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Hybrid Metasurfaces : From Optoelectronics to Nonlinear Optics

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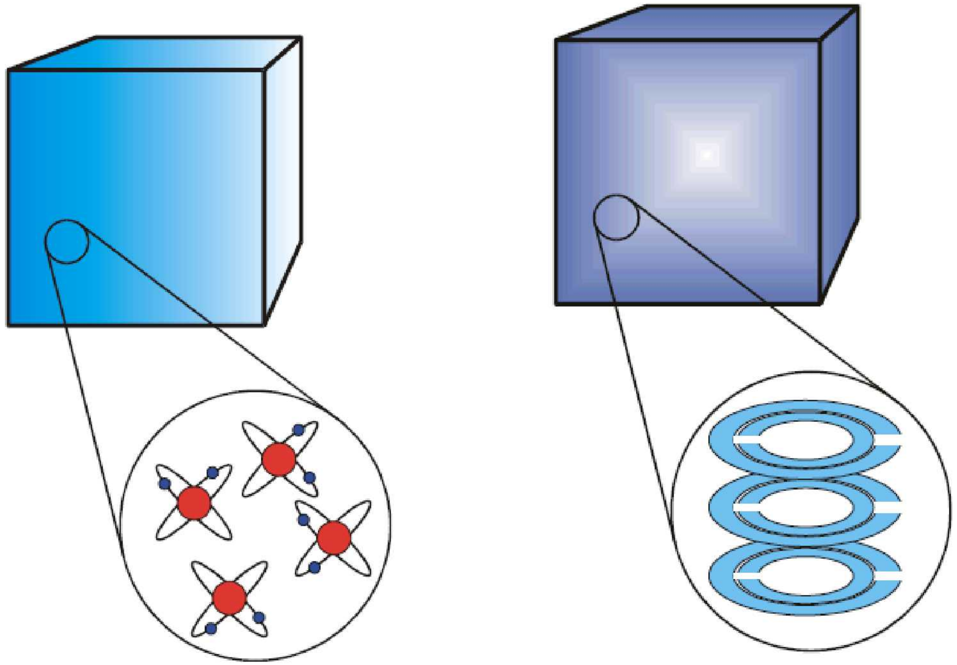
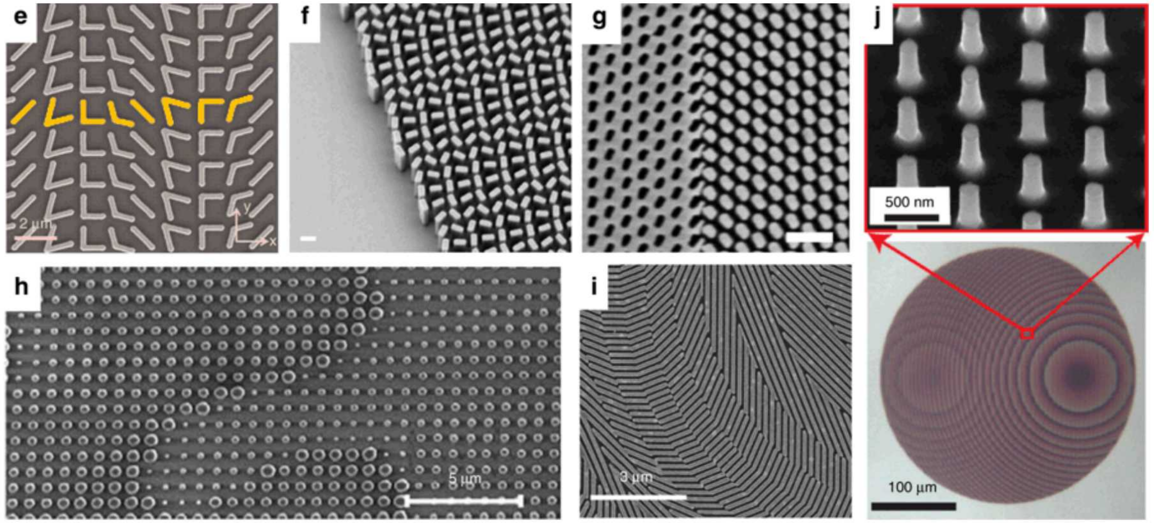
Metamaterials & Metasurfaces

Man-made "atoms" : Metamaterials



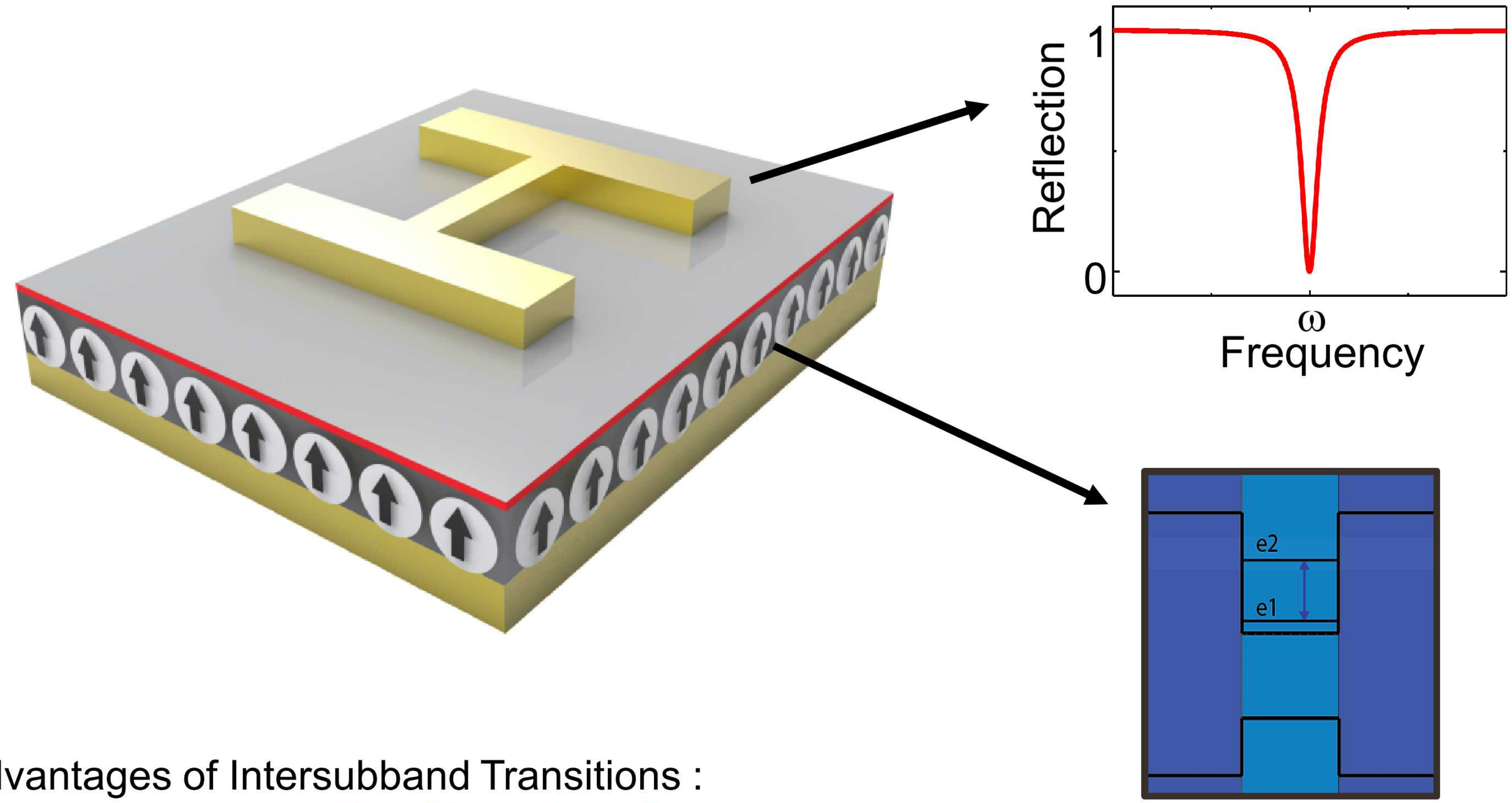
Metasurfaces



Neshev & Aharonovich, Light : Science & Applications 7 (58), 2018.

The constituent units need to be much smaller than the wavelength. Metasurfaces are planar (2D) equivalents of metamaterials.

Hybrid Metasurfaces : Metasurfaces Loaded with Heterostructures

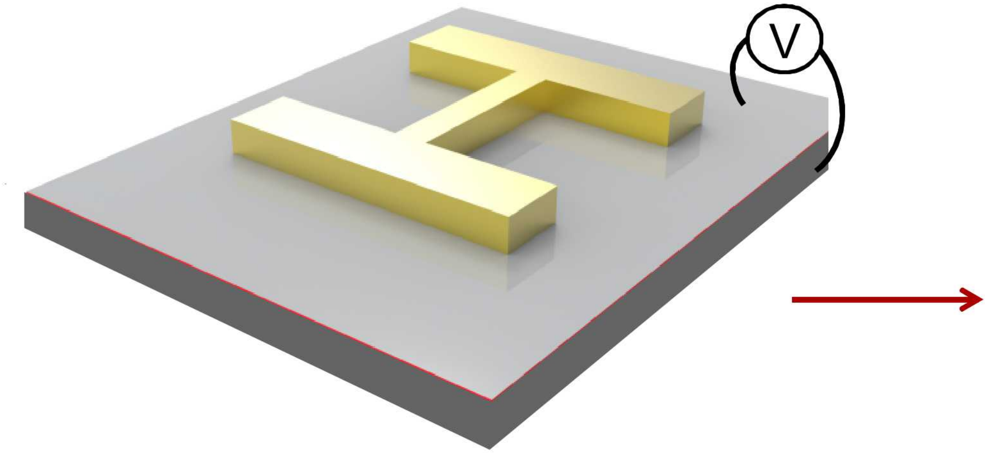


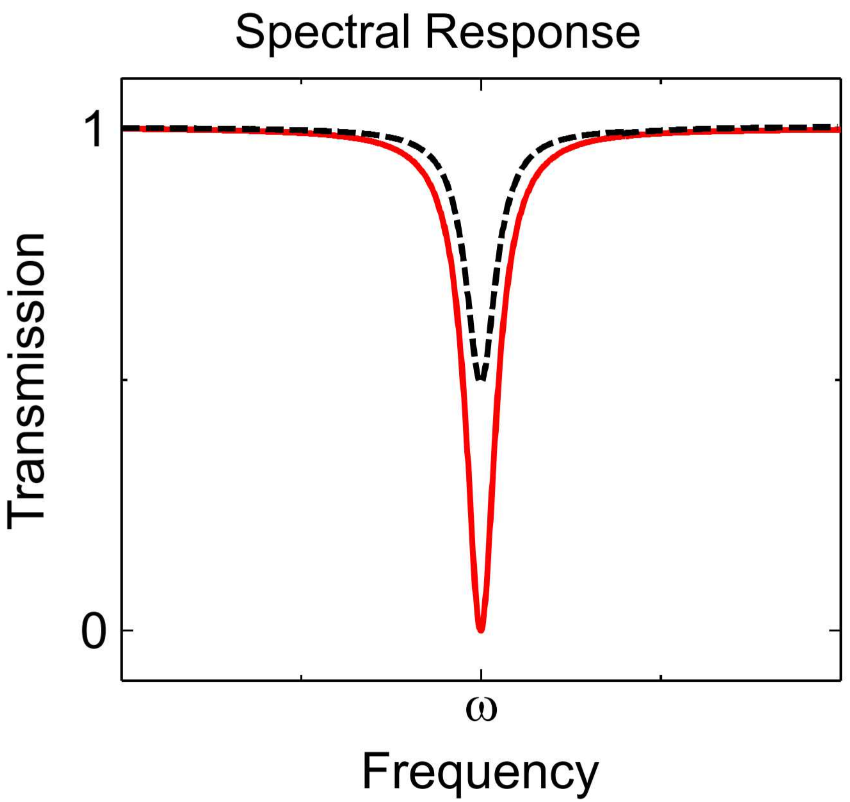
Advantages of Intersubband Transitions :

1. Voltage tunable : Tunable metasurface
2. The transition energies and dipole moments can be engineered : Extreme nonlinear optics
3. Large transition dipole moment : Strong light-matter interaction

1. Voltage Tunable Metasurface

An Ultrathin Optical Modulator





Metasurface : An optically-thin array of subwavelength sized and subwavelength spaced resonators

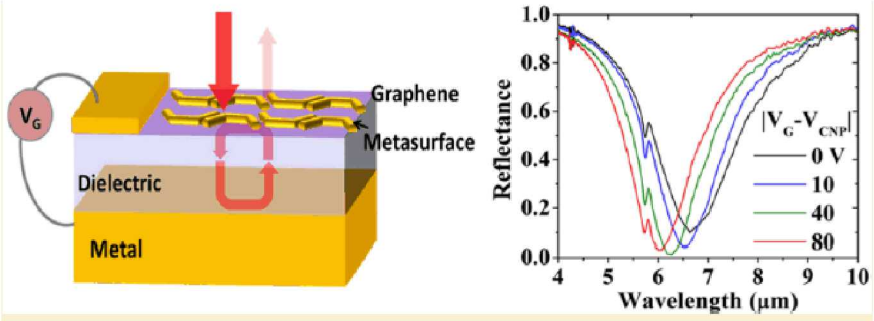
Modulate spectral response (using e.g. voltage) = An optical modulator!

Examples of Voltage-Tunable Approaches

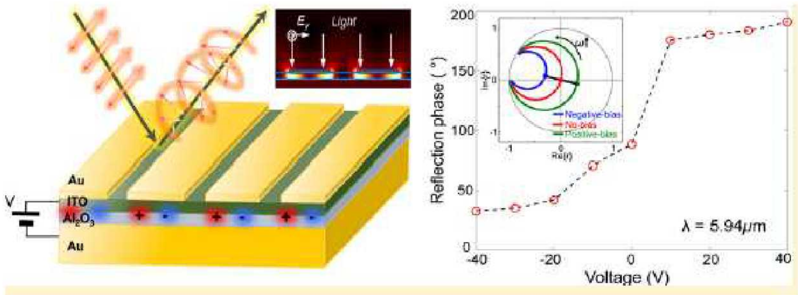
Graphene

ITO based

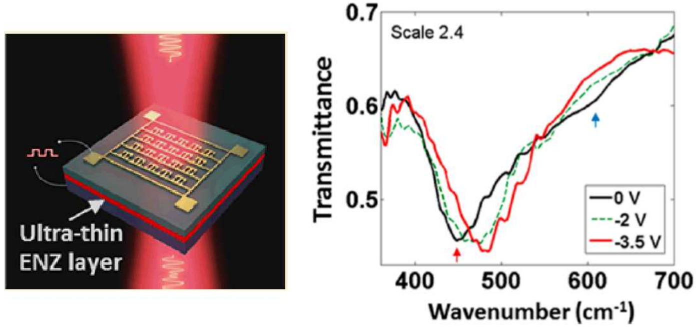
III-V based



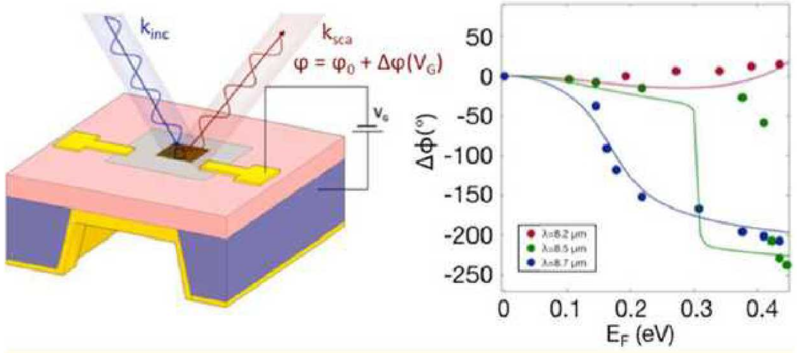
Nano Lett. 14(11), 6526 (2014)



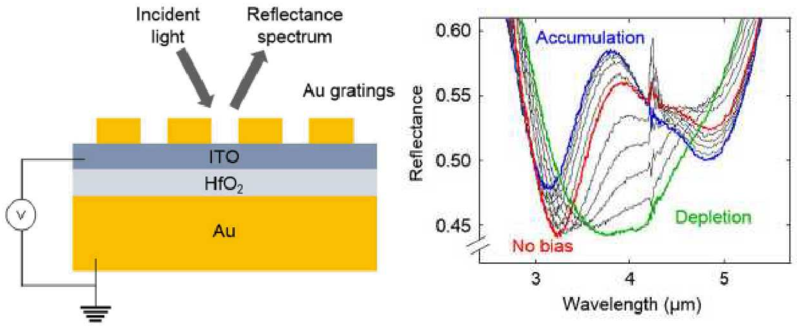
Nano Lett. 17(1), 407 (2017)



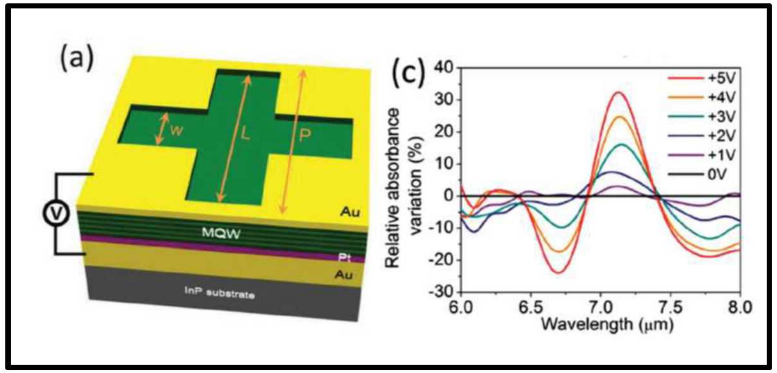
Nano Lett. 13(11), 5391 (2013)



Nano Lett. 17(5), 3027 (2017)



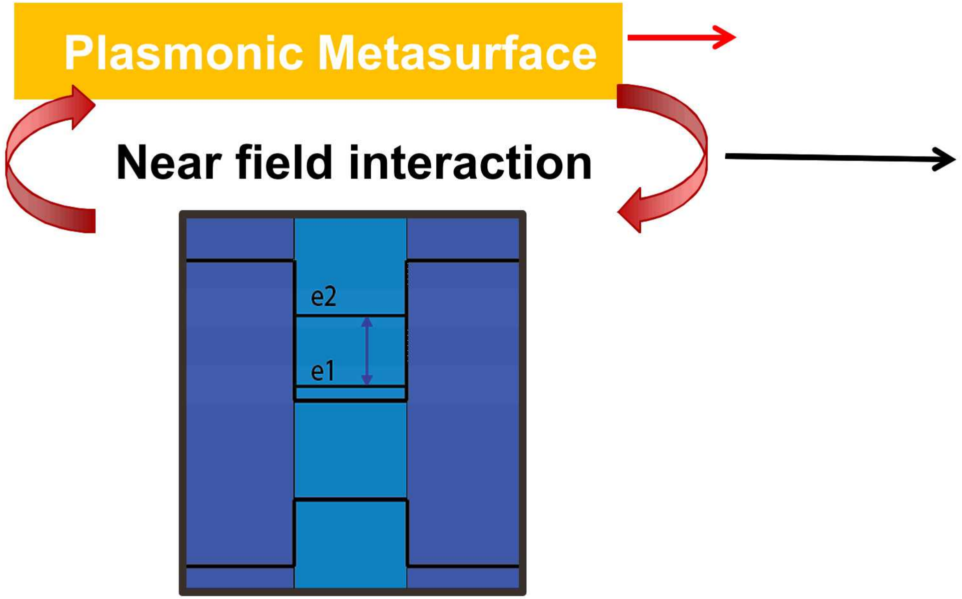
Scientific Reports 5, 15754 (2015)

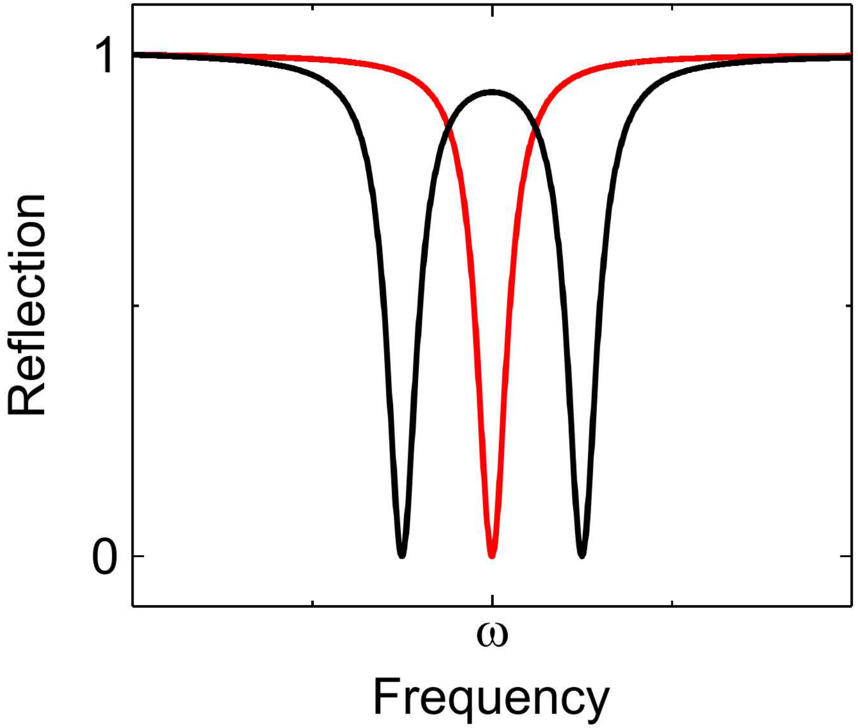


Adv. Opt. Mat. 2(11), 1057 (2014)

III-V based tunable metasurface approaches can be integrated to focal plane arrays.
Intersubband transition approach is wavelength scalable and works in the mid and long IR wavelengths.

Tuning via Stark Shift in Strongly Coupled Systems



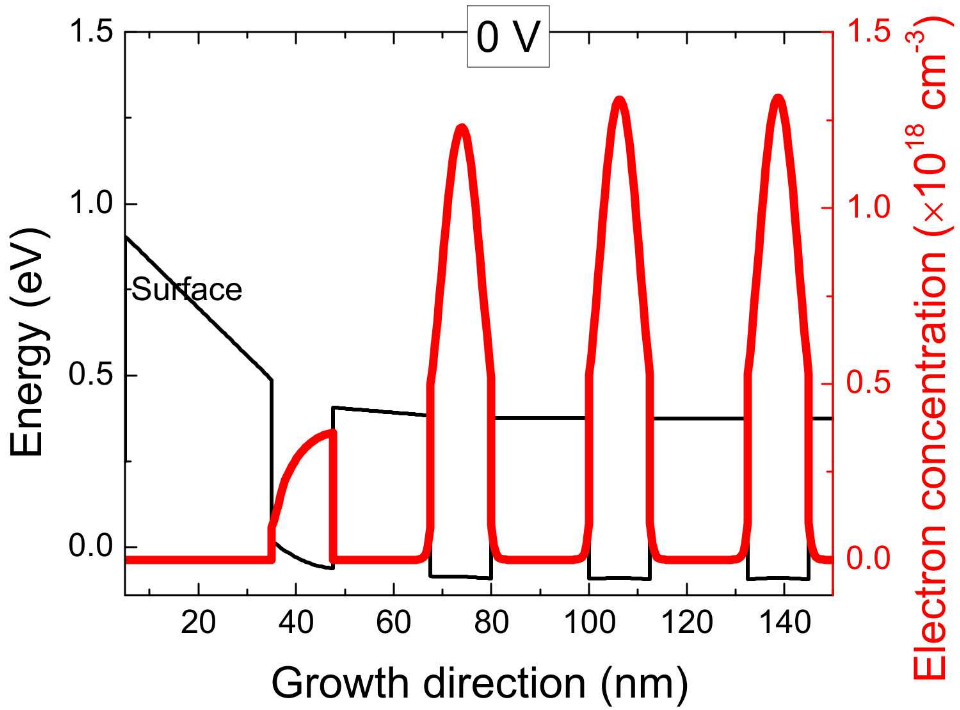


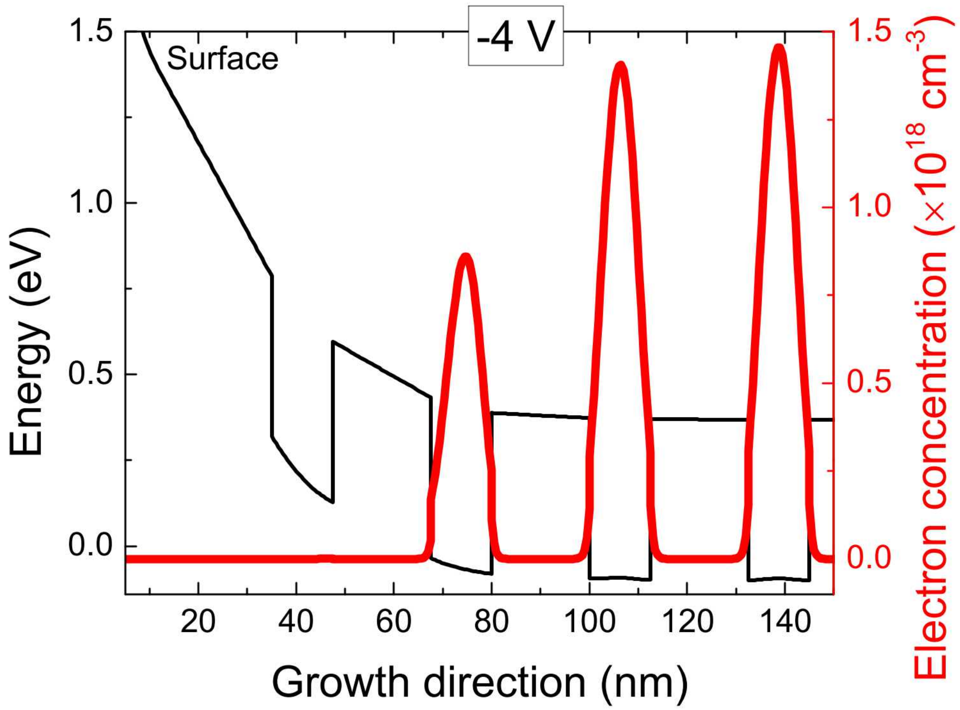
By applying bias e1 and e2 can be shifted = Modulation of spectral response

Previous approaches rely on strongly coupled system. Strong coupling requires wells with high doping !

Ref. : [1] A. Benz et al., Appl. Phys. Lett. 103, 263116 (2013)
[2] Lee et al., Adv. Opt. Mat. 2, 1057 (2014)

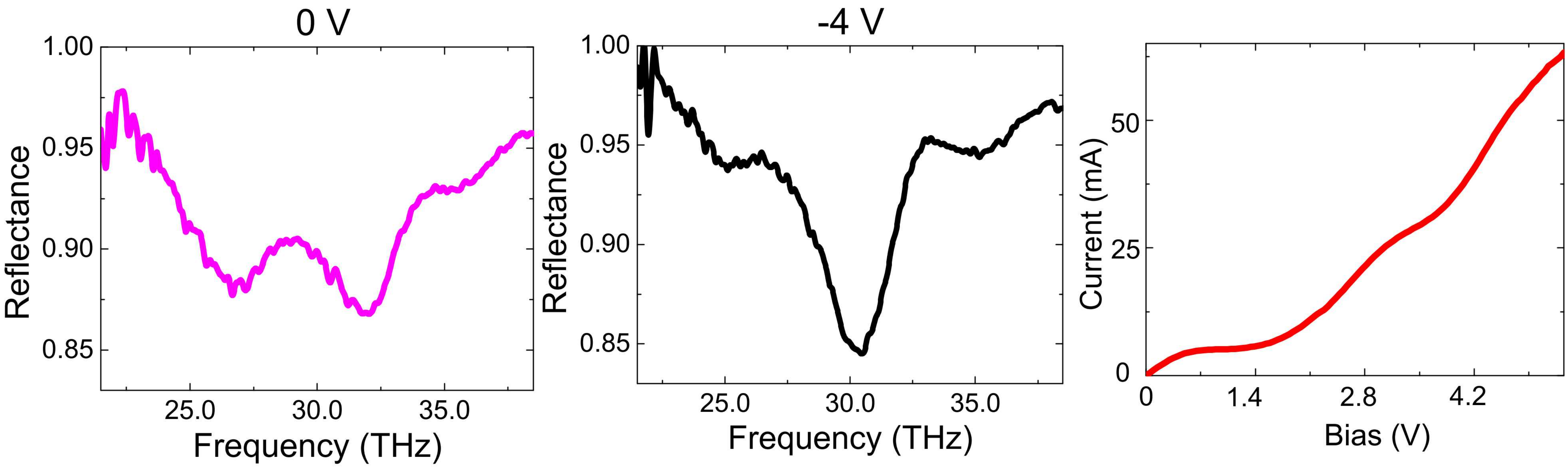
Reverse Biasing Highly Doped QWs : Problem !





- Applying reverse bias across QW-stack depletes well by well => no continuous tuning
- High doping concentration limits effect to first few wells only

Stabilizing Internal Electric Field : Allow Current Flow

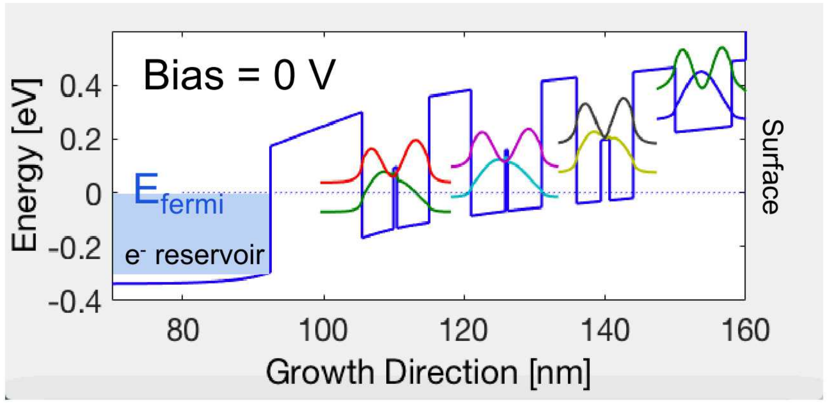


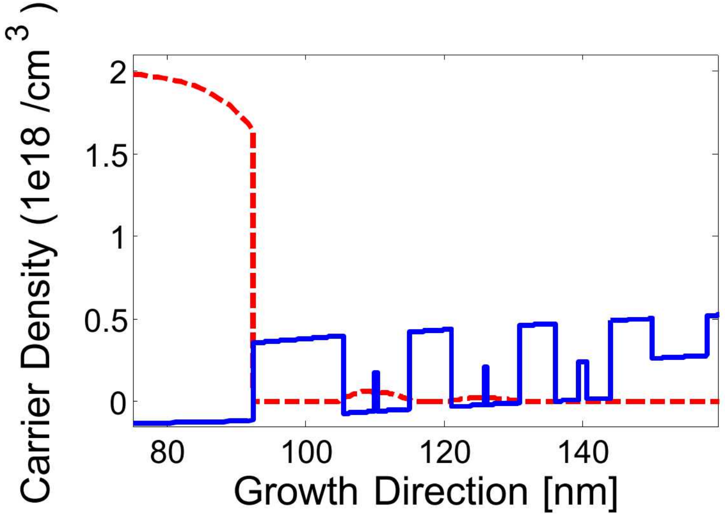
- Current flow through quantum well stack stabilizes internal electric field

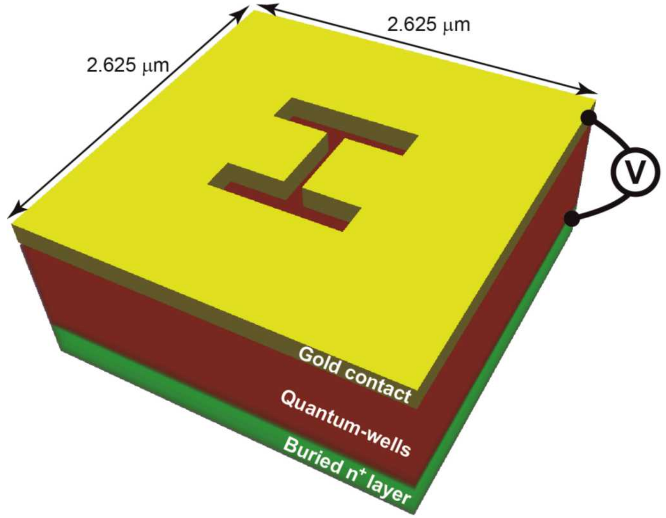
Ref. : [1] A. Benz et al., Appl. Phys. Lett. 103, 263116 (2013)
[2] Lee et al., Adv. Opt. Mat. 2, 1057 (2014)

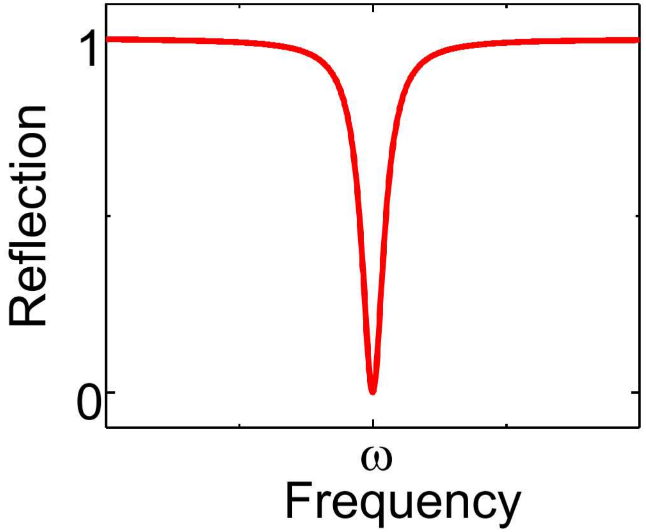
New Voltage Tunable Electrostatic Approach

At V=0 (start with uncoupled system)





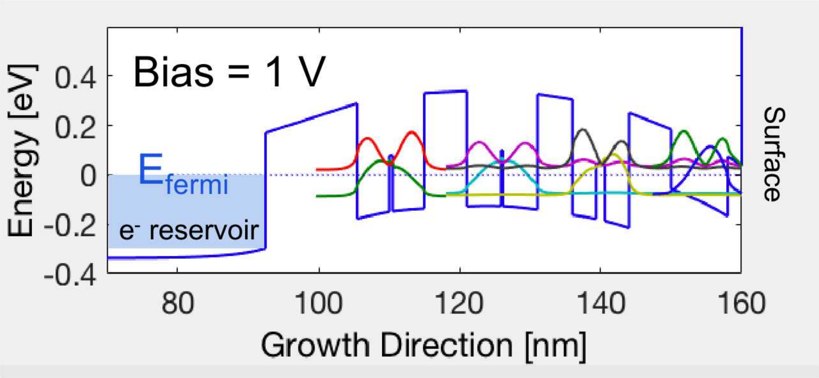


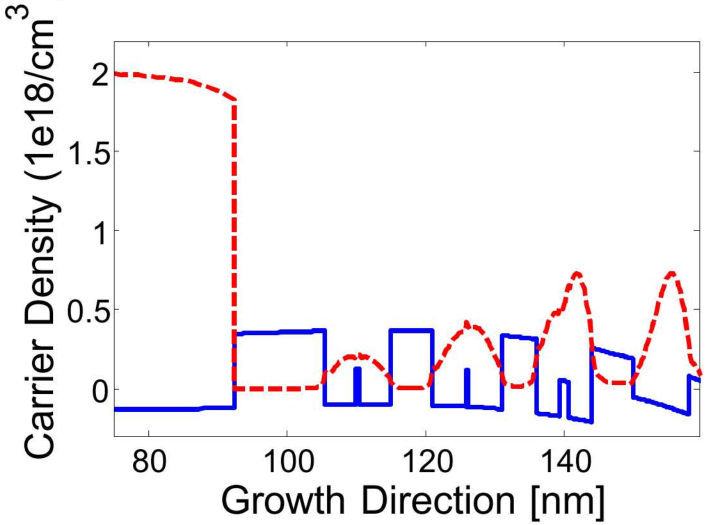


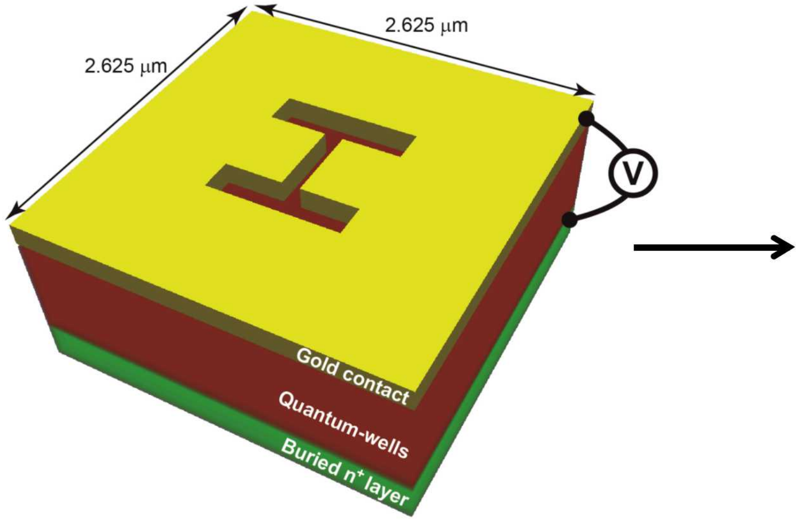
At 0V bias the wells have small carrier density and transitions are off

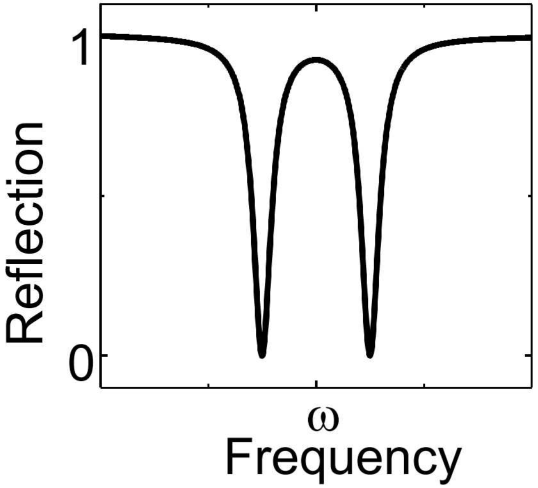
New Voltage Tunable Electrostatic Approach

At V=1 V (Achieve a coupled system)





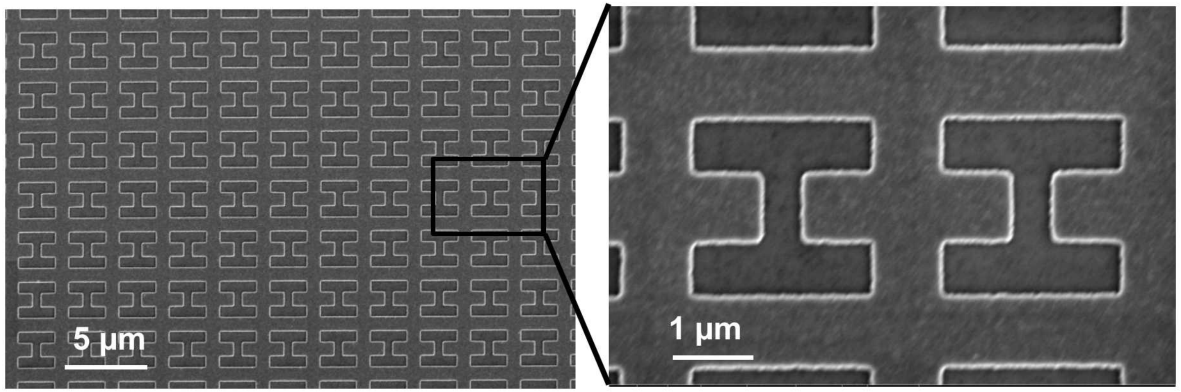




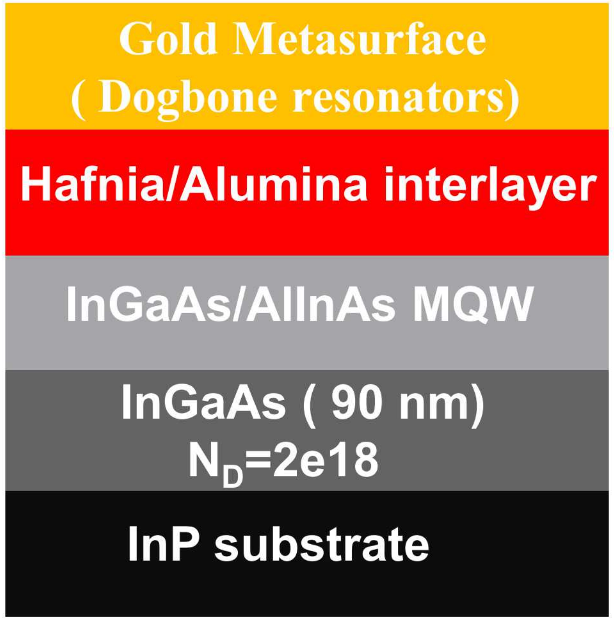
Strong coupling for large number of wells

At 1V bias the wells have large carrier density due to tunneling facilitated by band alignment and transitions are on

Device Fabrication



Device cross section



IST ~ 11 microns

Bias = 0 V

E_{fermi}

e^- reservoir

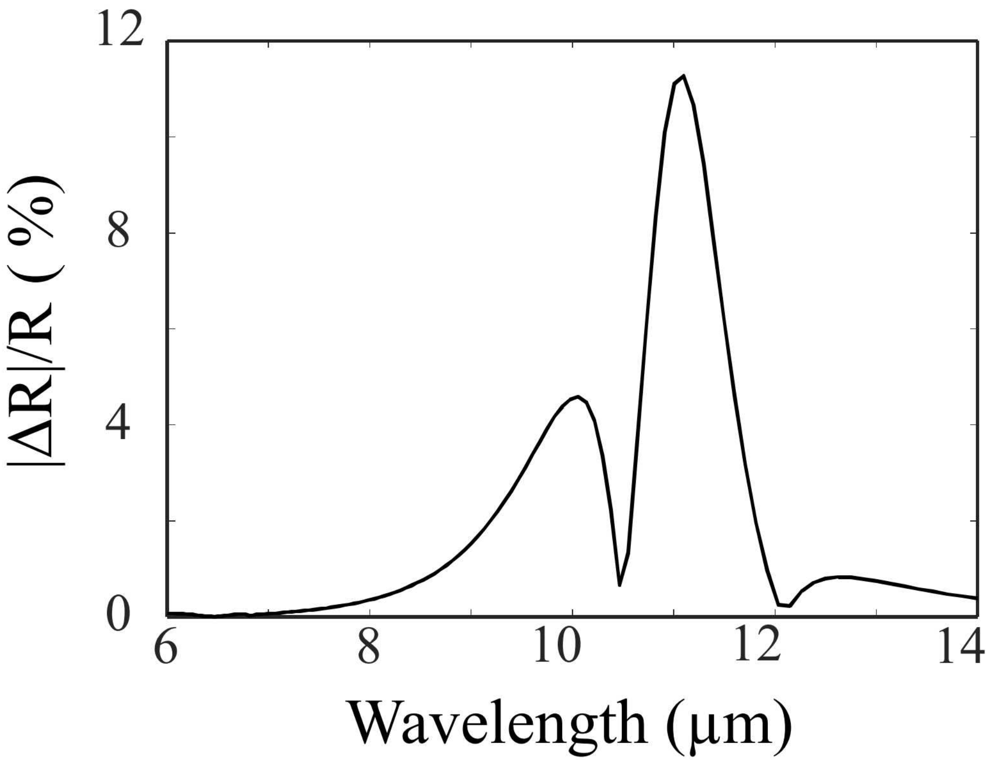
Surface

Used high k dielectric to remove leakage currents

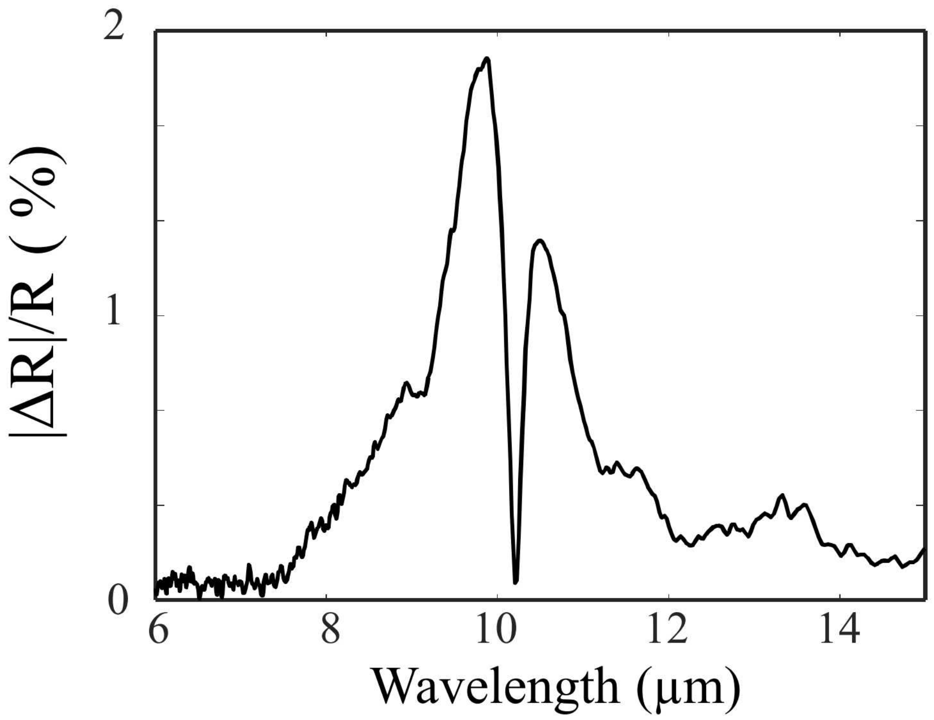
Complementary design for top contact and uniform voltage distribution and dogbone resonators for high capacitance

Simulation and Experiment Results

Simulation



Experiment



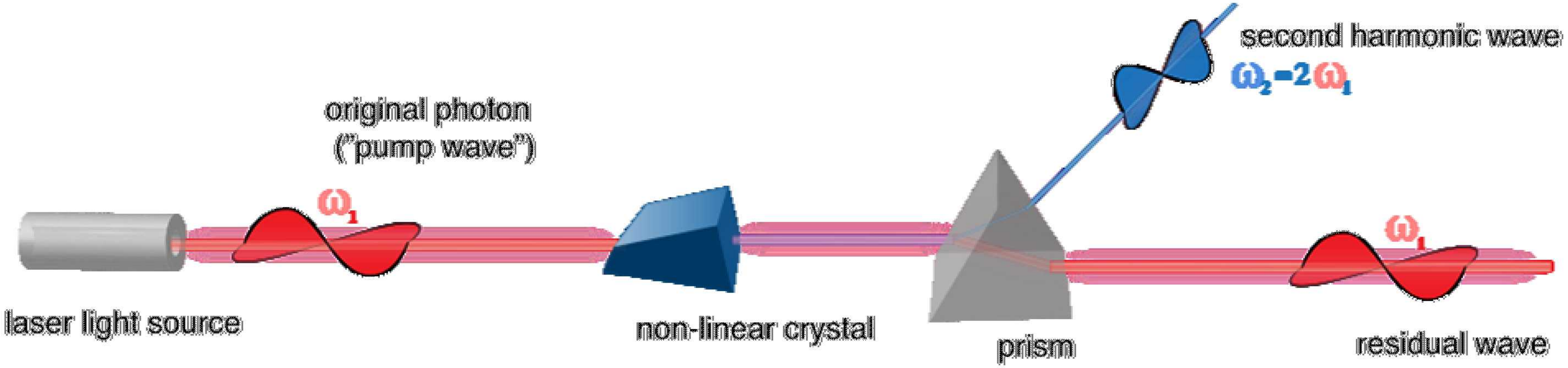
The leakage currents are ~ 6 pA. This demonstrates a proof of concept !

R. Sarma et al., Appl. Phys. Lett. 113, 201101 (2018)

2. Nonlinear Metasurface

Second-Harmonic Generation

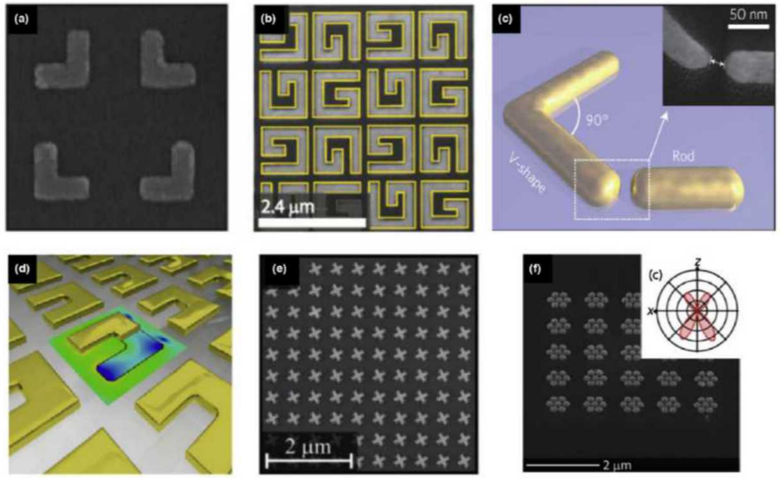
Traditional approach : High power laser, phase matching using nonlinear crystals



$$I_{2\omega} \propto \frac{(\chi^2)^2}{n_\omega {n_{2\omega}}^2}$$

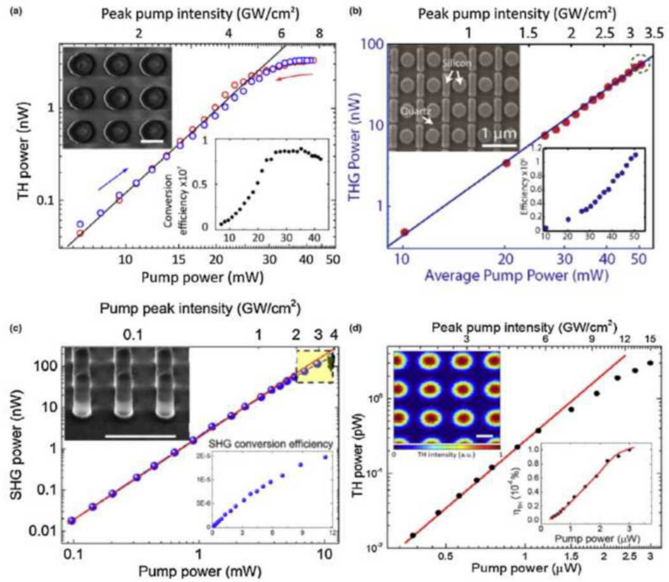
Nonlinear Metasurface Approaches

Plasmonic Metasurface



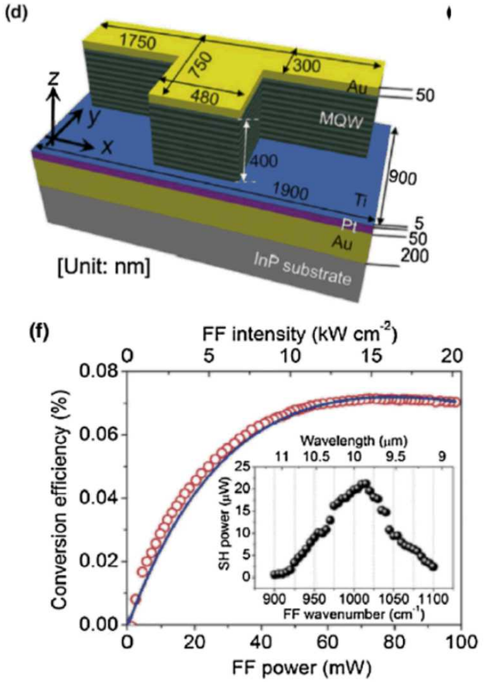
Max. Efficiency 6 x10^{-5} at ~ 0.5 GW/cm^2

All Dielectric Metasurface



Max. Efficiency ~ 10^{-4} -10^{-5} at ~ 5 GW/cm^2

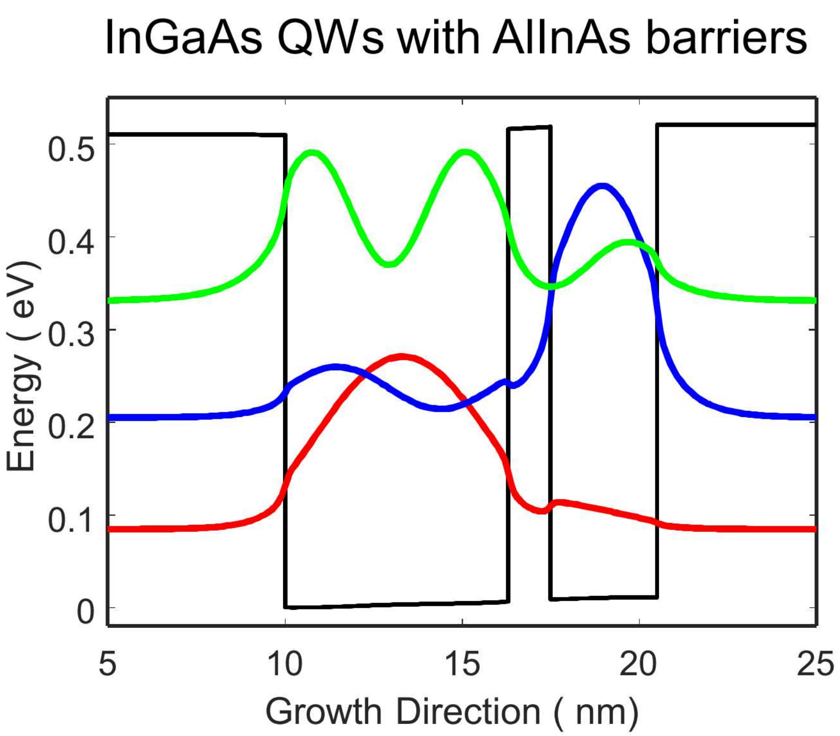
IST-Plasmonic Metasurface

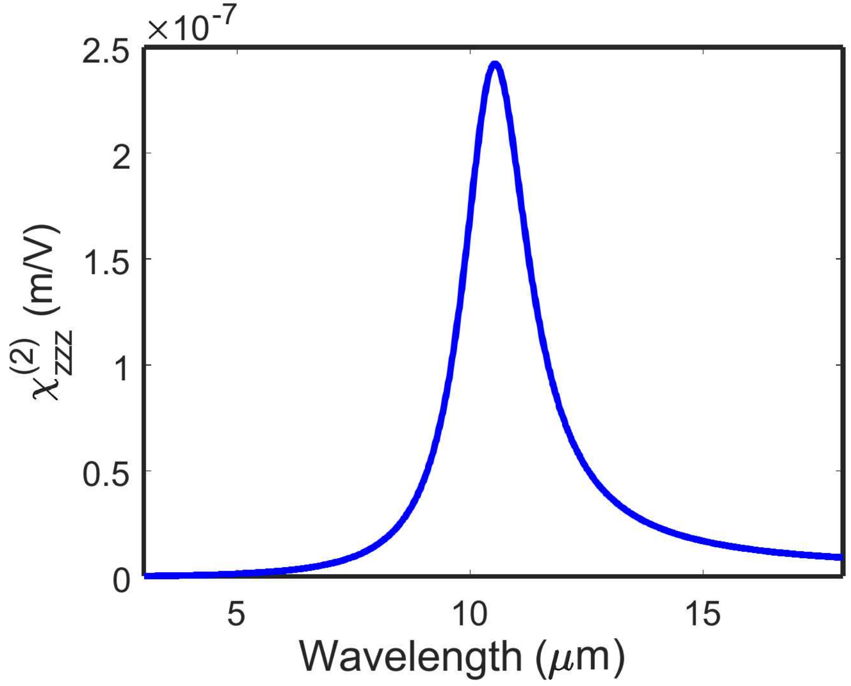


Max. Efficiency ~ 7 x 10^{-4} at 15 kW/cm^2

Ref. : A. Krasnok, M. Tymchenko, A. Alu, Materials Today 21, 8-21 (2018).

Resonant □$^{(2)}$ using Quantum Wells





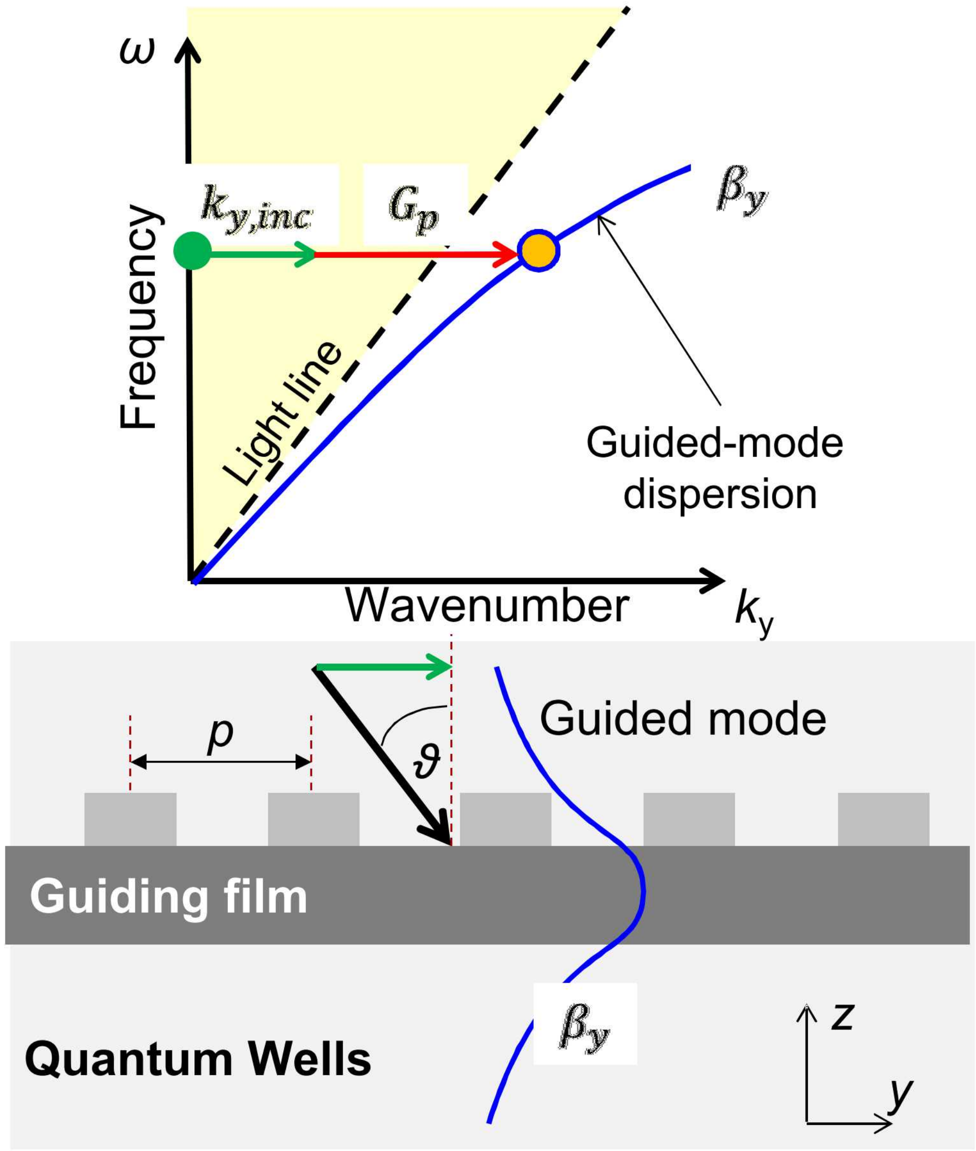
$$\chi^{(2)}(\omega) \propto \frac{N \cdot z_{12} z_{23} z_{13}}{(\omega - \omega_{12} - i\Gamma_{12})(2\omega - \omega_{13} - i\Gamma_{13})}$$

$$z_{ij} \propto \langle \Psi_i | \vec{R} | \Psi_j \rangle$$

The thickness of the InGaAs QWs is optimized to have transitions at 10 microns and 5 microns.

Ref. : IEEE J. Quantum Electr. 30, 1313 (1994)

Leaky Mode Resonance



Incident transverse wavenumber

$$k_{y,inc} = \frac{\omega}{c} \sin \vartheta$$

+

Lattice transverse momentum

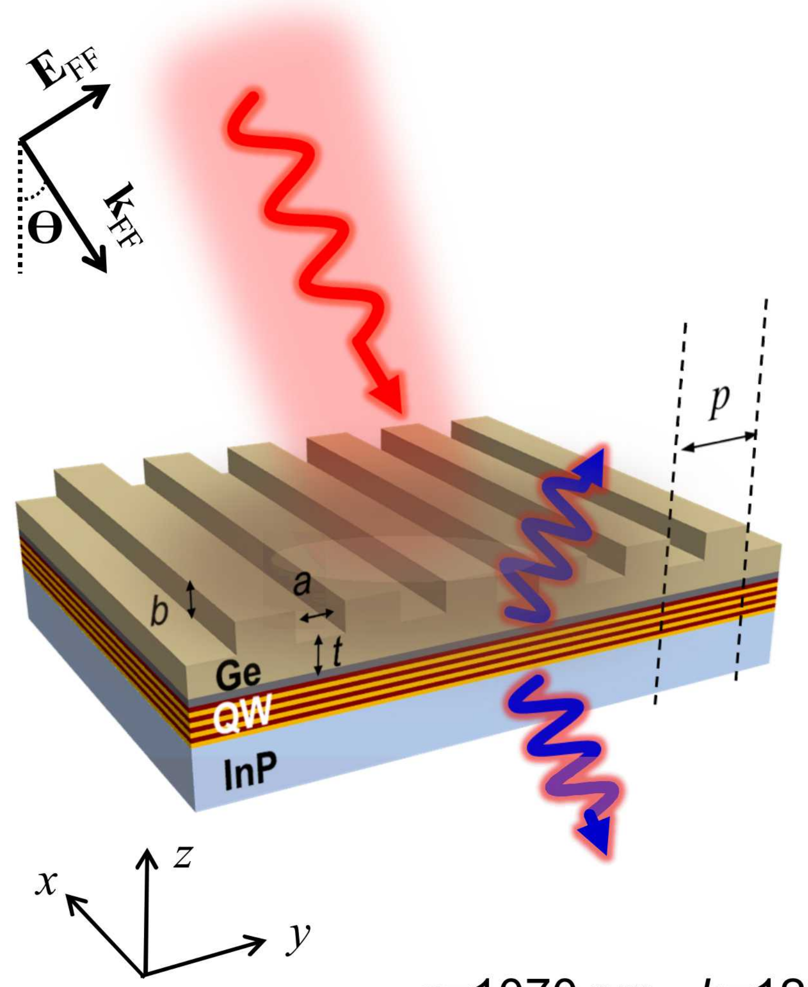
$$G_p = \frac{2\pi}{p} m, \text{where } m = \pm 1, \pm 2, \pm 3, \ldots$$

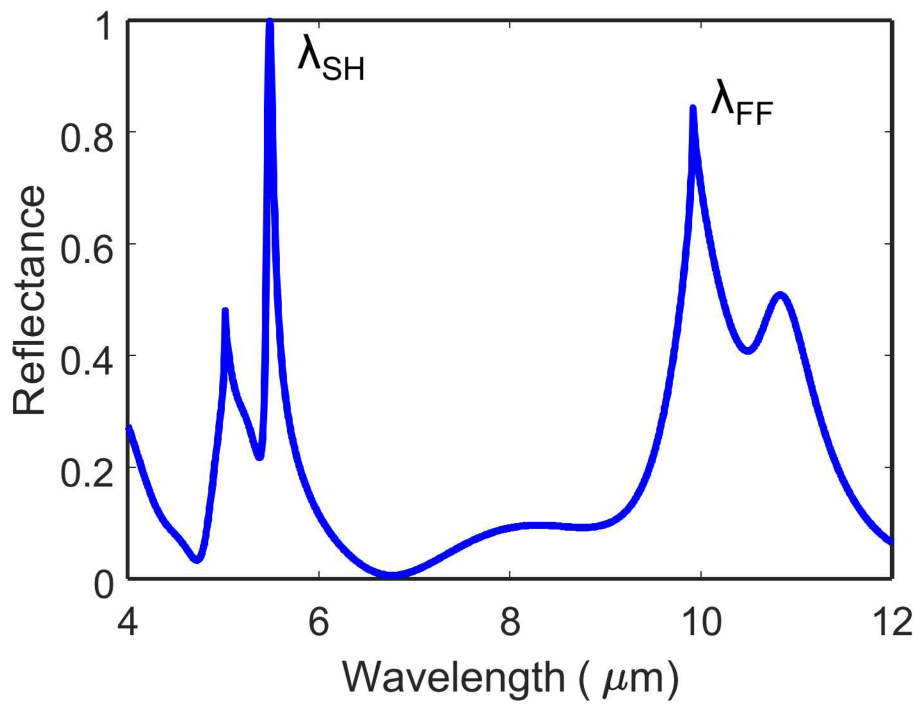
↓

Plane wave excitation of a Leaky Mode Resonance

$$\left| k_{y,inc} + G_p \right| = \tilde{\beta}_y$$

Hybrid Structure for Second Harmonic Generation

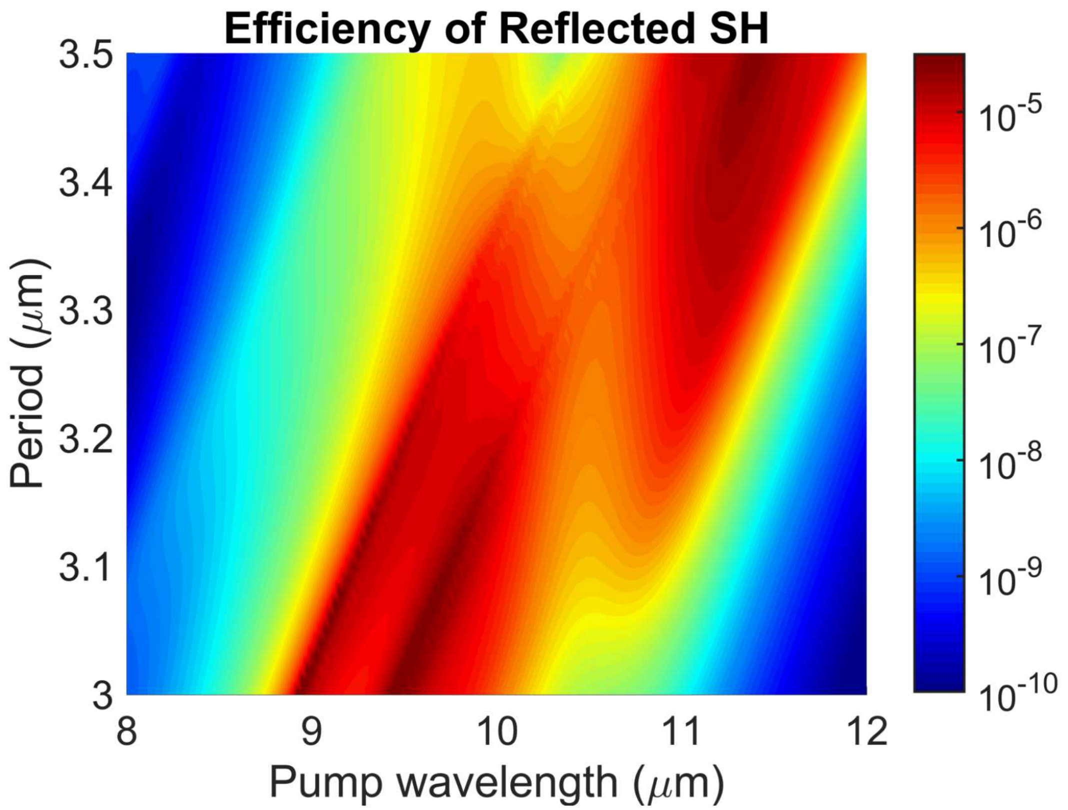




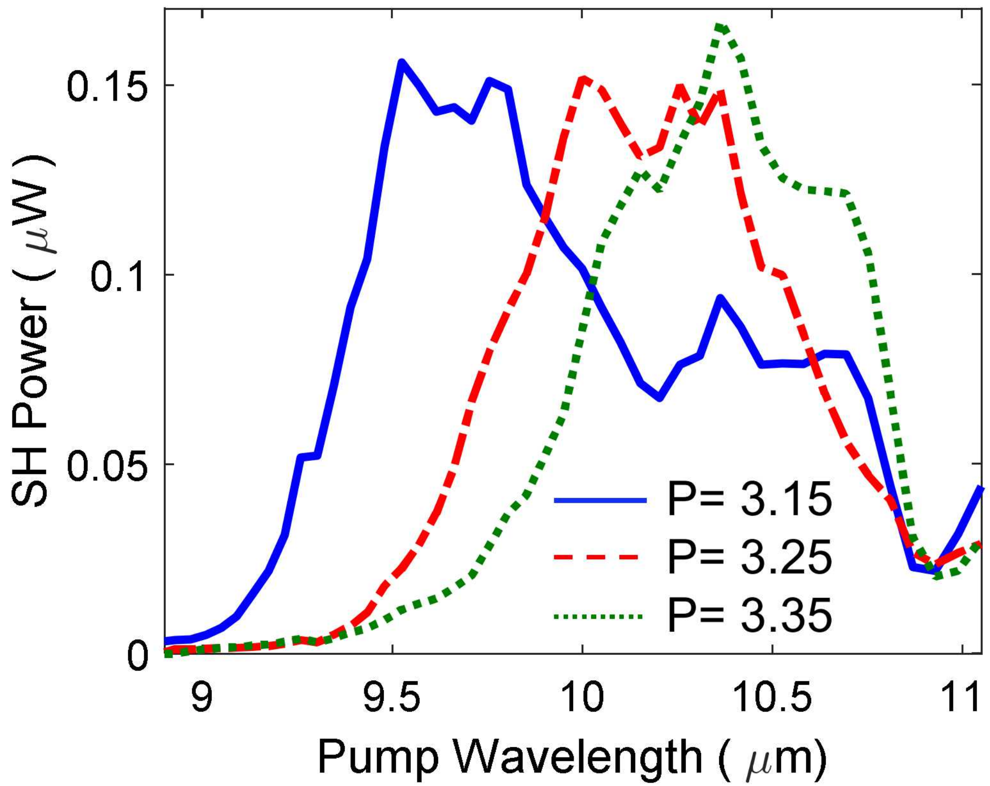
a=1070 nm , b=1200 nm , t=500 nm
p=3150, 3250, 3350 nm

Numerical Simulations and Experimental Data

Simulation

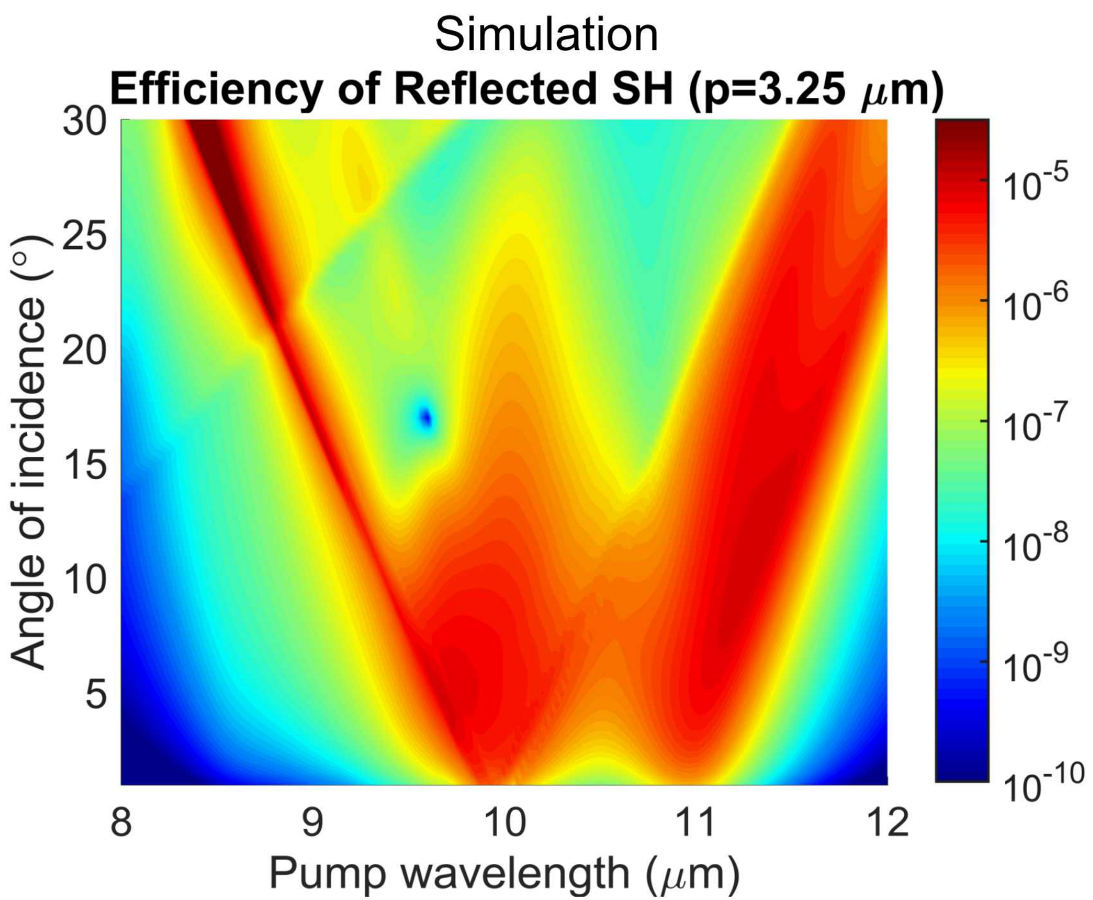


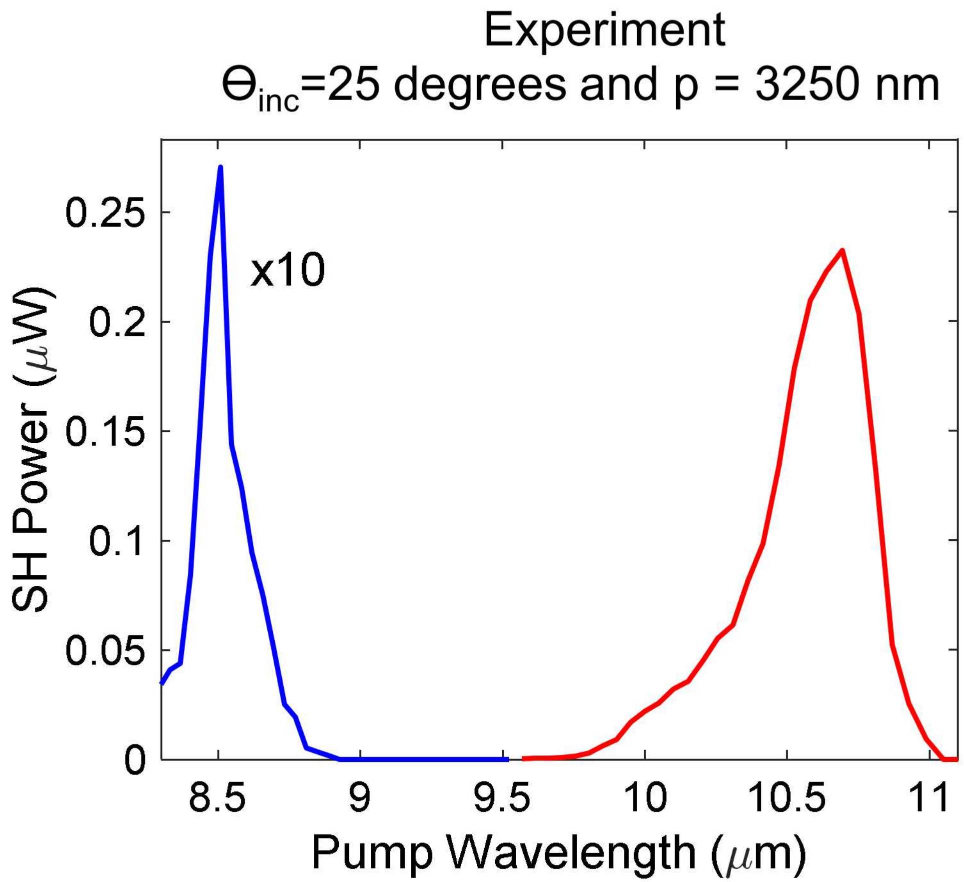
Experiment



The leaky mode resonances can exist for all wavelengths between 8-12 microns.
Efficiency ~ 10^{-5} for pump intensity 10 kW/cm^2

Experimental Data For Off Normal Incidence



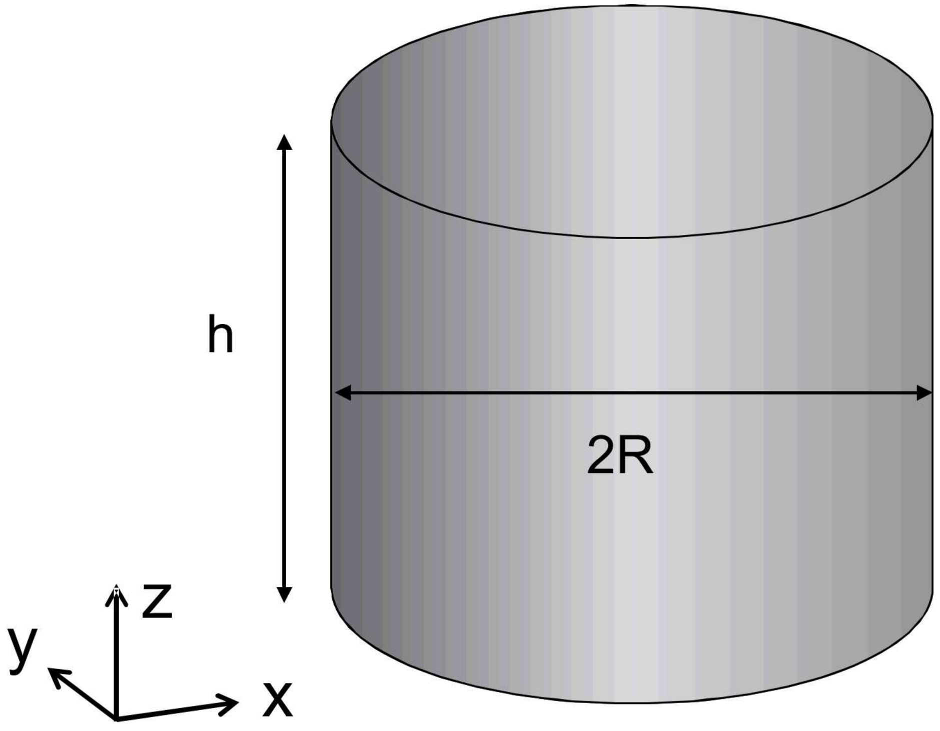


As predicted by simulations, at Θ_{inc}=25 degrees, two peaks of SHG are observed at 8.5 (narrower) and ~ 10.75 microns (broader).

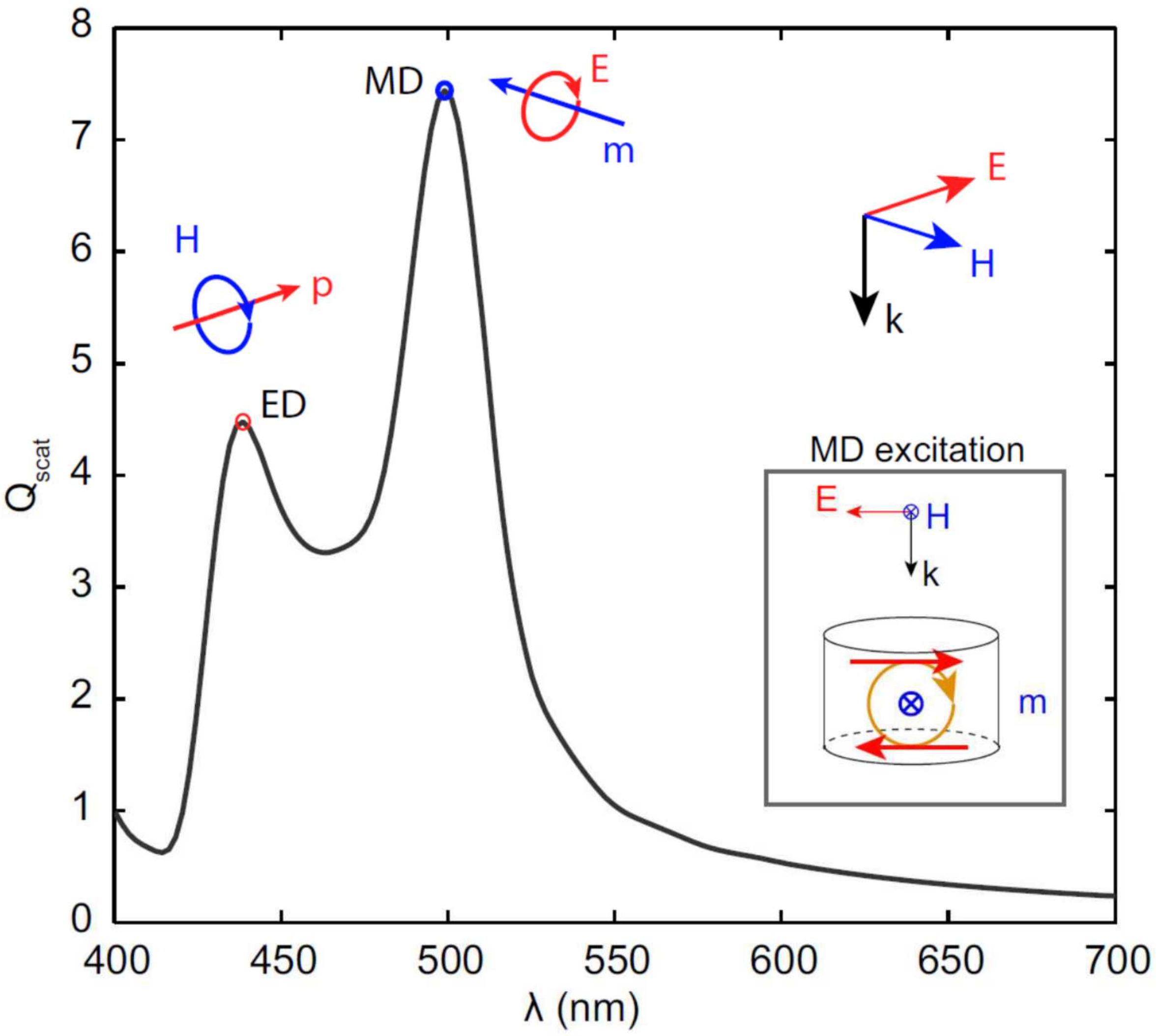
3. Strong Light-Matter Interaction in Dielectric Metasurfaces

Mie Modes in Dielectric Resonators

Dielectric Resonator

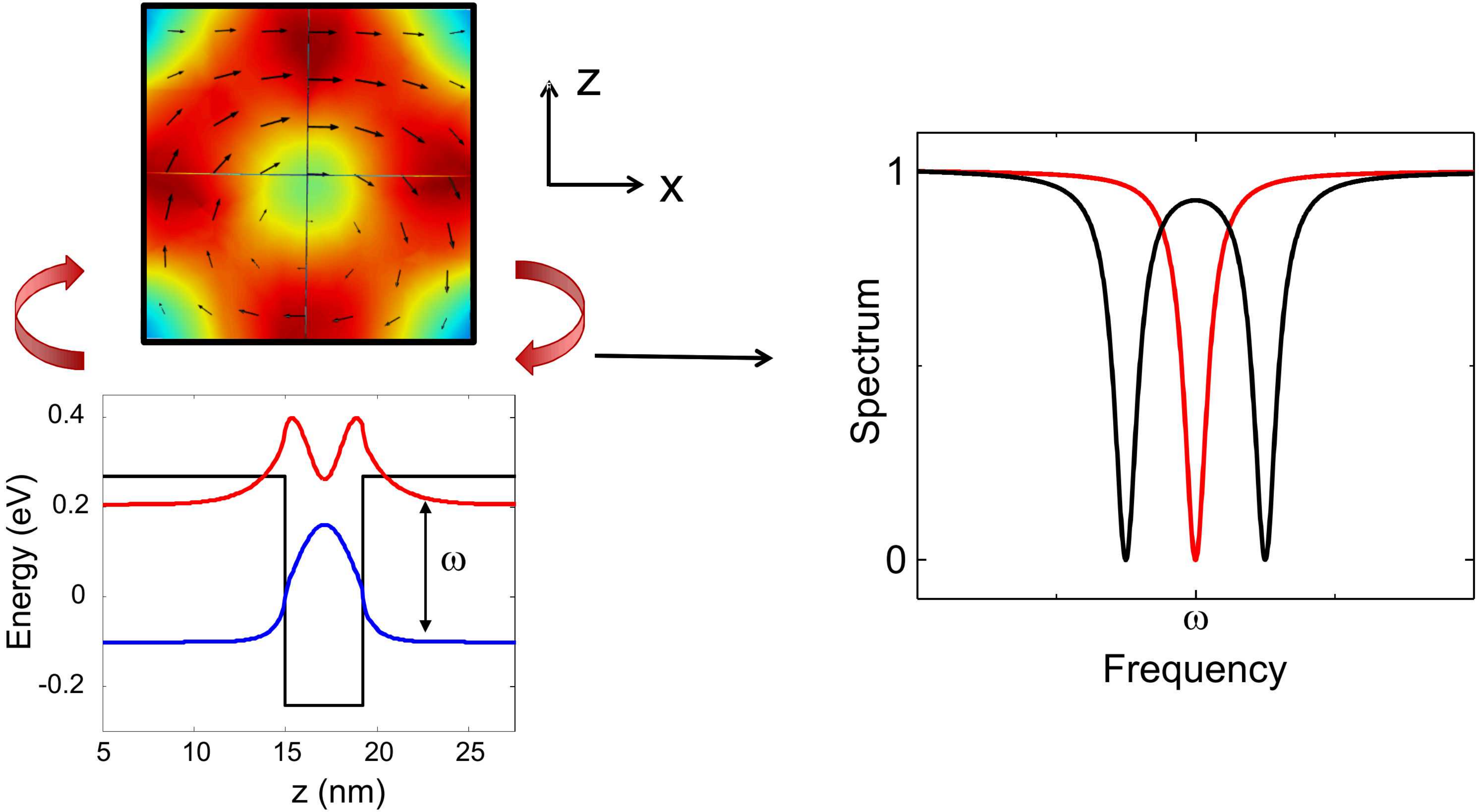


Refractive index of Resonator >> Surroundings



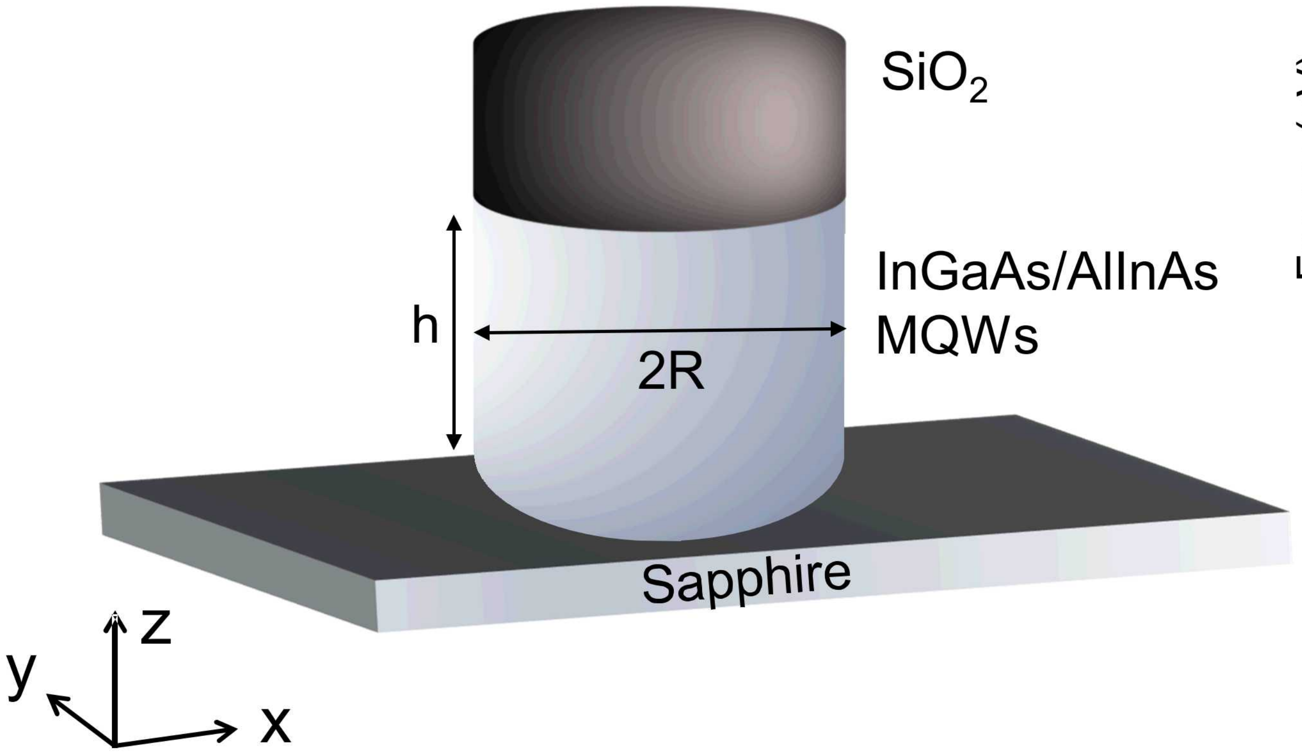
J. van de Groep & A. Polman, Optics Express 21, 26285 (2013)

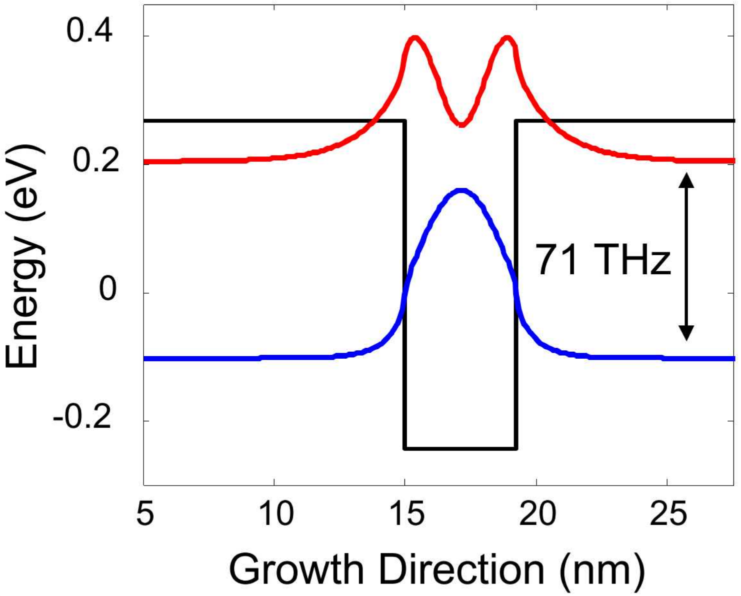
Strong Light-Matter Interaction

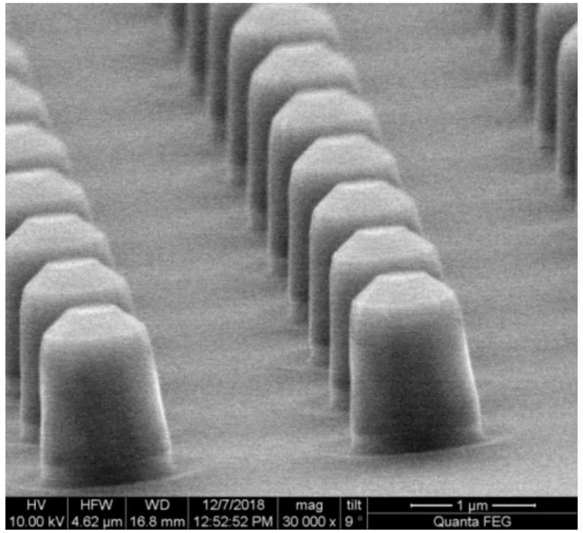


Strong coupling of the Mie resonance to intersubband transitions can lead to Rabi splitting of the resonance

Mie Resonators loaded with Quantum Wells

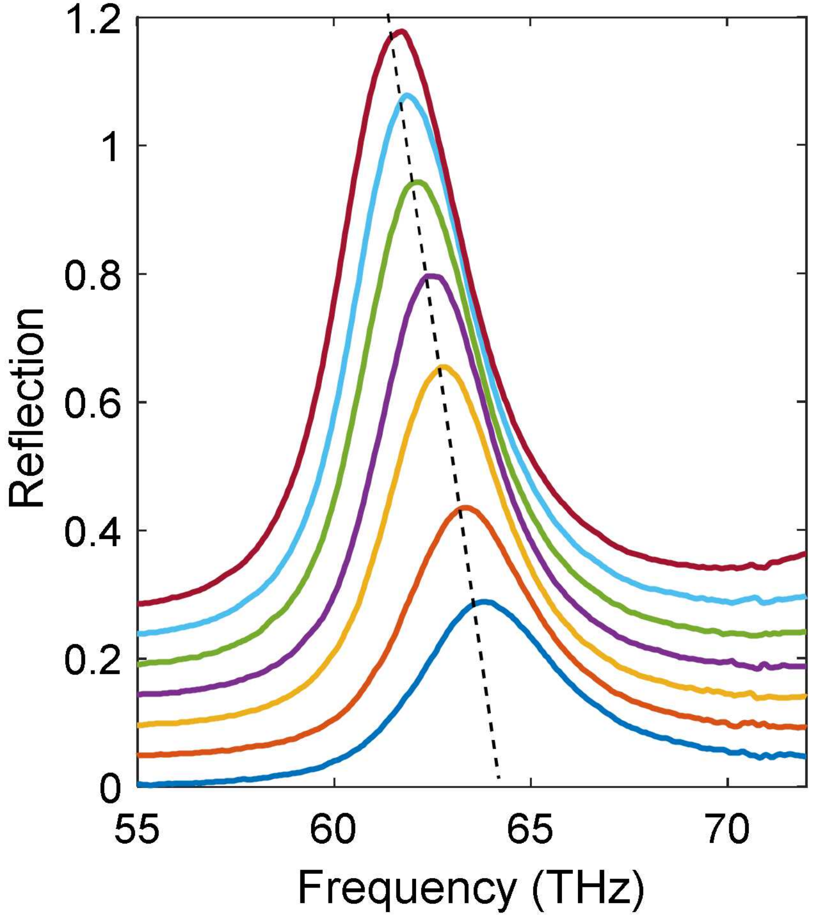


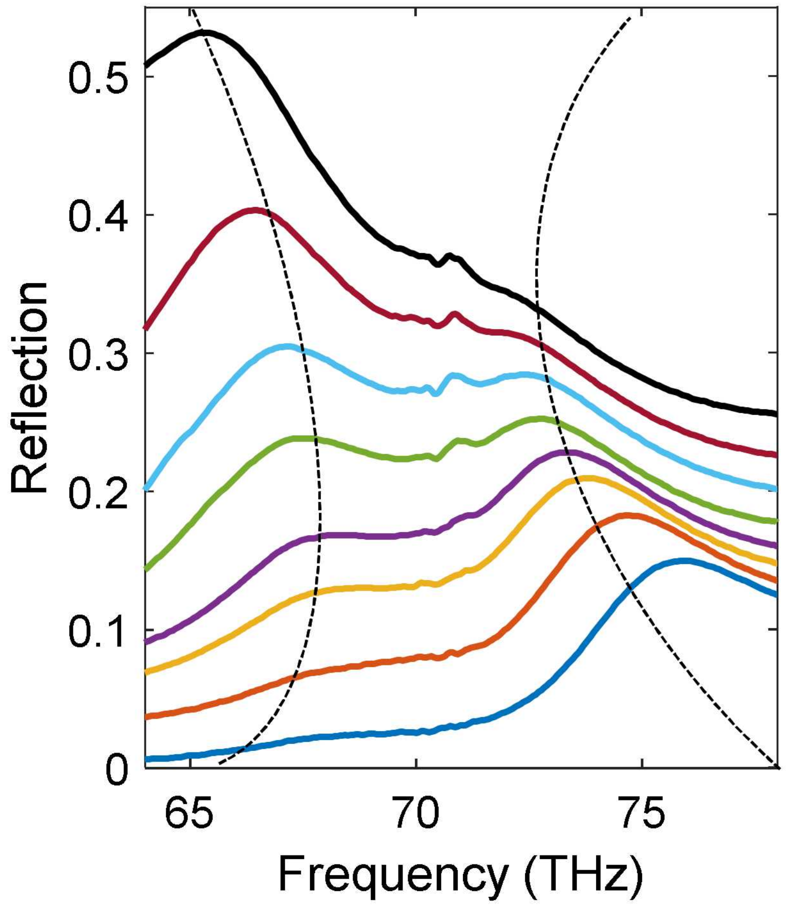




Refractive index of QWs >> Sapphire, SiO_2

Strong Light Matter Interaction

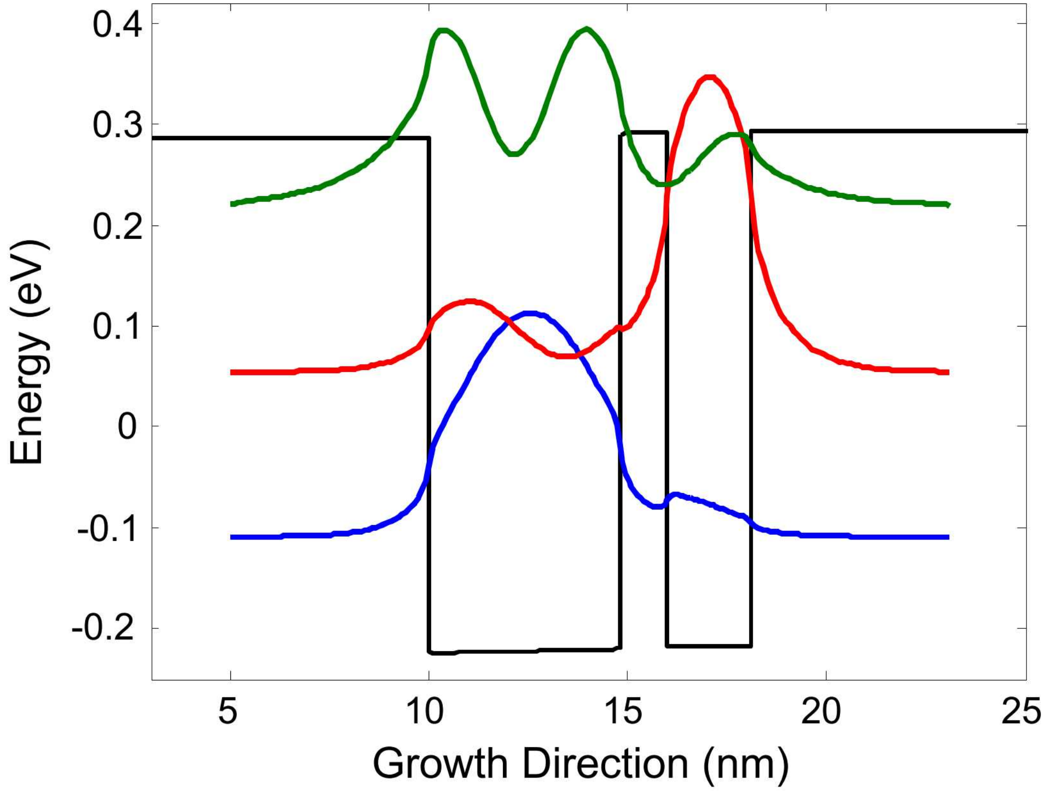




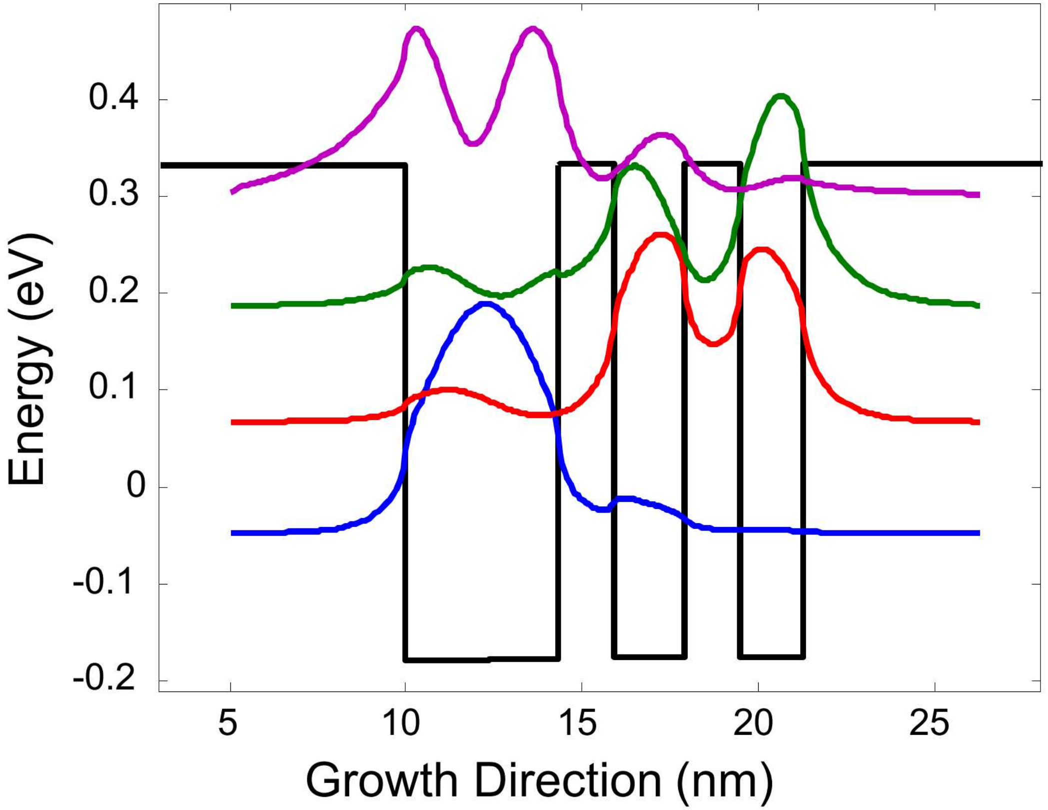
Rabi Splitting of ~ 10 % can be observed

Ongoing Work : Nonlinear Mie Metasurfaces

Resonant □^{2}



Resonant □^{2} and □^{3}



Achieve ultrathin and efficient nonlinear devices !

Summary

- Hybrid metasurfaces offer an efficient and flexible platform to study fundamental new physics and achieve new device functionalities.

- By simultaneous engineering of the intersubband transitions and the photonic resonances, we can realize strong light-matter interaction, ultrathin optoelectronic devices, and nonlinear devices with relaxed phase matching requirements.

- Finally, these approaches can be scaled to different wavelengths without loss of efficiency.