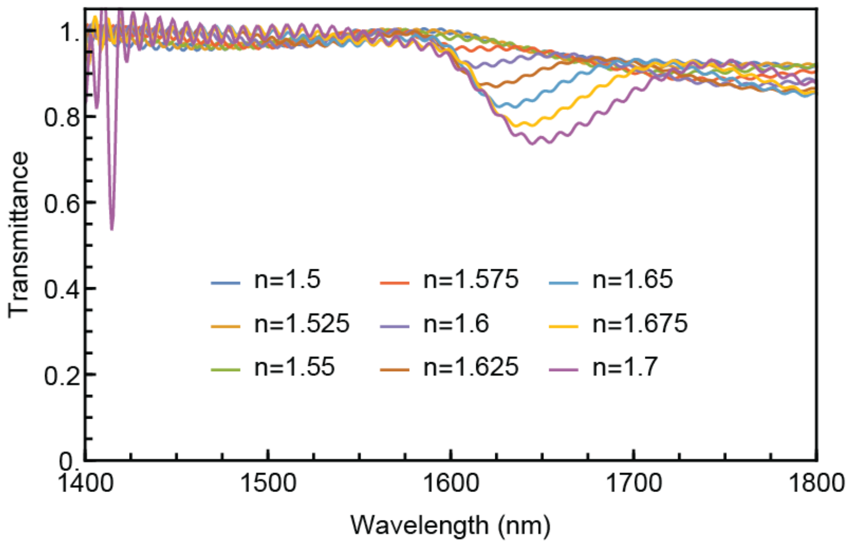


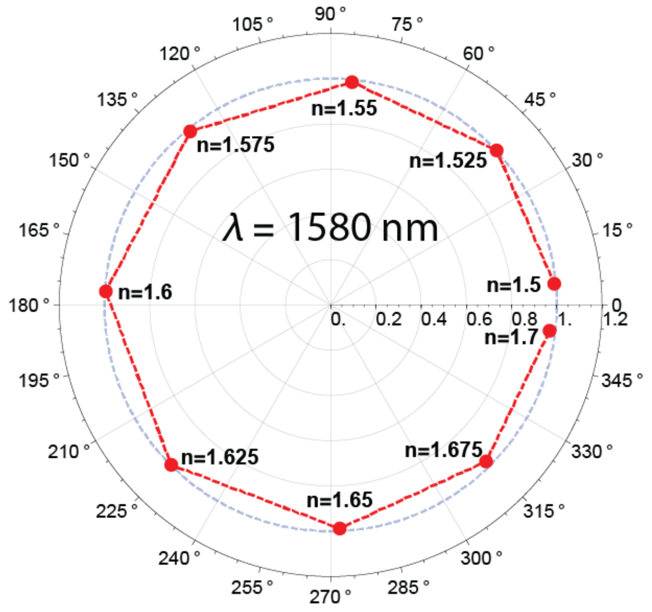
$\lambda = 745\ nm$



Transmission phase tuning of MS

Homogeneous tuning of refractive index leads to 2π control

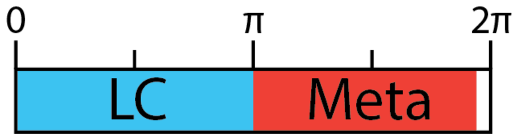




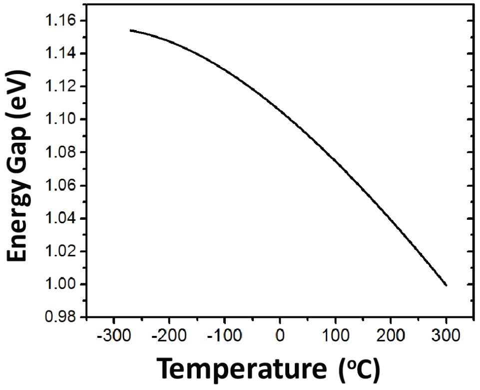
Phase change for anisotropic material

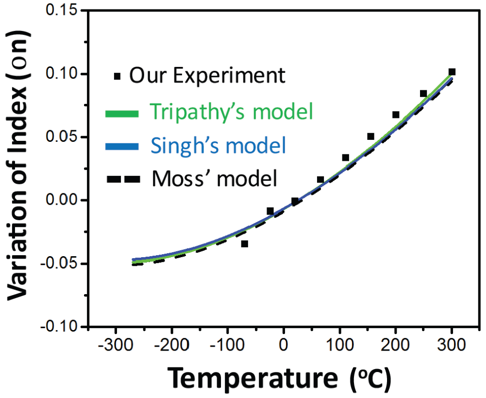
$$\Delta\varphi = \frac{2\pi\,\Delta n\,d}{\lambda}$$

$\Delta\varphi$ – phase change
Δn – anisotropy
d – thickness
λ – wavelength



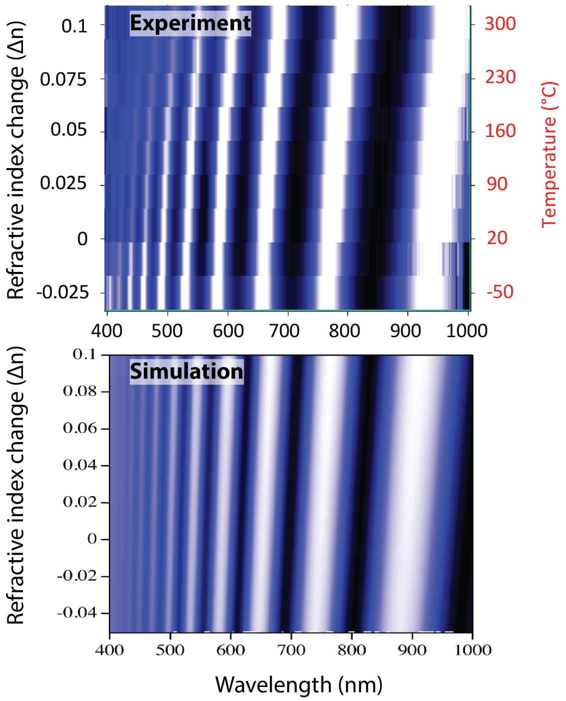
Refractive index of Si nano-slab matches refractive index of bulk Si





$$R = 1 - \frac{(1-R_1)(1-R_2)}{\left(1-\sqrt{R_1R_2}\right)^2 + 4\sqrt{R_1R_2}\sin^2\phi}$$

$$\frac{\partial\phi}{\partial T} = \frac{2\pi d}{\lambda}\frac{dn}{dT} \qquad \Delta\lambda = \frac{2d}{(m+0.5)}\left(\frac{dn}{dT}\right)\Delta T$$



$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta}$$

Moss

$$n^4 E_g = 95 \text{ eV}$$

Singh

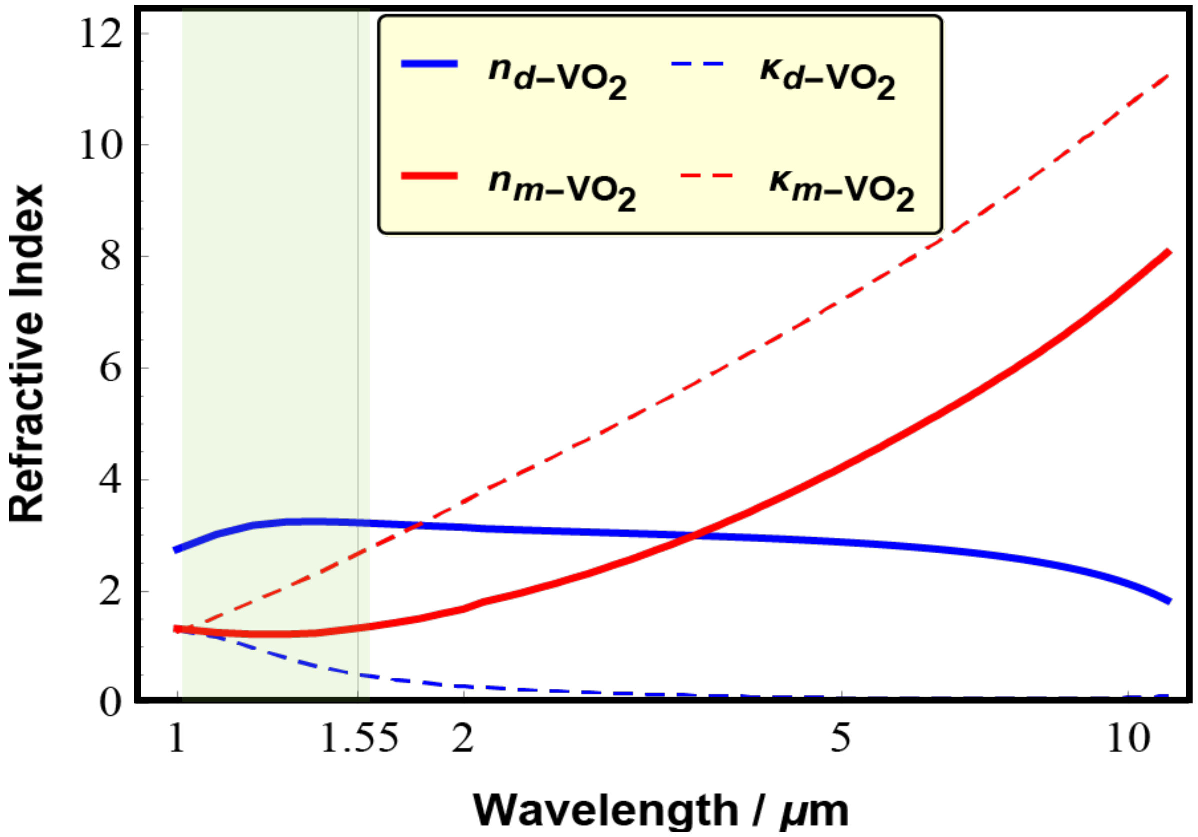
$$n = K(E_g)^C$$

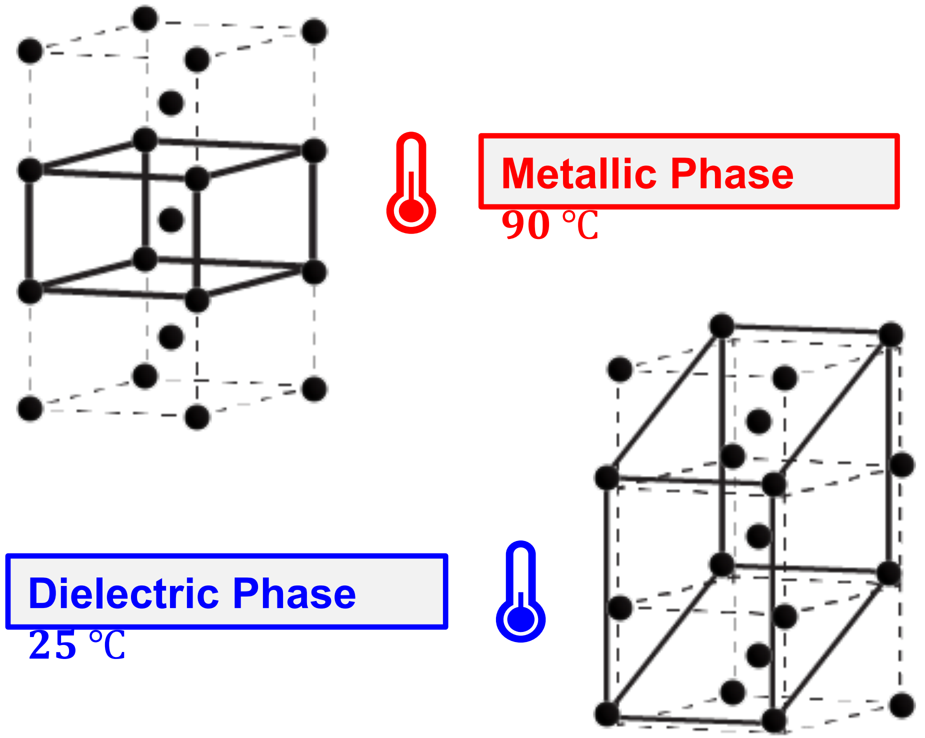
Tripathy

$$n = n_0\left(1 + \alpha e^{-\beta E_g}\right)$$

Practical Case: VO_2 Nano-Optics

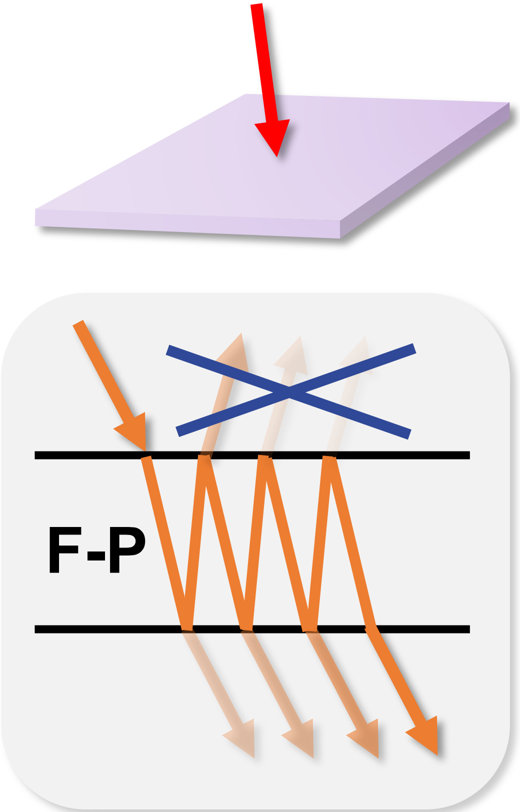
- A type of ***Phase Change Materials*** with distinct phases (dielectric and metallic).
- Phase transition behaviour at ~**65**℃, alongside with a large index modulation. $\tilde{n} = n + i\kappa$
- Downside: ***Lossy***, more severe at shorter wavelength.

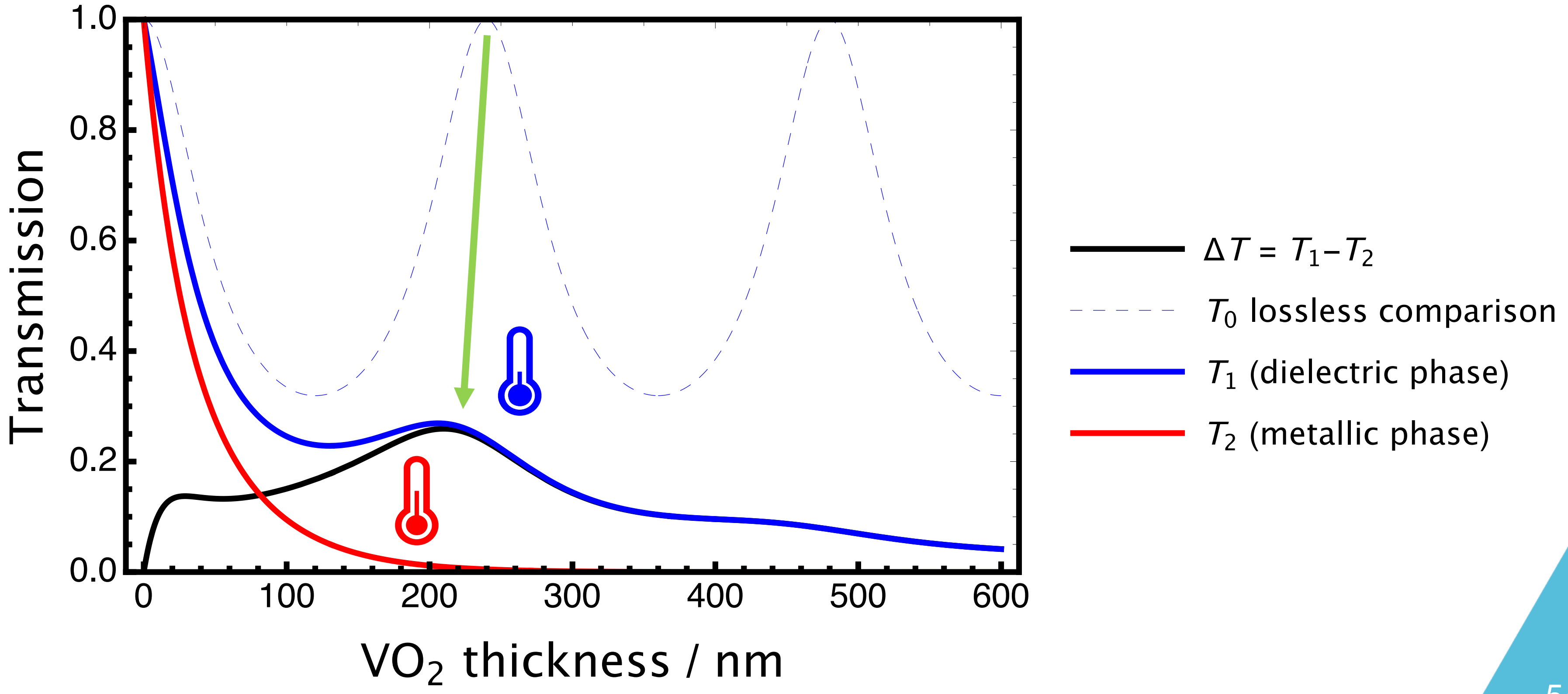




Bare VO_2 Layer

- Maximum ΔT of a bare layer of VO_2 at $1.55\ \mu$m wavelength: ~ 0.26.
- The relatively high transmission at dielectric phase is attributed to ***Fabry-Perot type anti-reflection***; while the low transmission at metallic phase is due to loss.





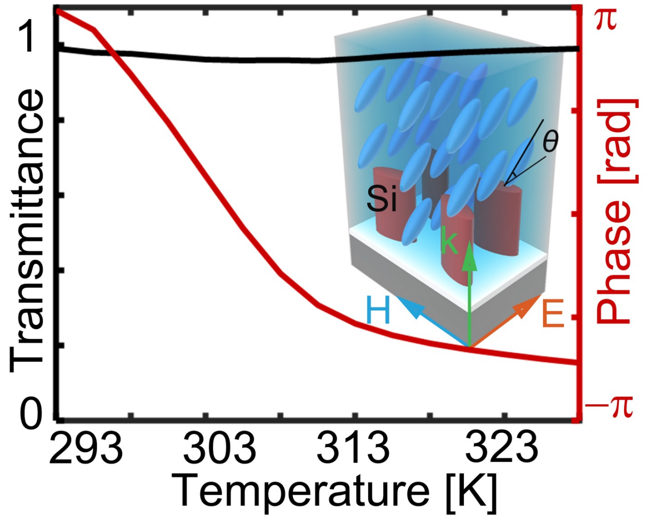
Mechanism of optical anisotropic tuning

Our goal

1. To manipulate the resonance direction and shifting rate.

2. To generate a sufficiently large phase change with the limited external stimulus and refractive index change.

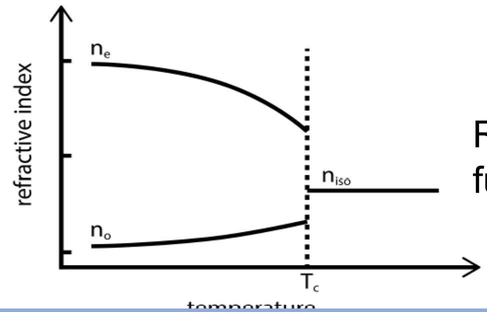
3. To maintain the Huygens' condition



Pure phase tuning of optical metasurfaces in the full 2π range with unitary efficiency.

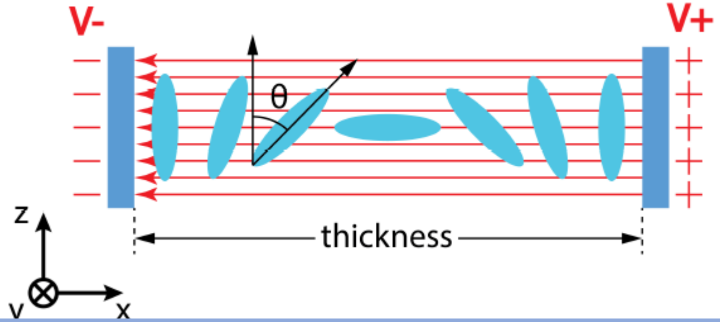
LC tunable metasurfaces

1. Temperature tuning



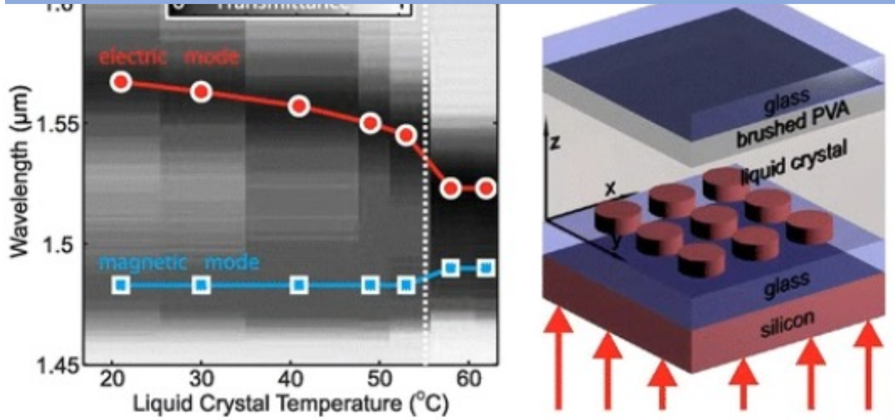
Refractive index of LC as a function of temperature

2. Electric tuning

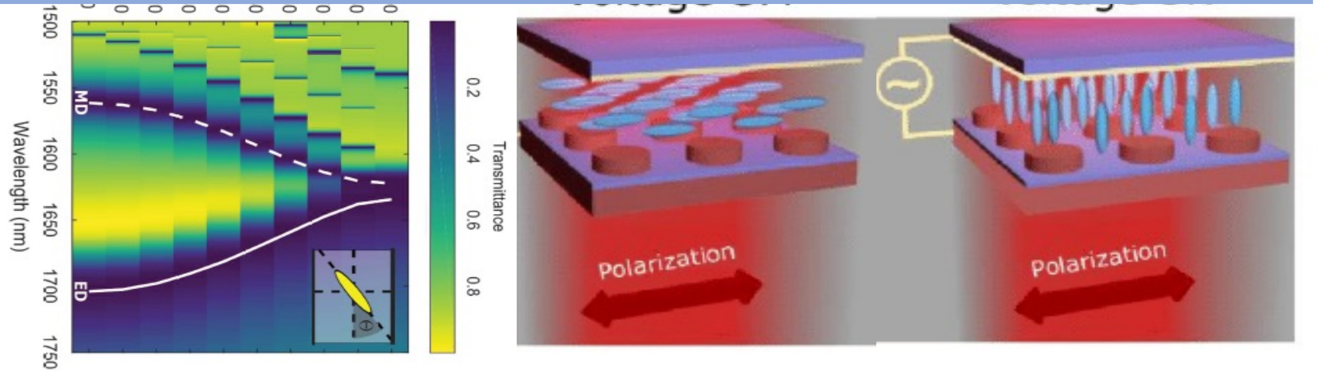


Alignment of LC molecules along the external applied electric field

Cannot independently control the tuning rate of each resonance.

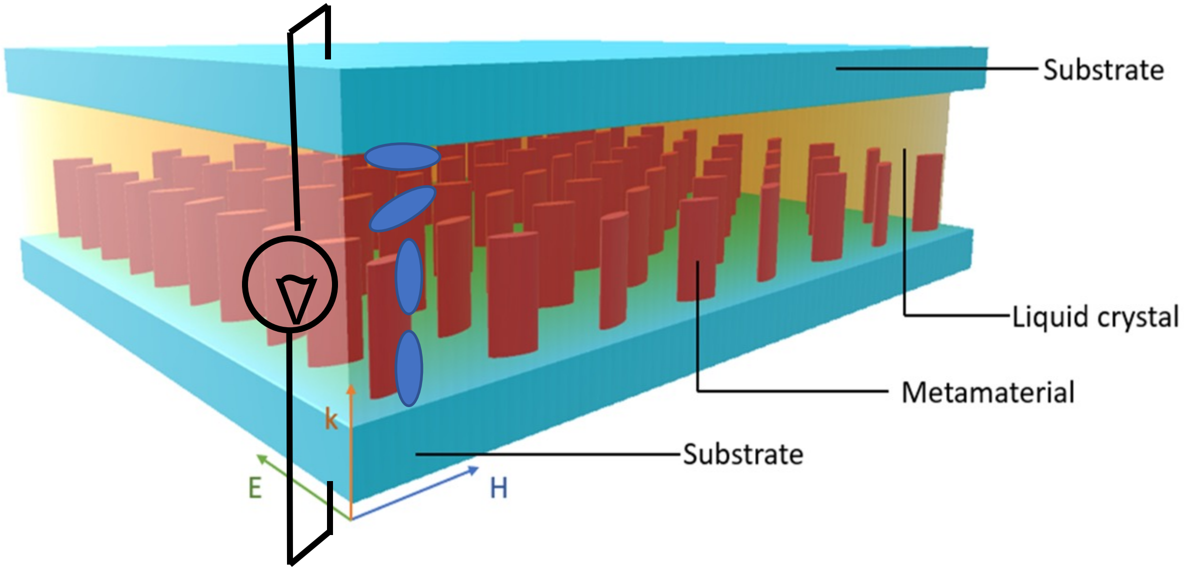


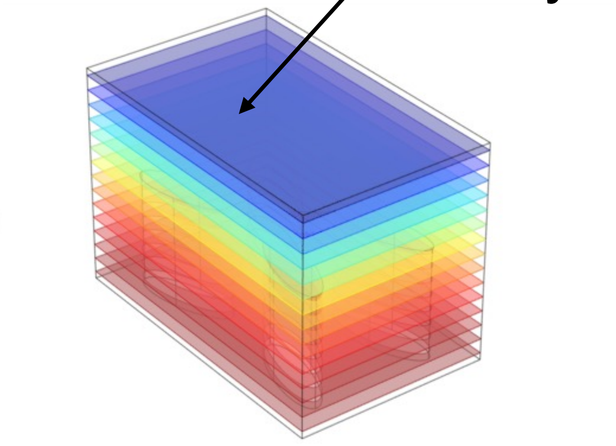
Sautter et al., ACS Nano. **9**, 4308 (2015)

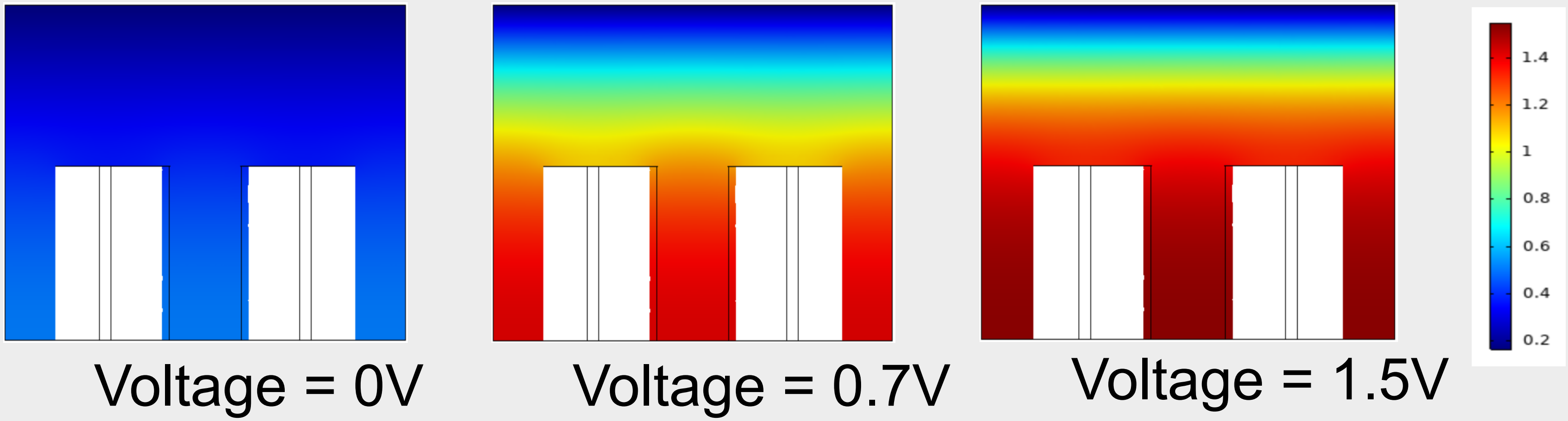


Komar, et al., Appl. Phys. Lett. **110**, 071109(2017)

Simulation model with LC

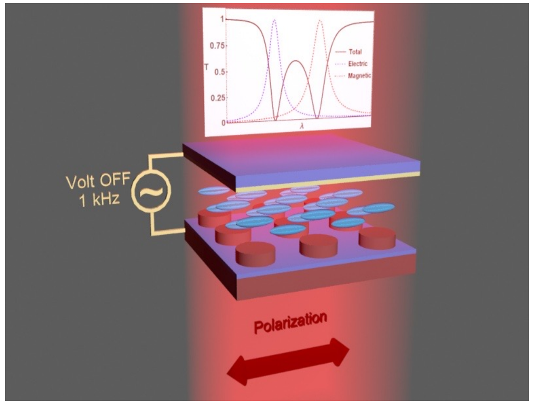


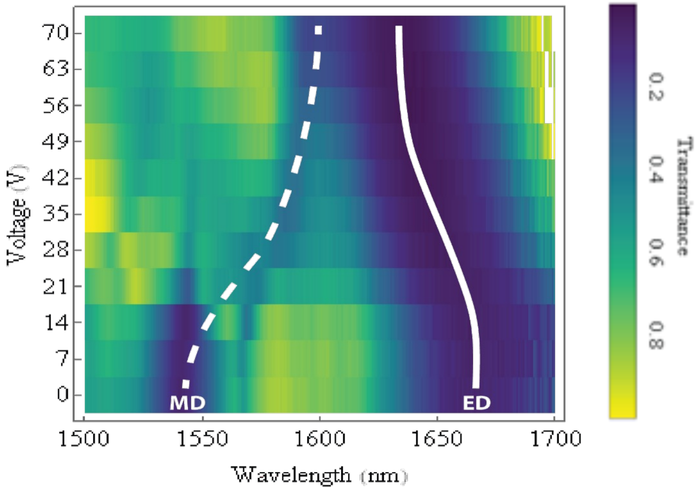


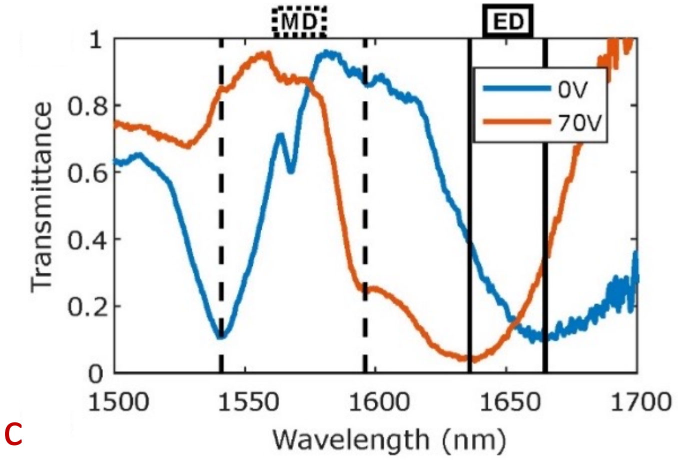


Electrical tuning of LC infiltrated MSs

Experiments: tuning of transmission

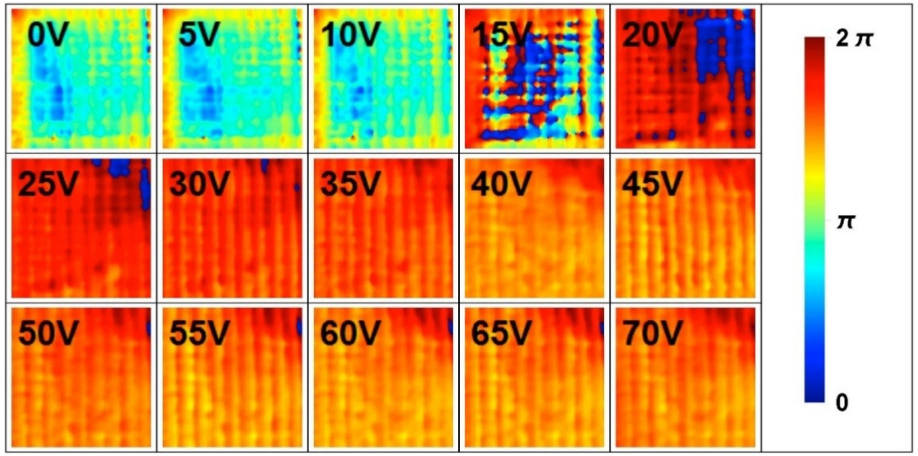


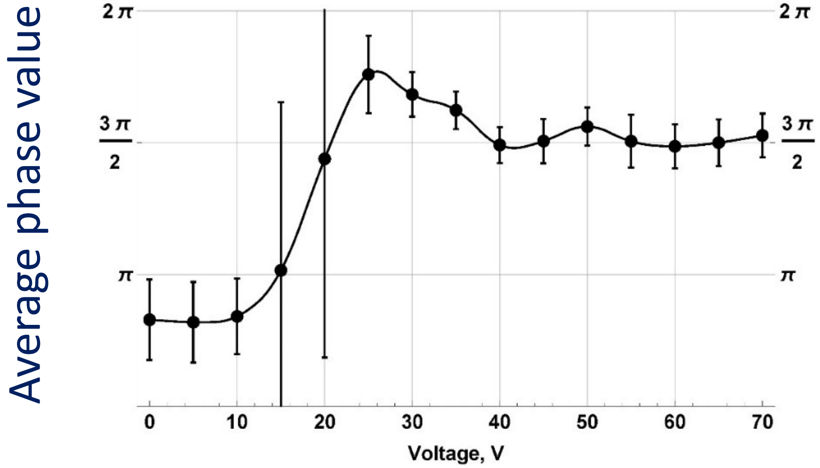




29 nm shift for the electric
55 nm for the magnetic resonance

Tuning of phase

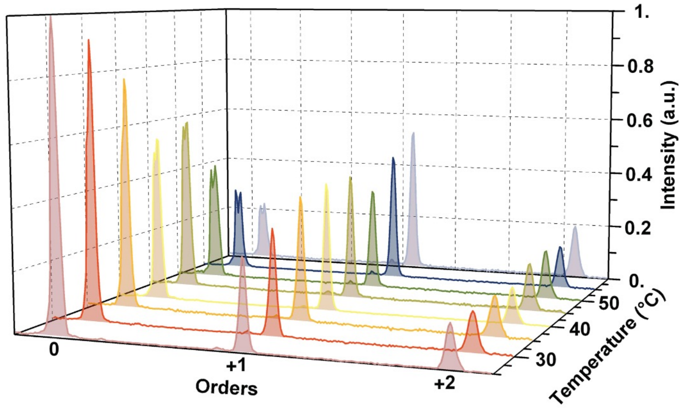


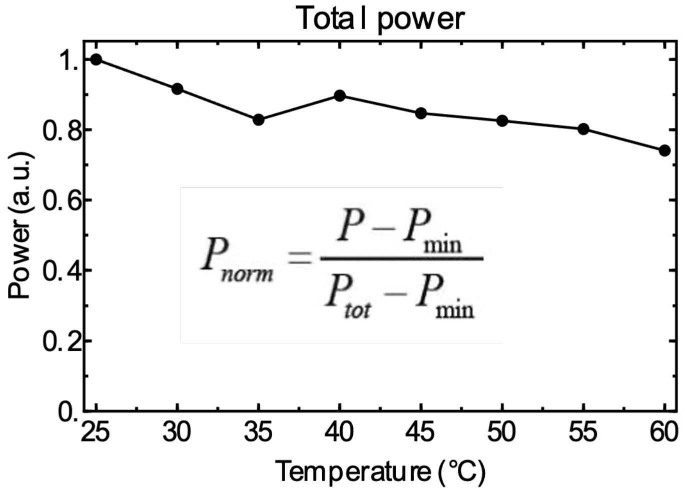


Measured phase change of ~π

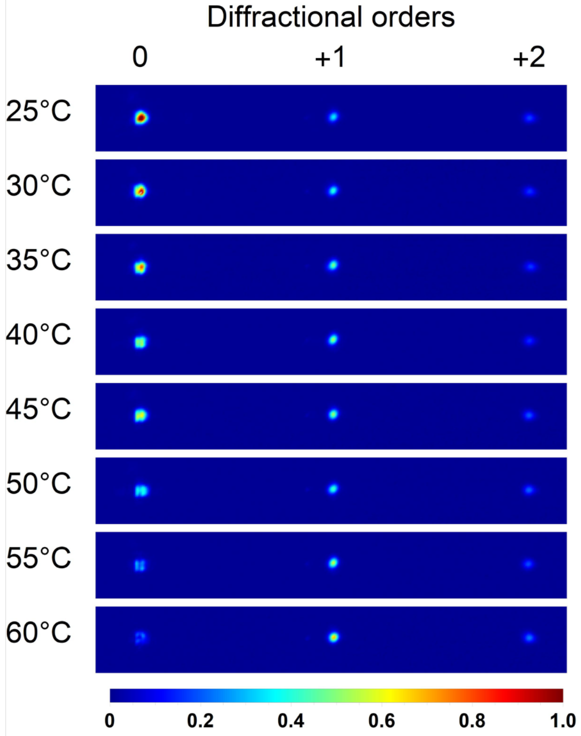
Komar *et al.*, *Appl. Phys. Lett.* **110**, 71109 (2017)

Beam deflection switching





$$P_{norm} = \frac{P - P_{\min}}{P_{tot} - P_{\min}}$$



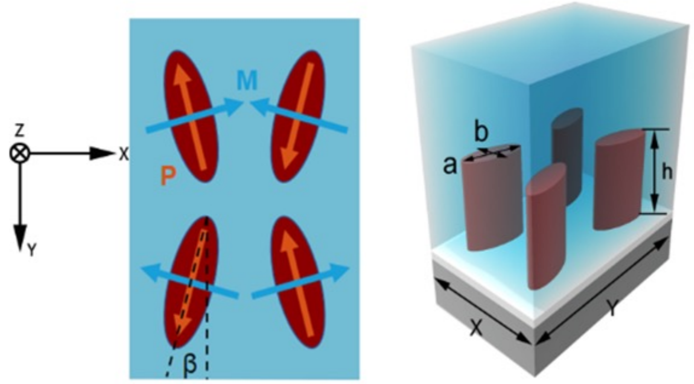
$$FoM_{experiment} = 0.48$$

$$FoM_{theory} = 0.45$$

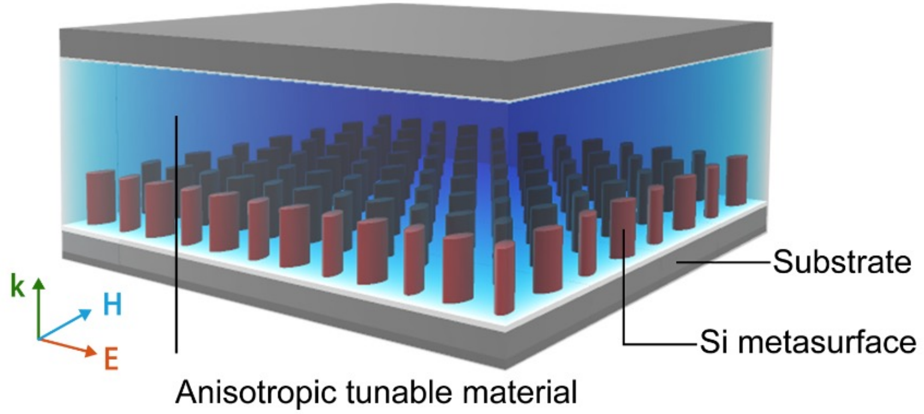
Komar *et al.*, *ACS Photonics* 5, 1742 (2018)

Mechanism of optical anisotropic tuning

Anisotropic material + BIC metasurface =



Unit cell of the zig-zag infiltrated metasurface



Total BIC structure infiltrated with anisotropic material.

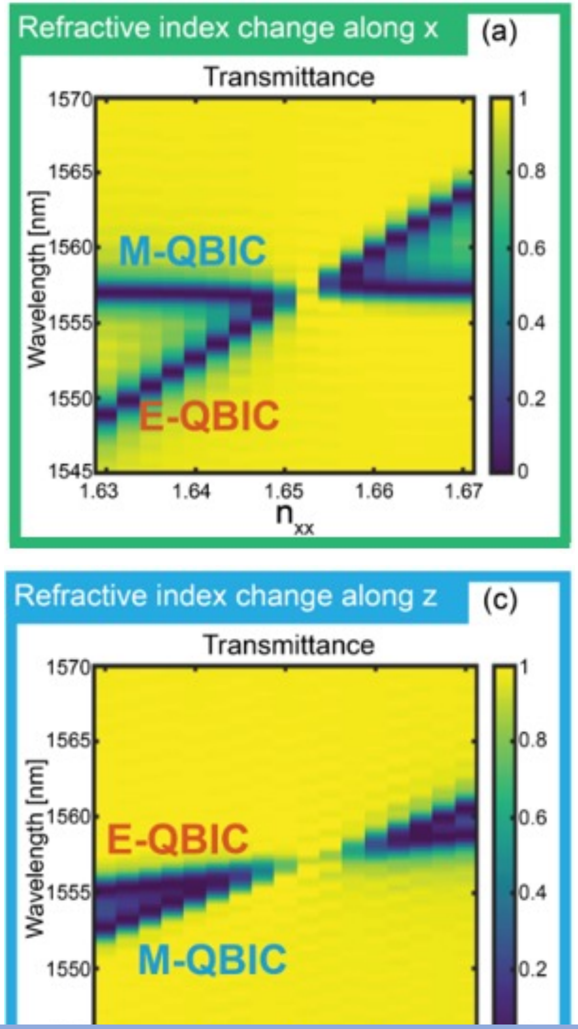
$$\text{Anisotropic material } \hat{\boldsymbol{n}} = \begin{bmatrix} n_{xx} & 0 & 0 \\ 0 & n_{yy} & 0 \\ 0 & 0 & n_{zz} \end{bmatrix}$$

?

- The resonances shift
- Electric field variation

Yang *et al.*, *Adv. Opt. Mat.* **10**, 2101893 (2022)

Resonance in anisotropic material



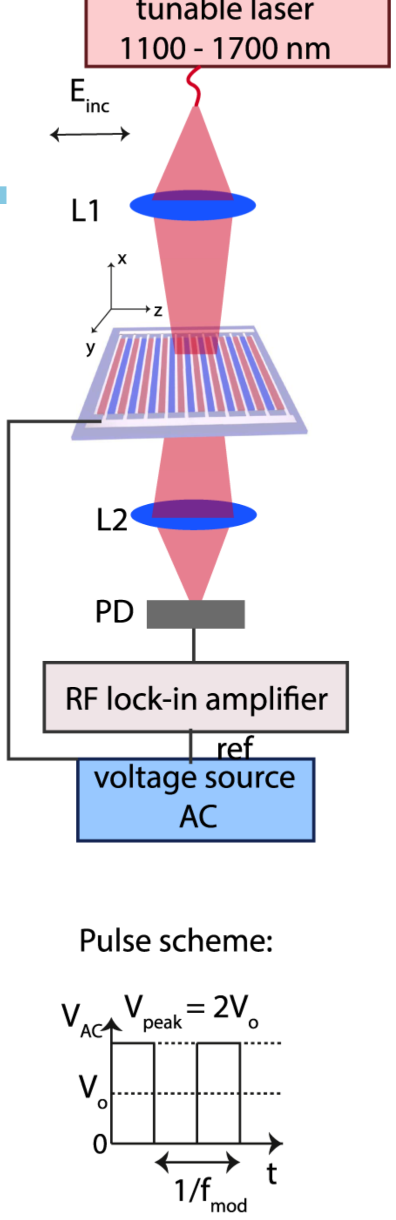
diagonal tensor

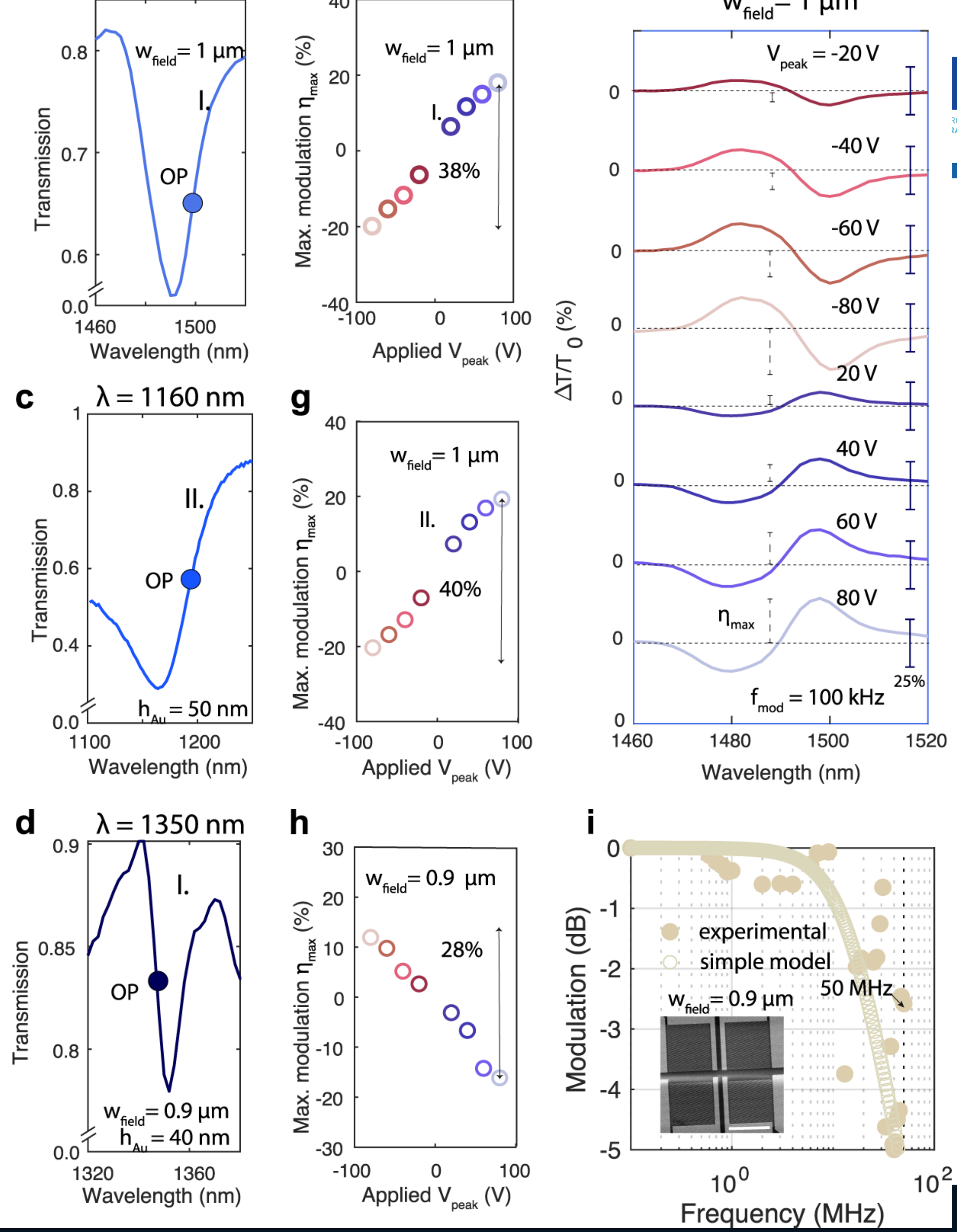
$$\hat{\boldsymbol{n}} = \begin{bmatrix} n_{xx} & 0 & 0 \\ 0 & n_{yy} & 0 \\ 0 & 0 & n_{zz} \end{bmatrix}$$

- ✓ Two resonances have different tuning rate.
- ✓ Resonances tuning rate can be controlled by the refractive index change.
- ✓ High transmittance area (Huygens regime) happens around 1.65 surrounding refractive index.

It is possible to control the resonances tuning rate and direction separately.

Yang *et al.*, *Adv. Opt. Mat.* **10**, 2101893 (2022)





Benea-Chelmus et al., Nature Communications **12**, 5928 (2021)

What is the MS with highest contrast?

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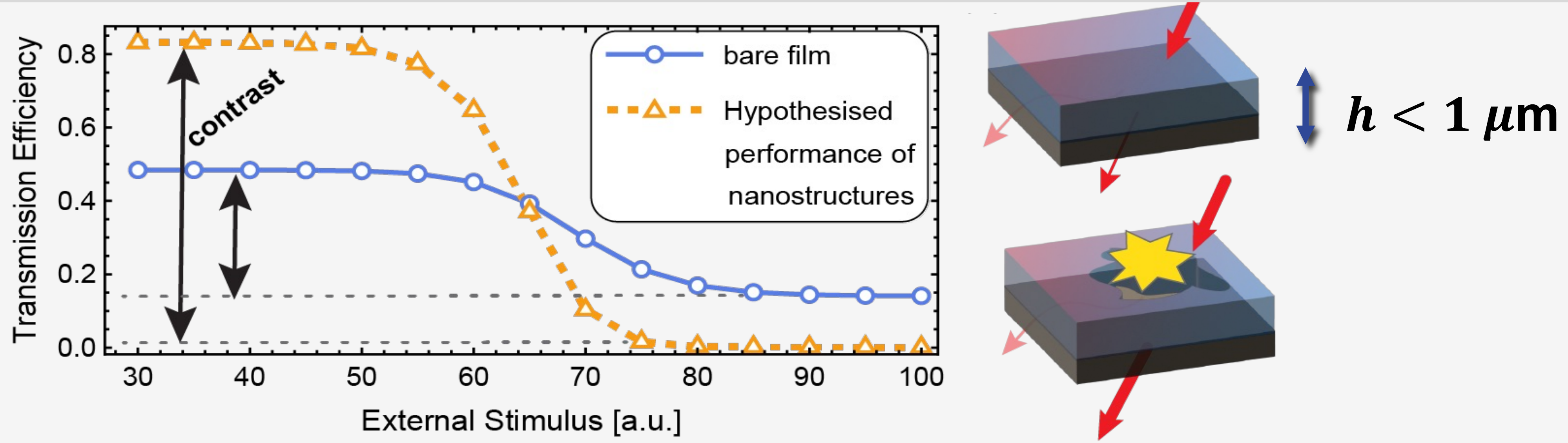
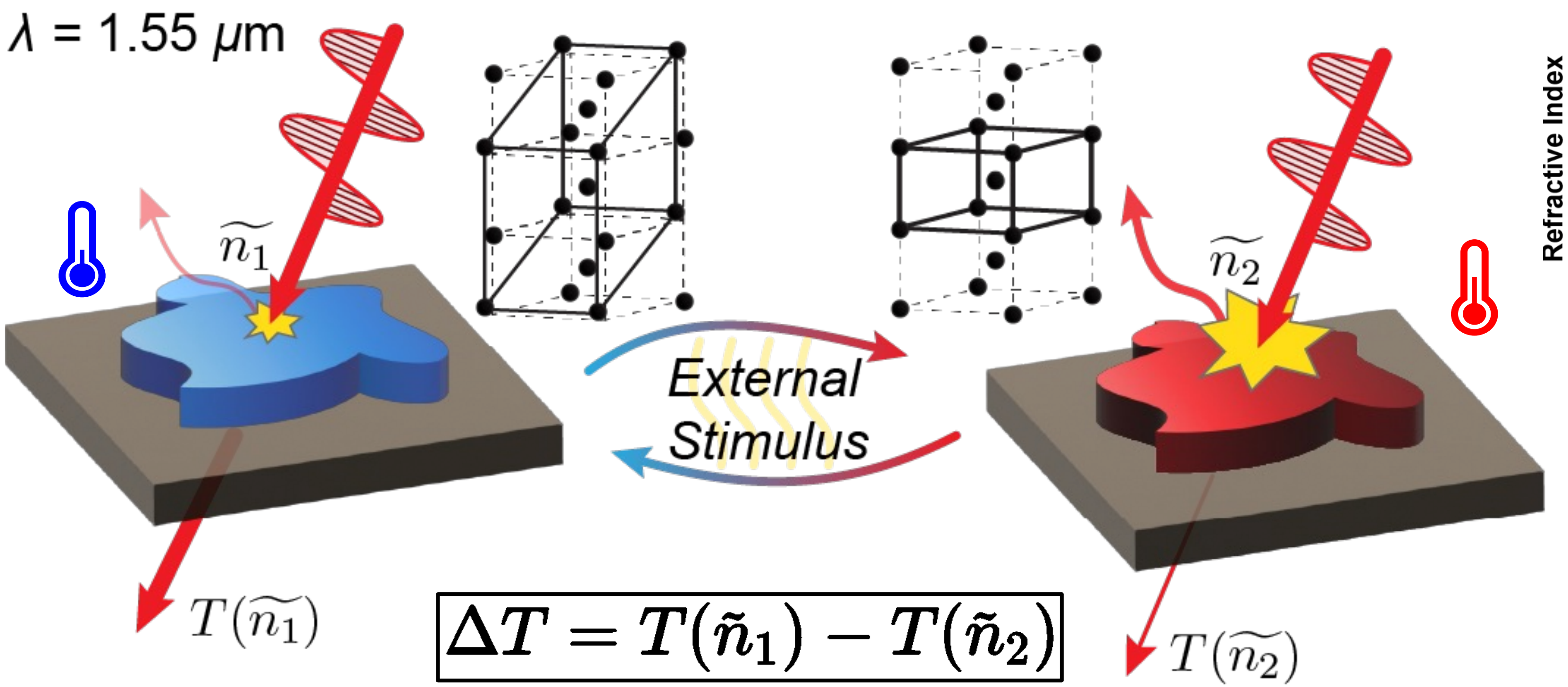
Challenge: *Use of materials with loss, such as phase change materials* $\tilde{n} = n + i\kappa$

How to design nanostructures to enlarge transmission contrast?
What is the fundamental limit?

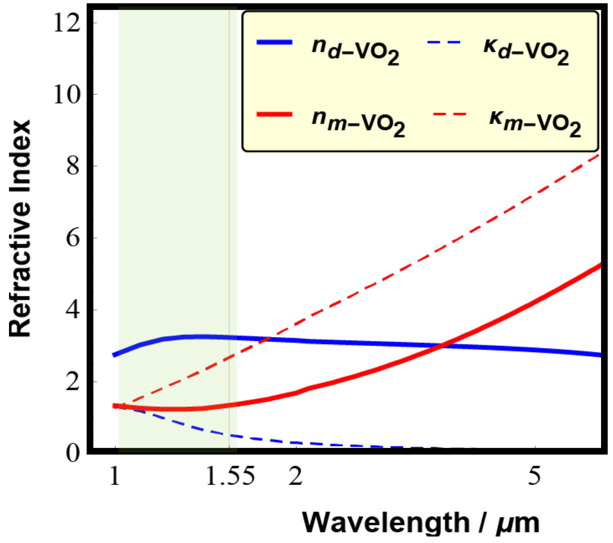


Design optimisation: maximise transmission contrast

Maximise the transmission contrast of VO_2 nanostructures, fundamental limit?

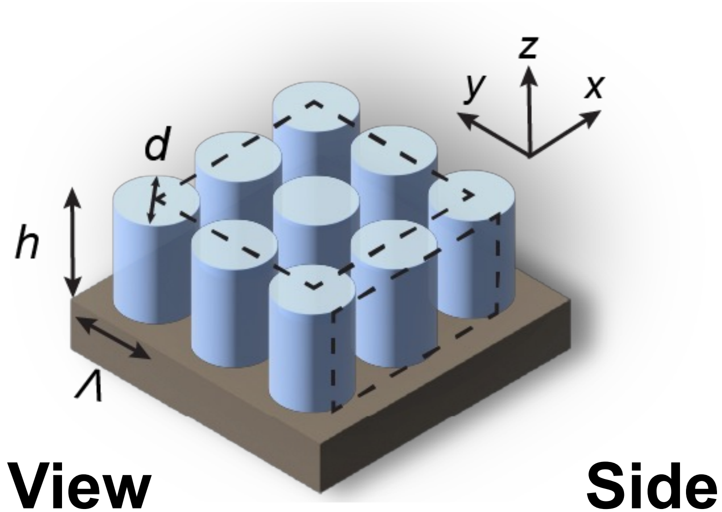


$$\Delta T = T(\tilde{n}_1) - T(\tilde{n}_2)$$

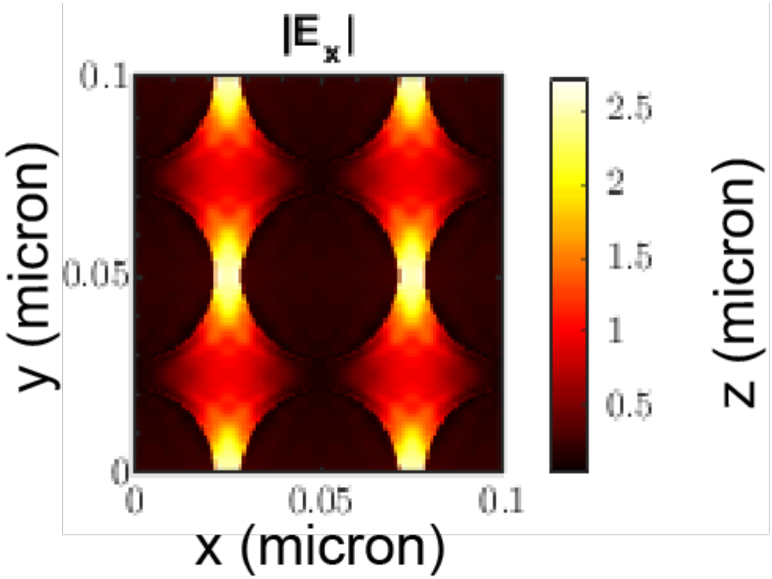


- Achieved by manipulating Reflection (***R***) and Absorption (***A***). $\boldsymbol{T + R + A = 1}$

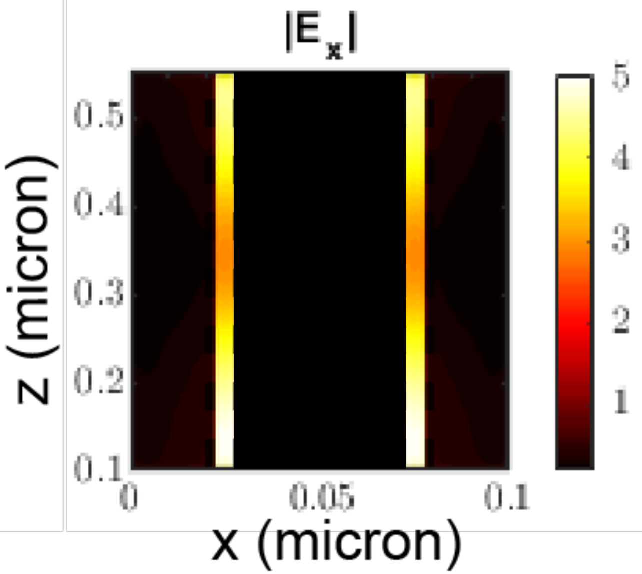
VO_2 nanodisks metasurface



Top View



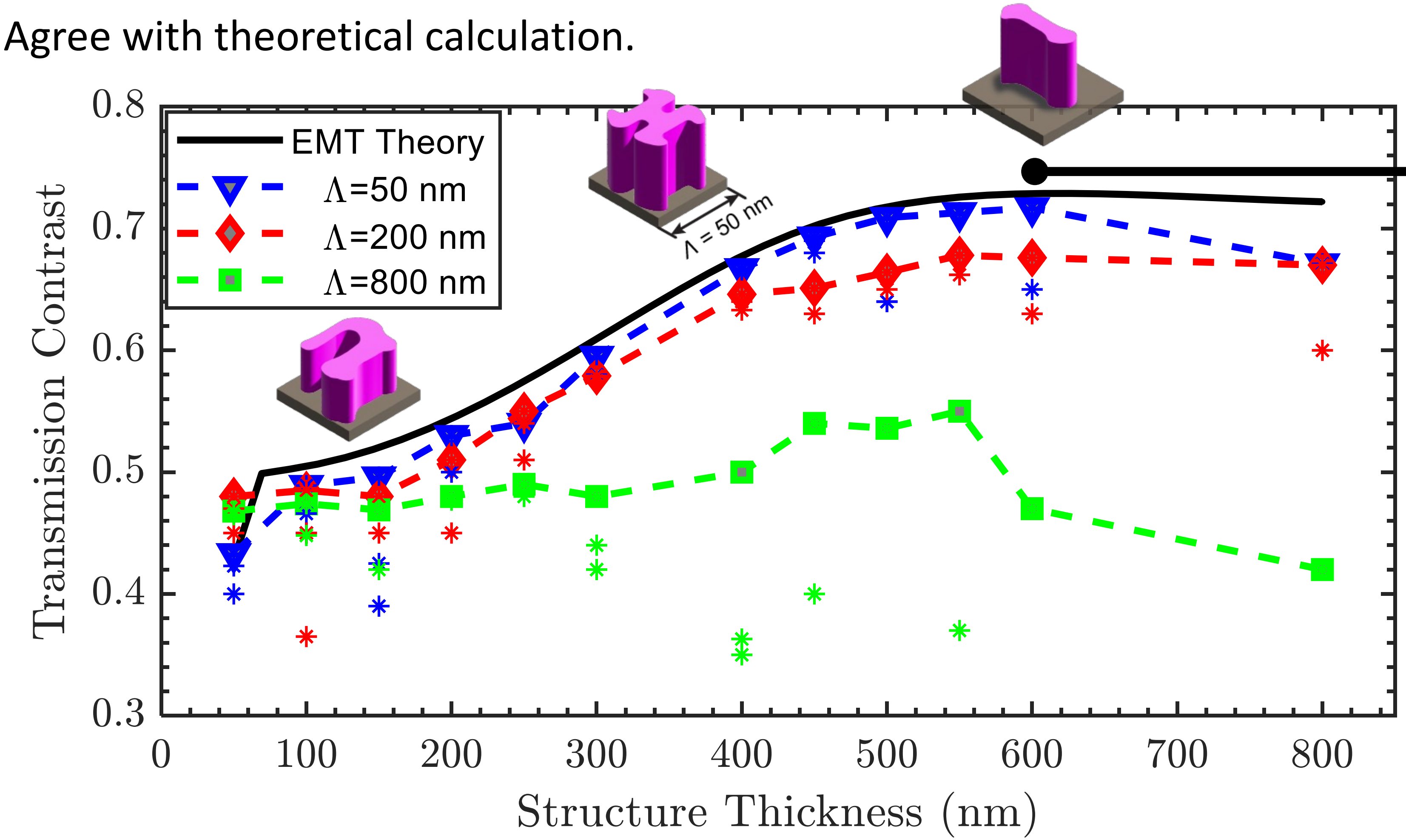
Side View

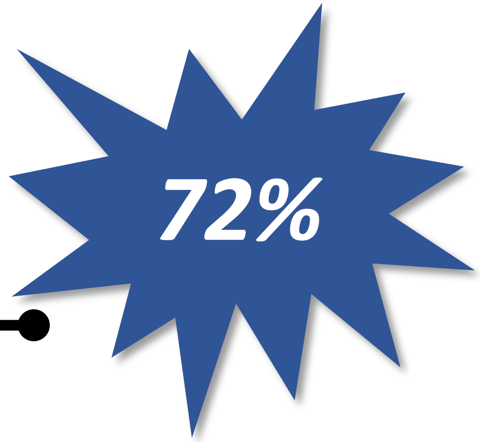


- **MAX $\Delta T \sim \mathbf{0.64}$**, in deep subwavelength regime (h=500 nm).
- Resonances are washed out by the loss.
- The high transmission contrast originates from a ***localised electric gap mode*** and it does ***NOT*** rely on the specific geometry!

Topology optimised metasurfaces

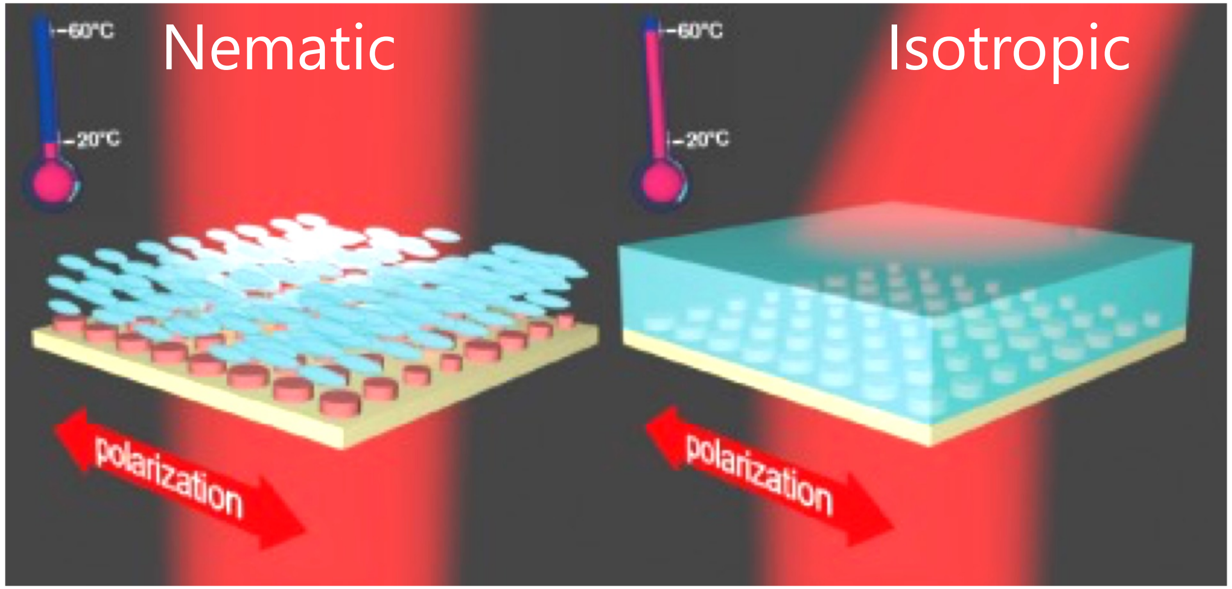
- The maximum contrast is **0.72** achieved with 50 nm periodicity.
- Contrast is enhanced due to the extra transverse freedom.
- Agree with theoretical calculation.

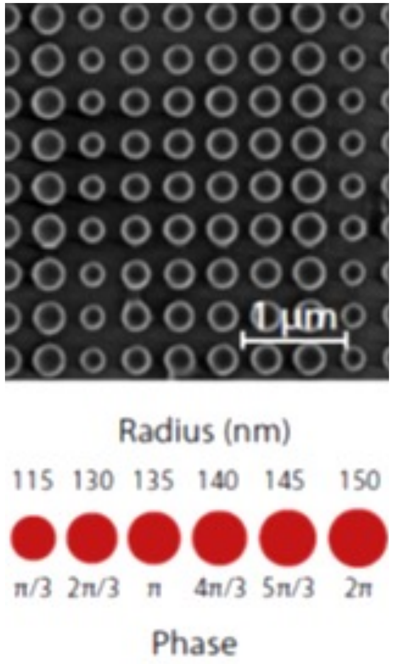


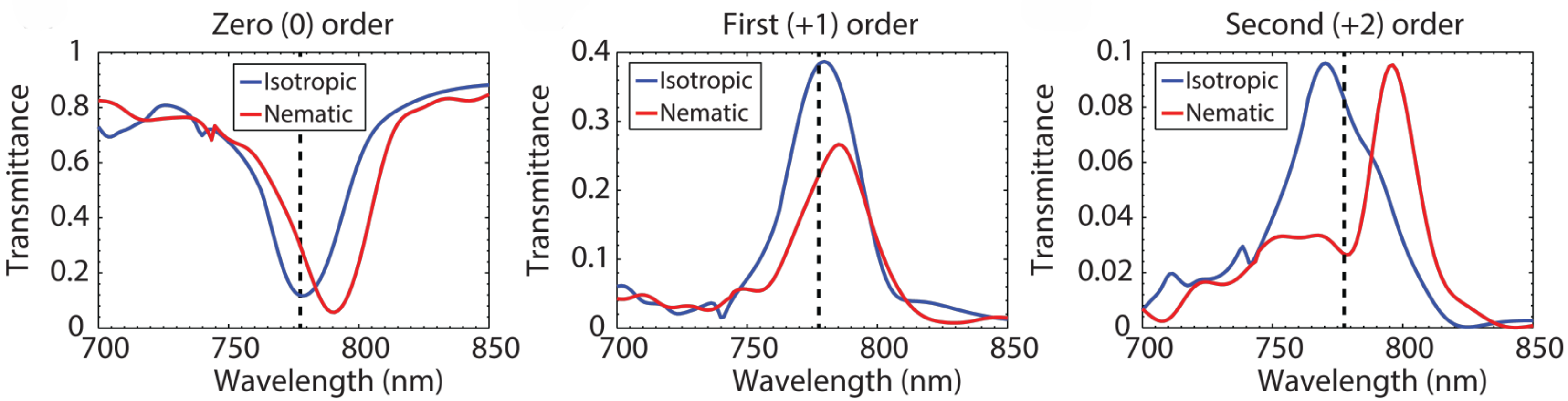


Again the high transmission contrast originates from a ***localised electric gap mode***

Switchable beam deflection

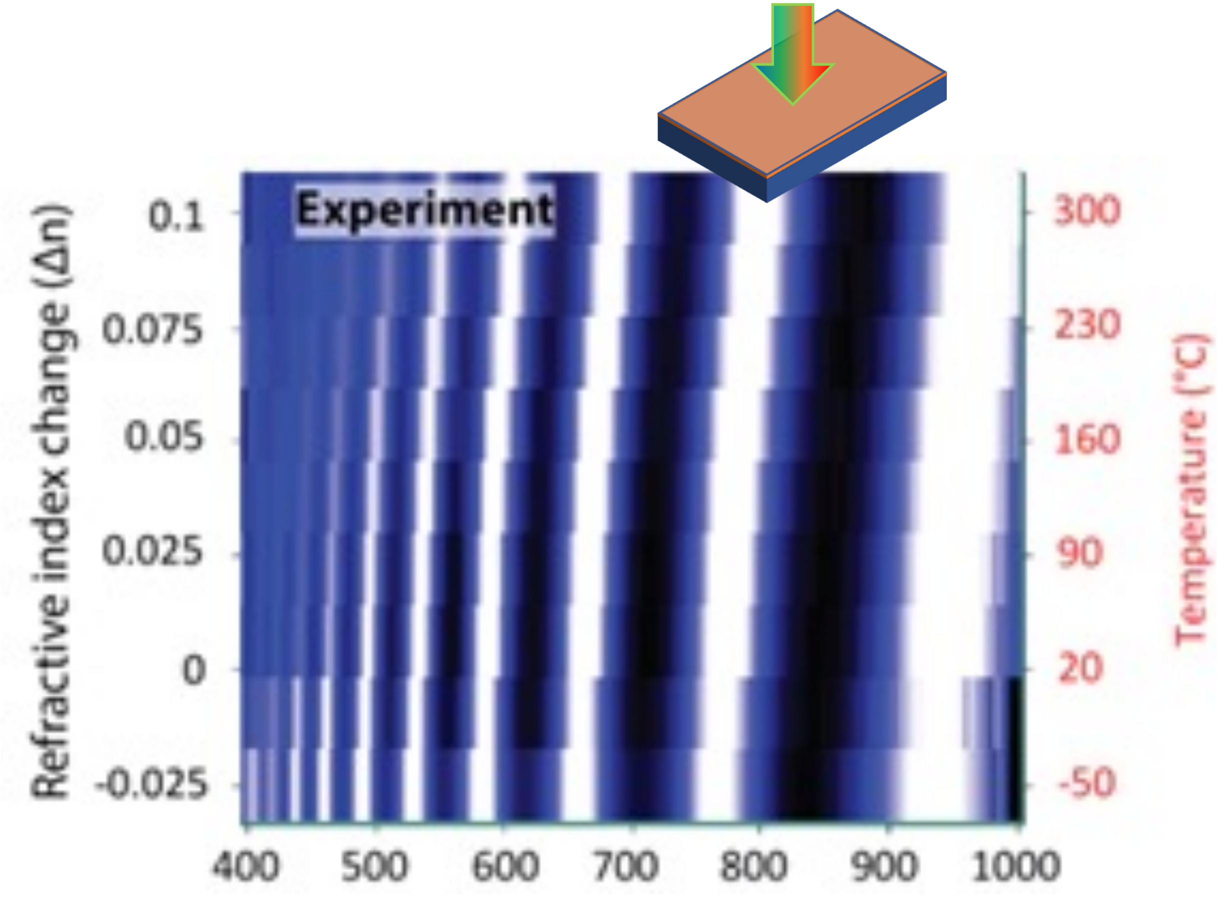




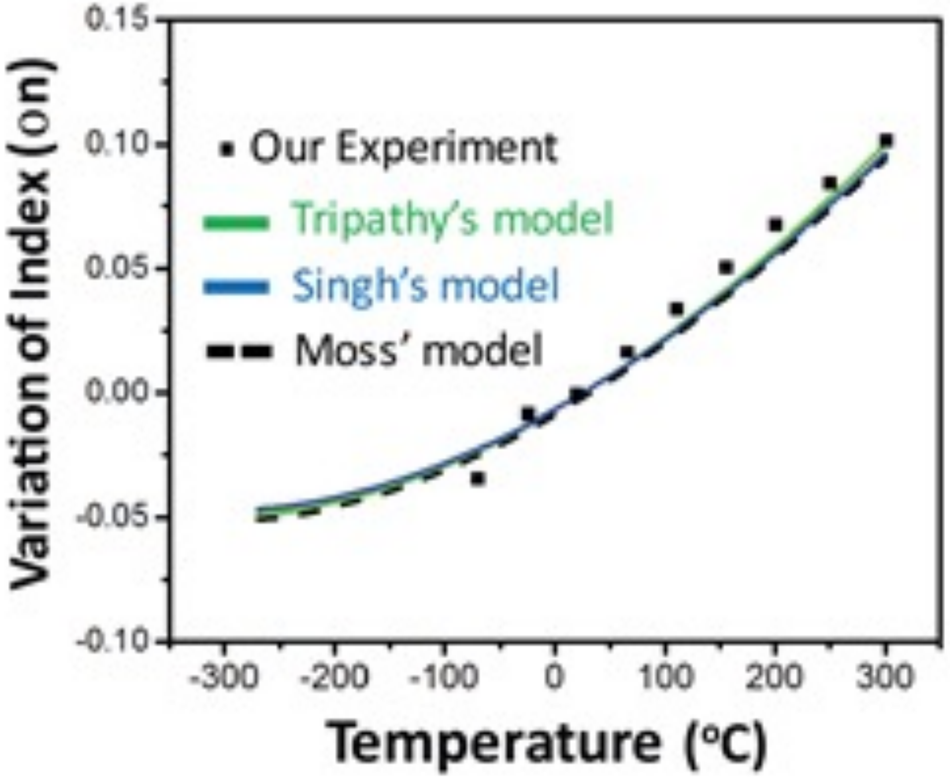


Komar *et al.*, *ACS Photonics* 5, 1742 (2018)

Large thermo-optic effect in Si

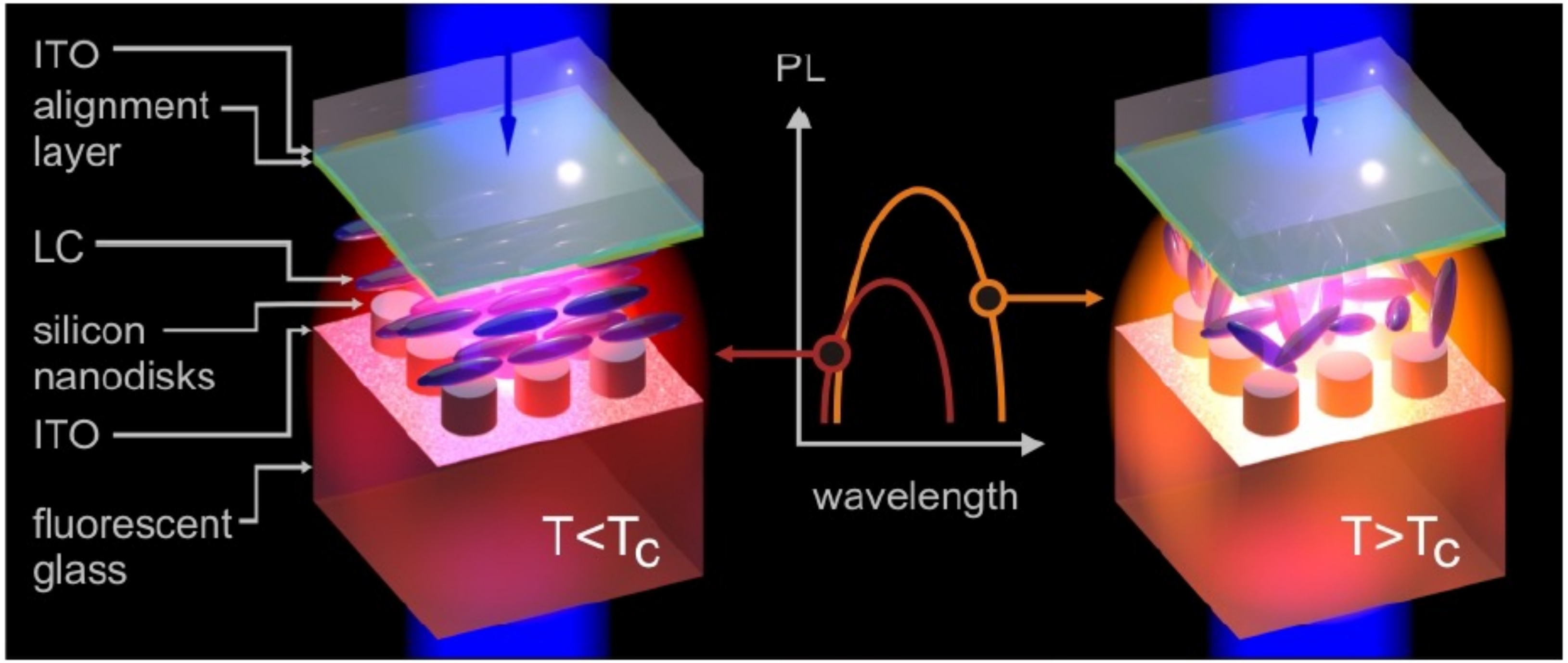


Temperature tuning



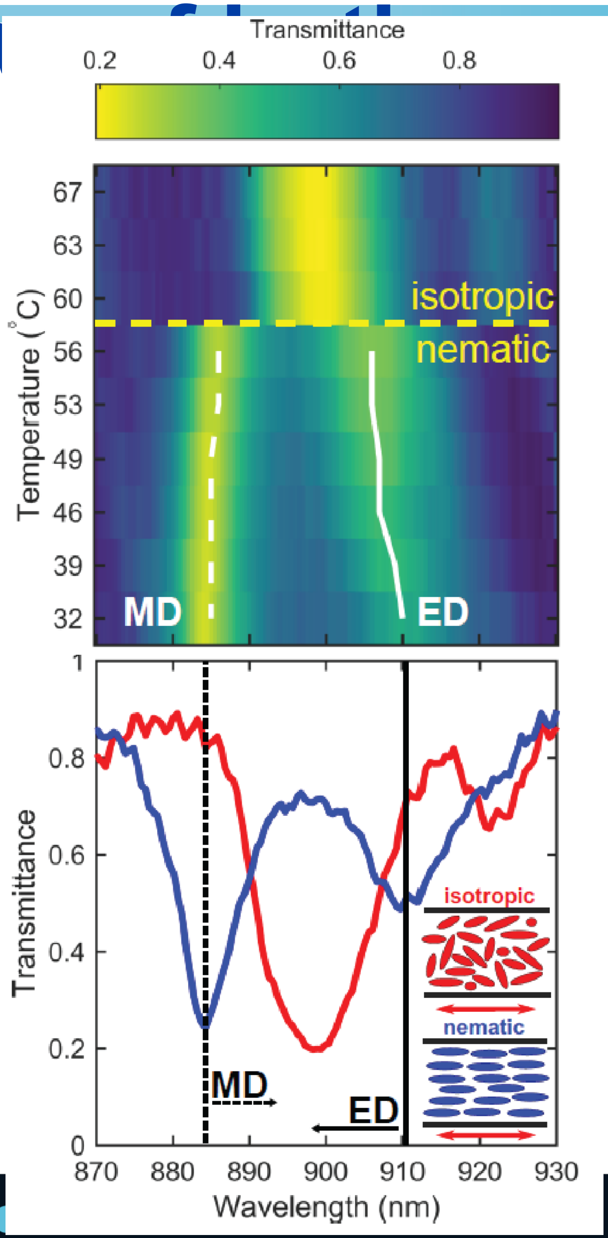
Rahmani *et al.*, Adv. Func. Mat. **27**, 1700580 (2017)

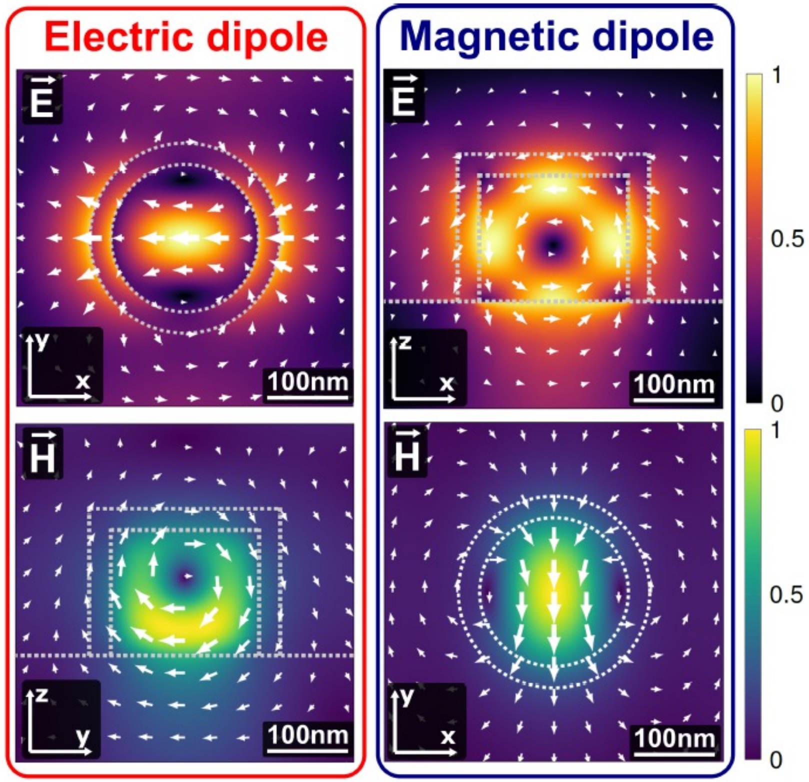
Tuning spontaneous emission by liquid crystals



Metasurface parameters:
height $h = 182\ nm$
diameter $d = 237\ nm$
lattice constant $a = 560 nm$

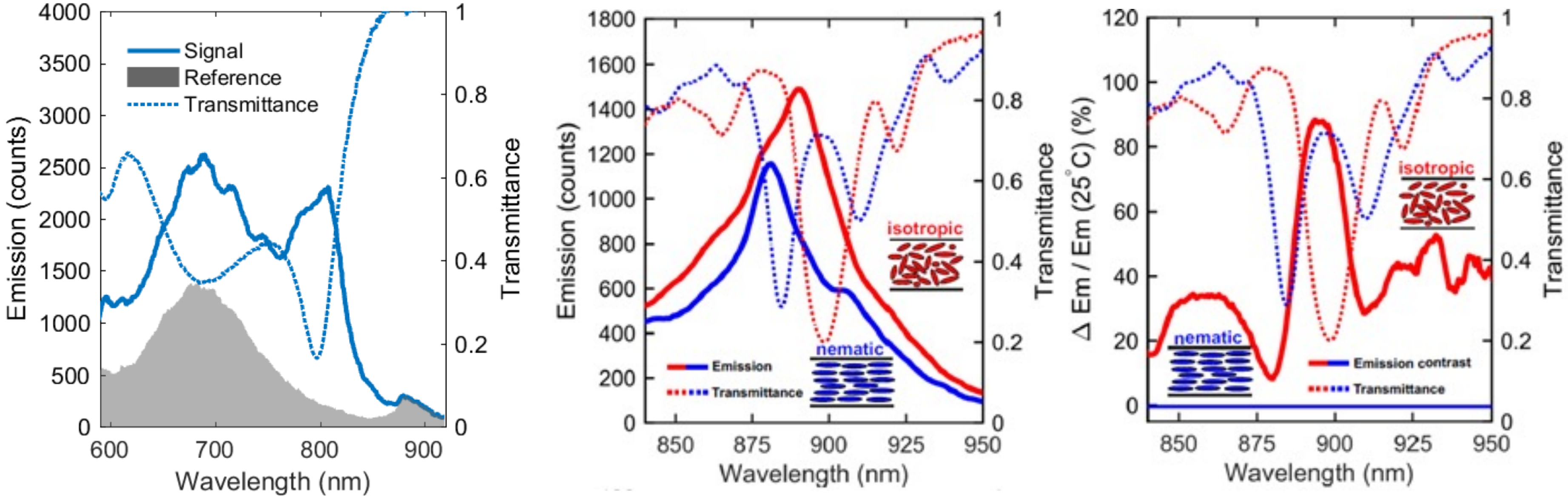
Transition to isotropic state leads to overla … onances





Tuning of emission of colour centres by LC

The emission increases by up to 90% near 900 nm after isotropic transition

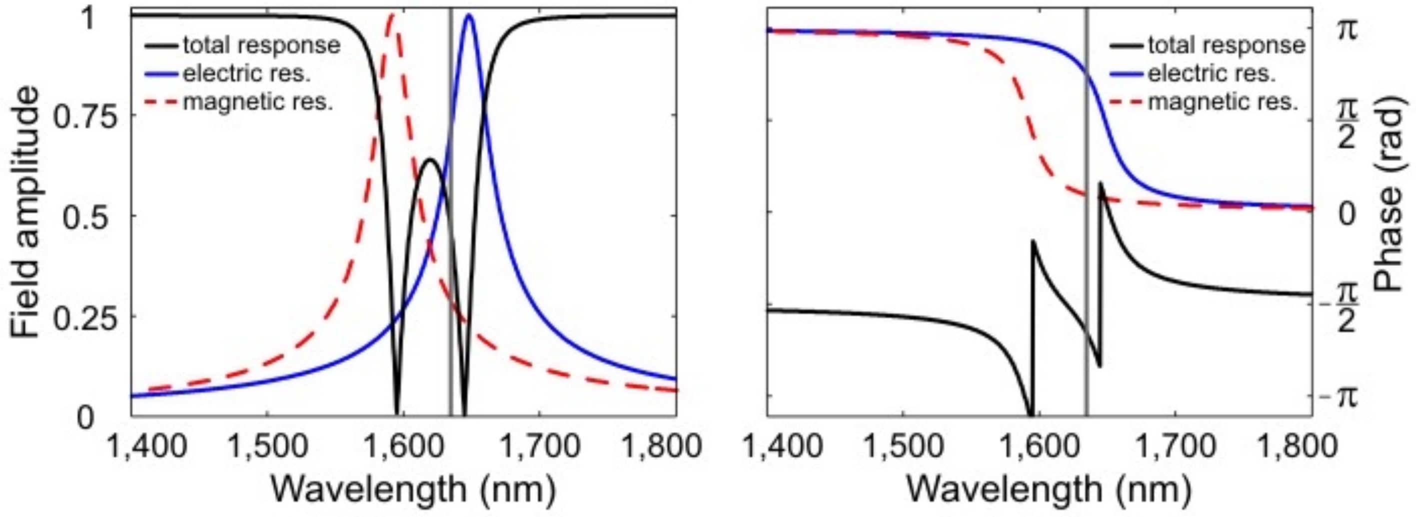


Excitation source:
wavelength $532\ nm$
average power $1.4\ mW$
pulse-width $100\ ps$
repetition rate $80\ MHz$

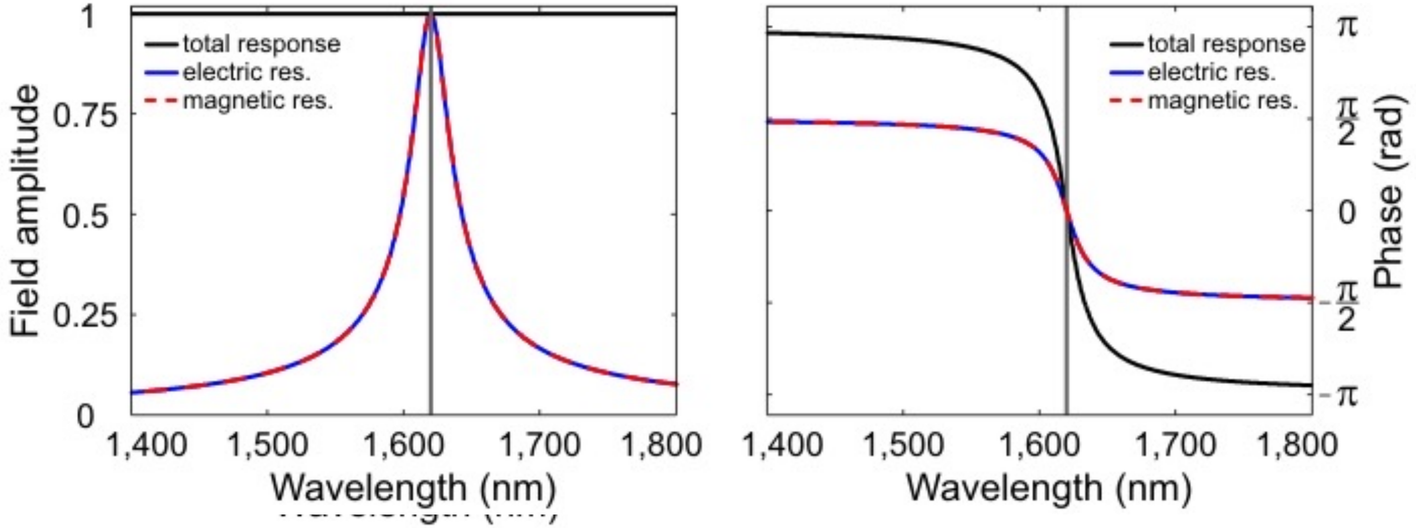
Bohn, Komar *et al.*, (2018)

Overlap of E&M resonances

Separate resonances



Overlapping resonances



Decker *et al.*, Adv Opt Mat **13**, 813-820 (2015)