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An All-Dielectric Polaritonic Metasurface with Giant Second-Order Nonlinear Response

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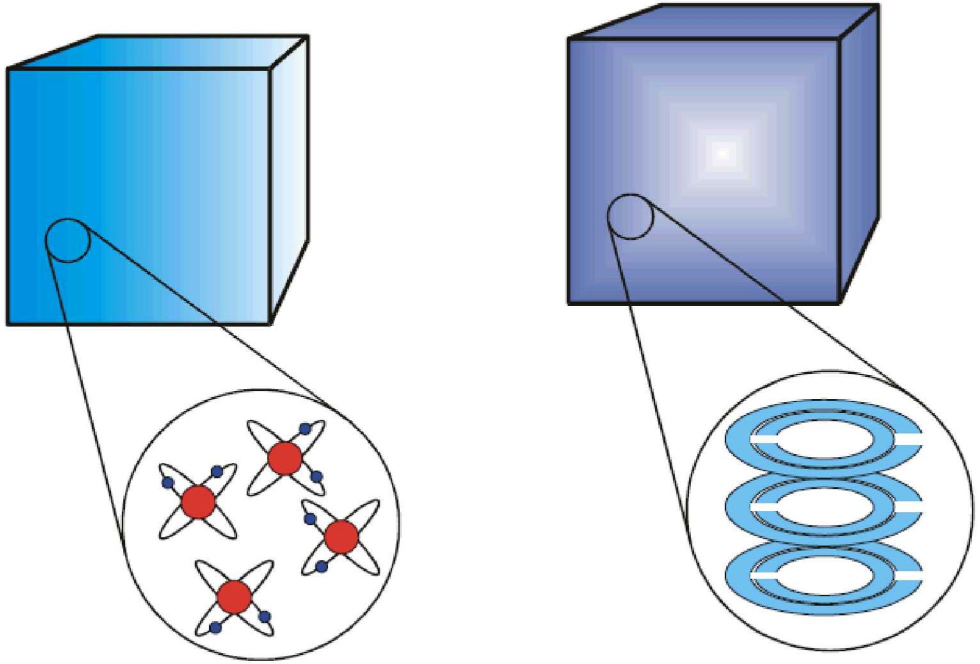
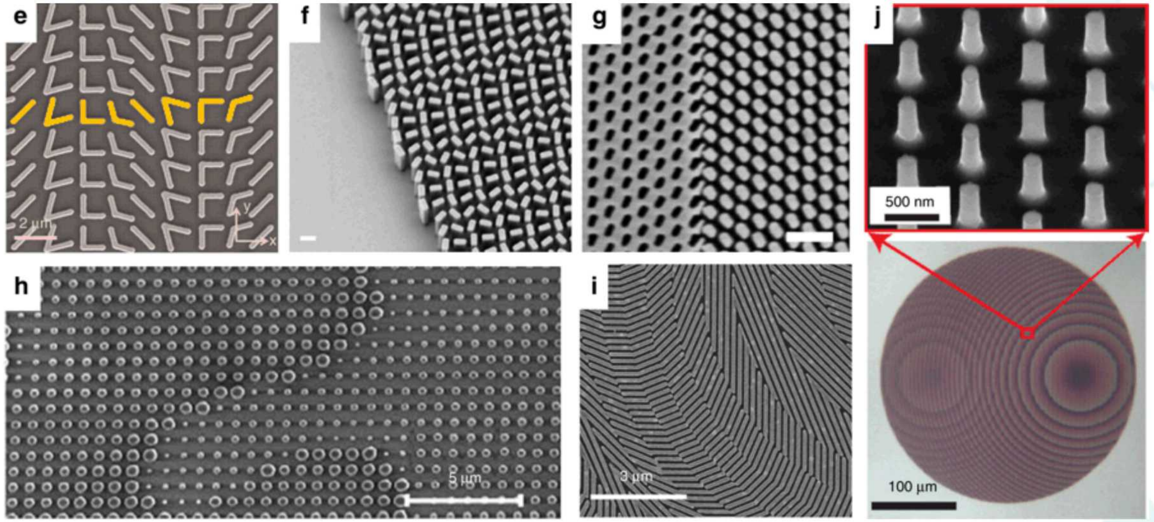
Metamaterials and Metasurfaces

Man-made “atoms” : Metamaterials



Metasurfaces



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

In metamaterials, optical properties are determined by configuration and properties of meta-atoms.

Metasurfaces are planar (2D) equivalents of metamaterials.

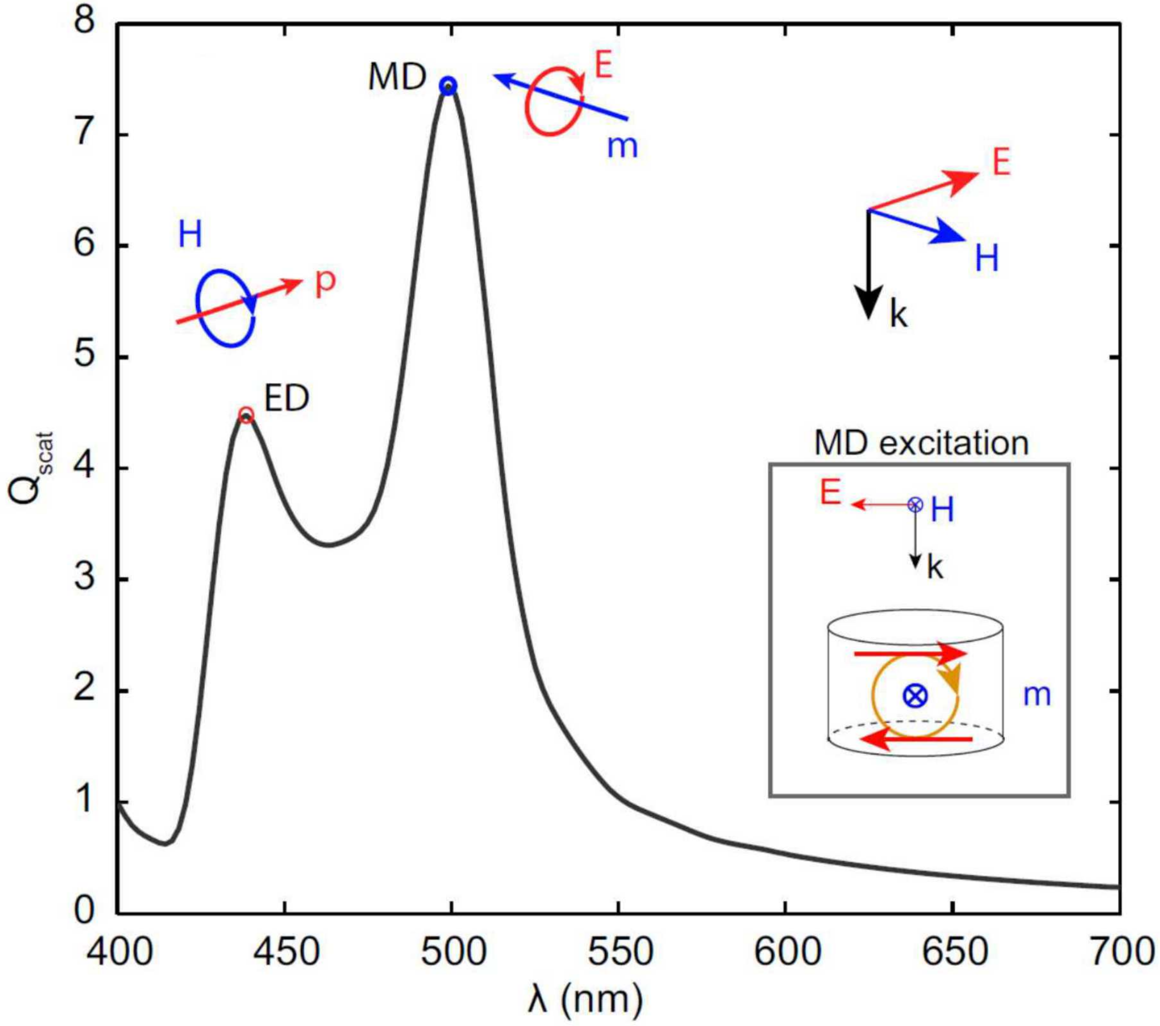
The All-Dielectric Approach: Mie modes

Dielectric particles much smaller than wavelength λ

Wikipedia

Rayleigh << λ

Mie modes in dielectric particles comparable ~ λ



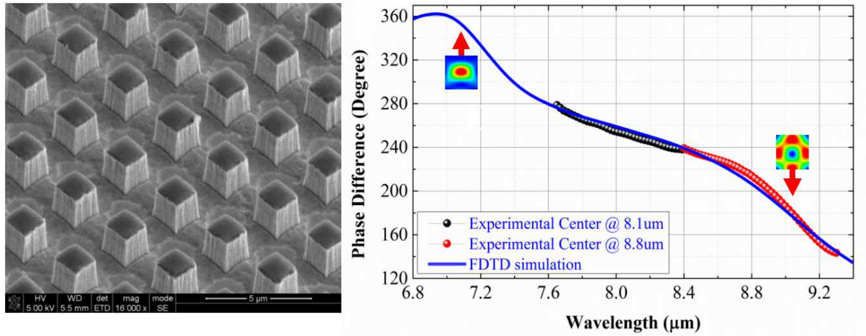
Ref. : Optics Express 21, 26285 (2013)

For dielectric particles, the polarizabilities of the electric and magnetic dipole resonances are <u>comparable at optical frequencies</u>

This is not the case for metallic resonators at optical frequencies because of metal losses

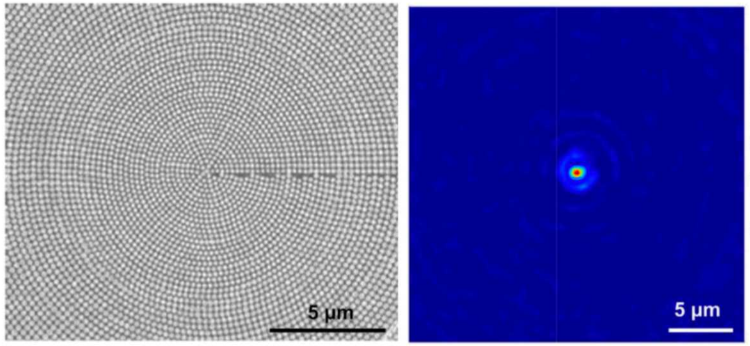
Applications of Mie Modes in Dielectric Metasurfaces

Magnetic Response

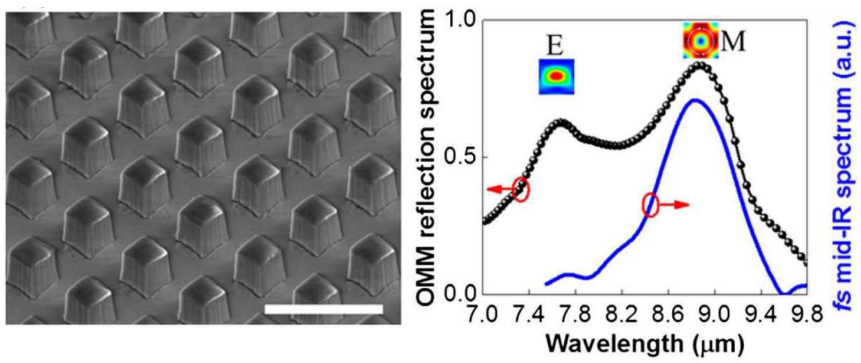


PRL. 108, 097402 (2012)

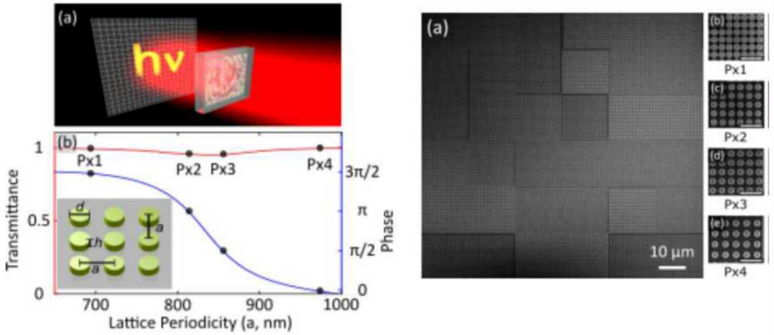
Tailoring Linear Transmission



Argonne National Labs

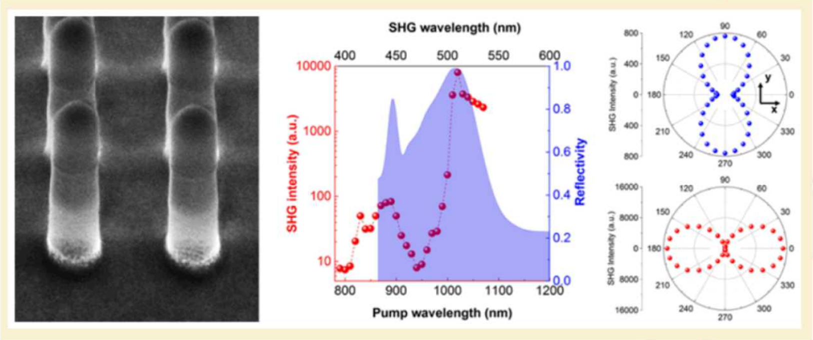


Optica 1, 250 (2014)

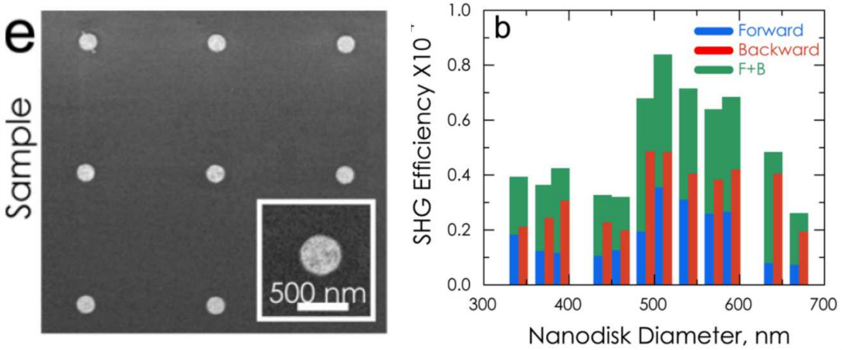


ACS Photonics 3, 514 (2016)

Nonlinear Optics



Nano Lett. 16, 5426 (2016)

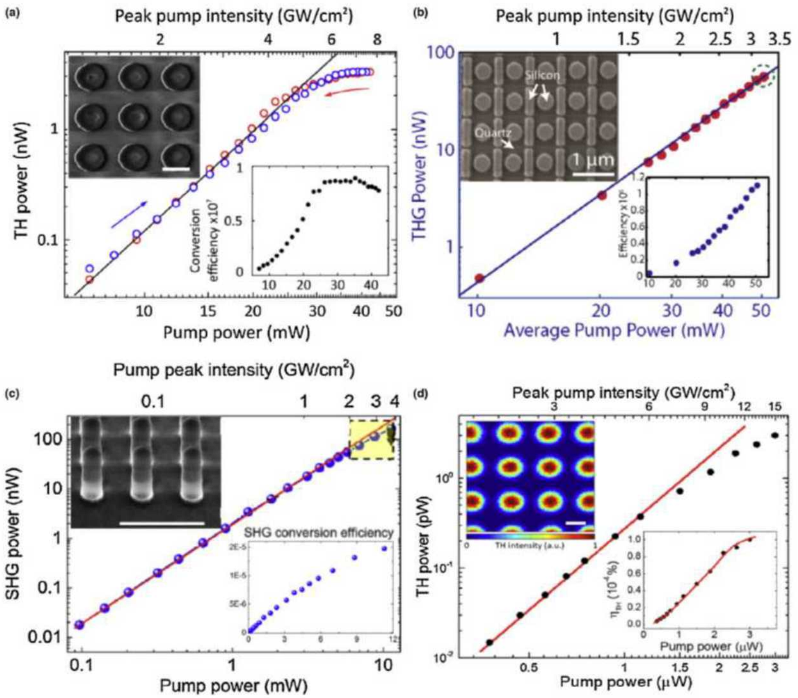


Nano Lett. 16, 7191 (2016)

Advantages of Nonlinear Mie Metasurfaces : **1. Ultrathin (relaxed phase matching) 2. Low loss and high damage thresholds 3. Large mode volume (enhanced light-matter interaction) 4. Ease of fabrication**

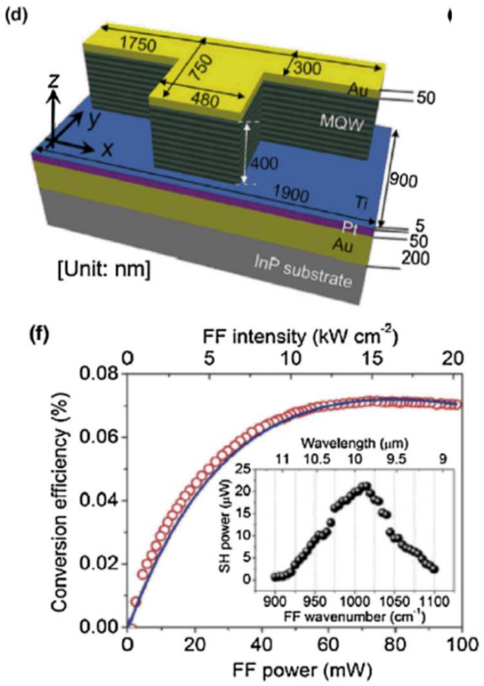
Two Prominent Nonlinear Metasurface Approaches for Second Harmonic Generation

1. Mie Based All Dielectric Metasurface



Max. Norm. Efficiency ~ **10^{-6}** W/W^2

2. IST-Plasmonic Metasurface



Max. Norm. Efficiency ~ **10^{-3}** W/W^2

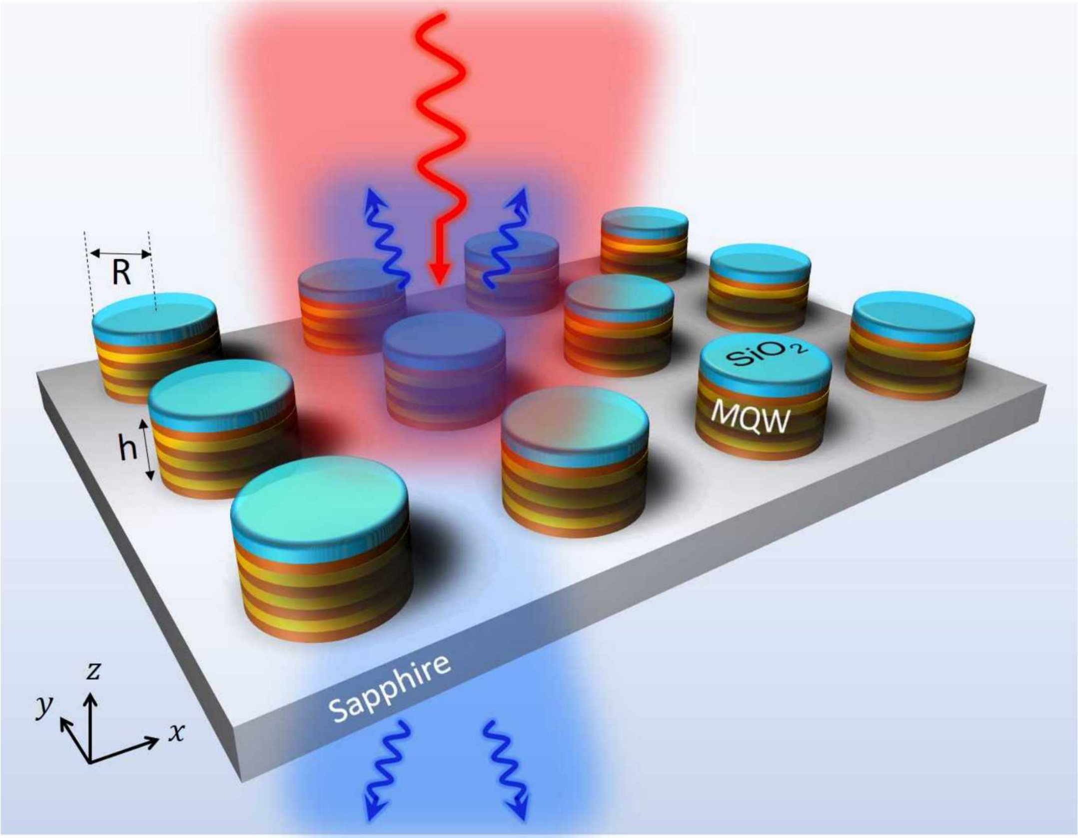
Problem of Approach 1 : Low efficiency

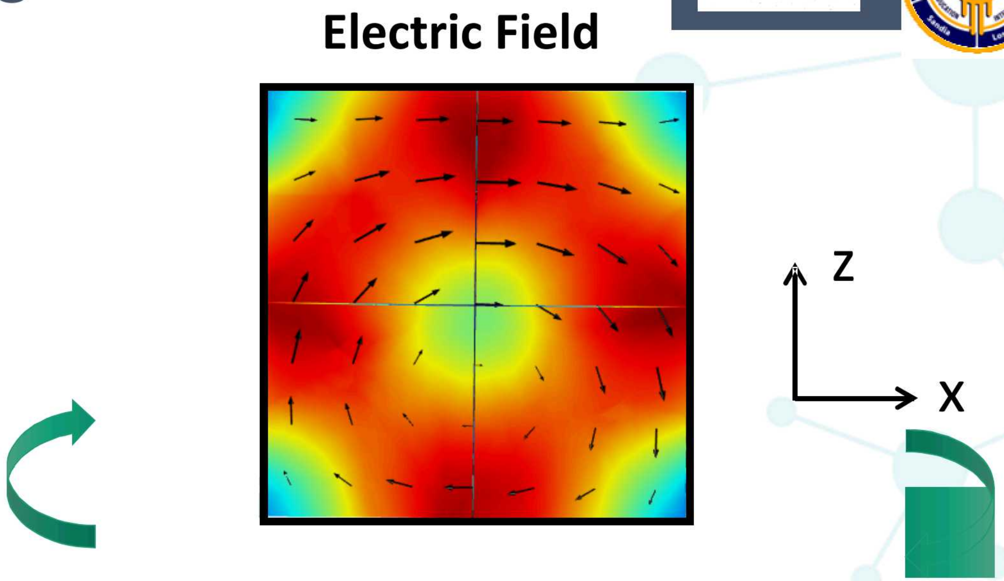
Problem of Approach 2 : Losses due to plasmonic structures

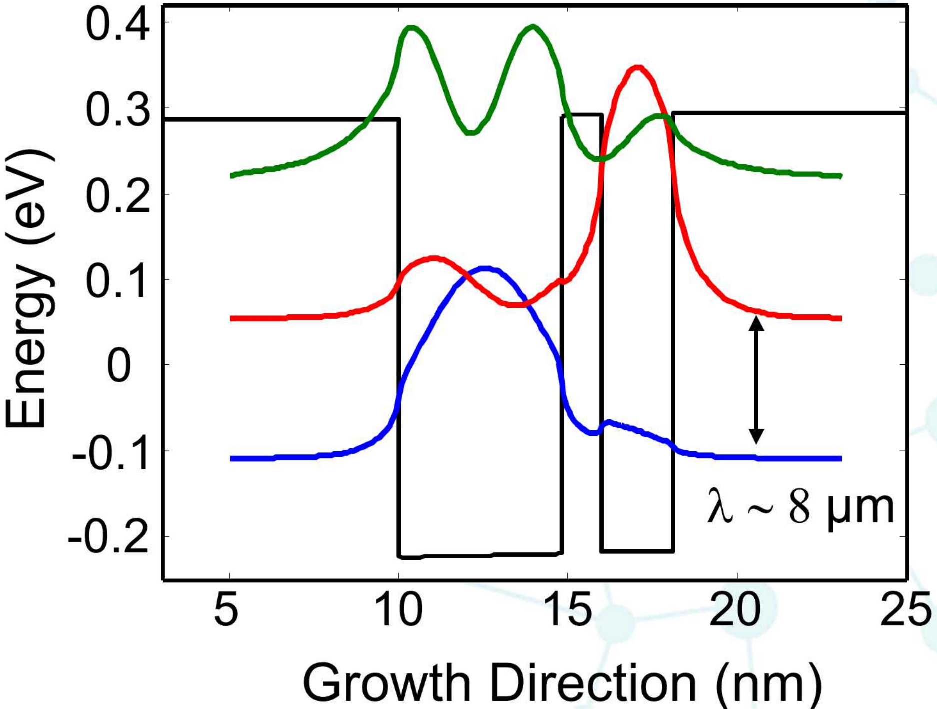
Our new approach : An All-Dielectric Polaritonic Metasuface that combines both approaches !

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

Polaritonic Metasurface : Light-Matter Coupling

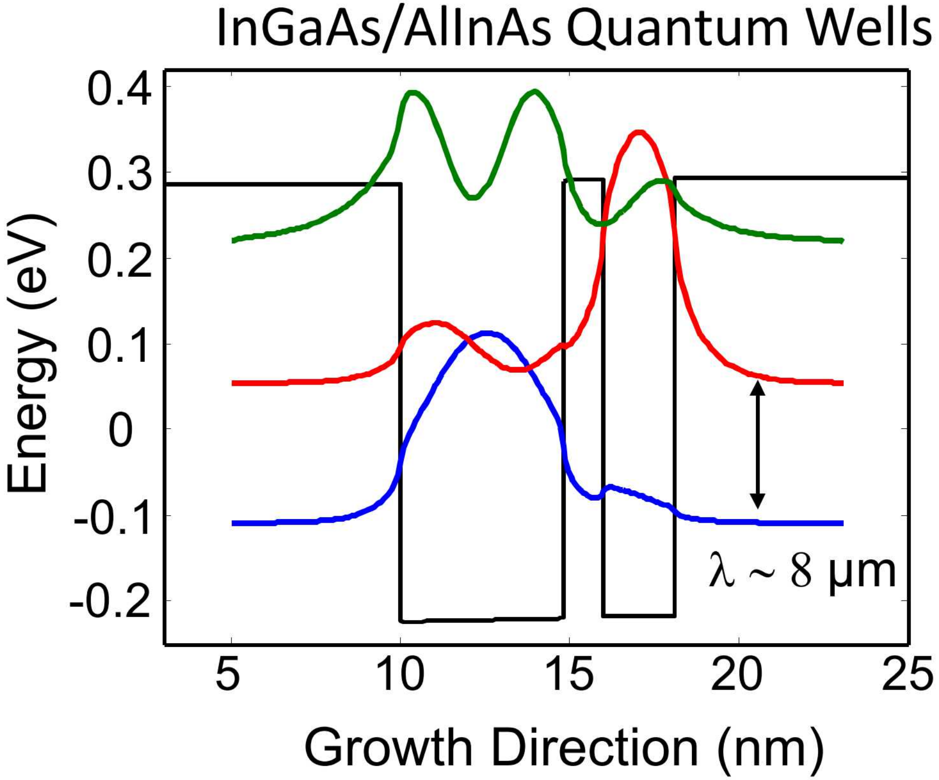


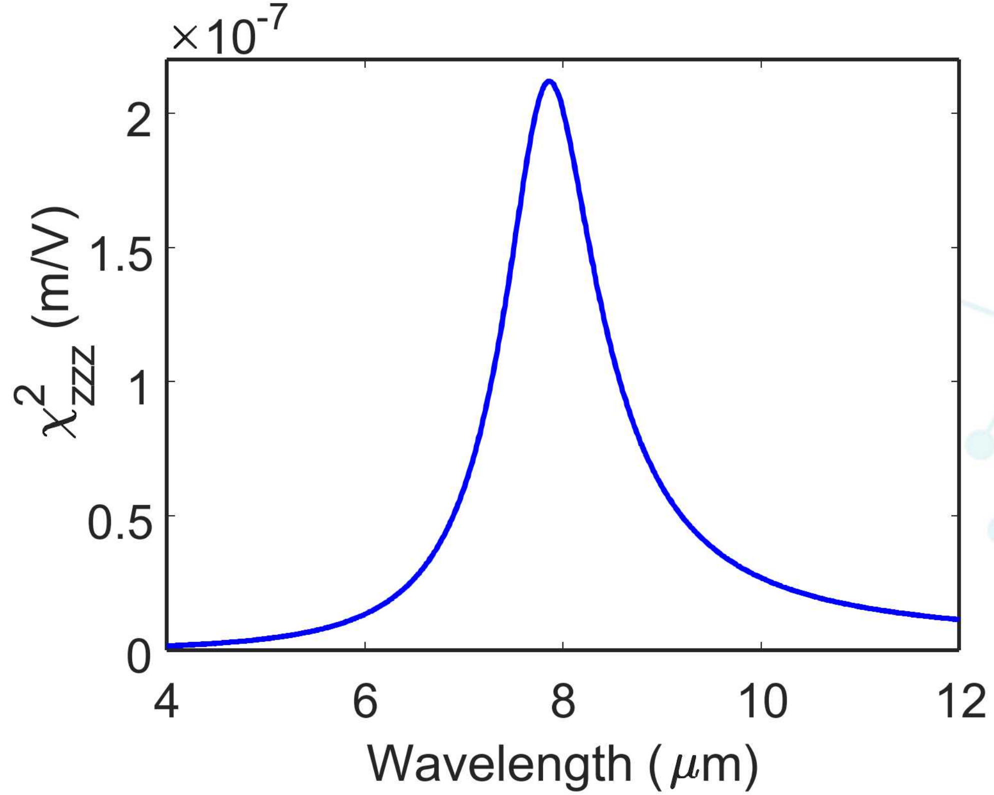




- Light-matter coupling between a MD Mie mode and intersubband electronic excitations.
- MD mode has strong z electric field components, allows for normal incidence, and smallest size of the resonator.

Resonant $\chi^{(2)}$ using Intersubband Transitions



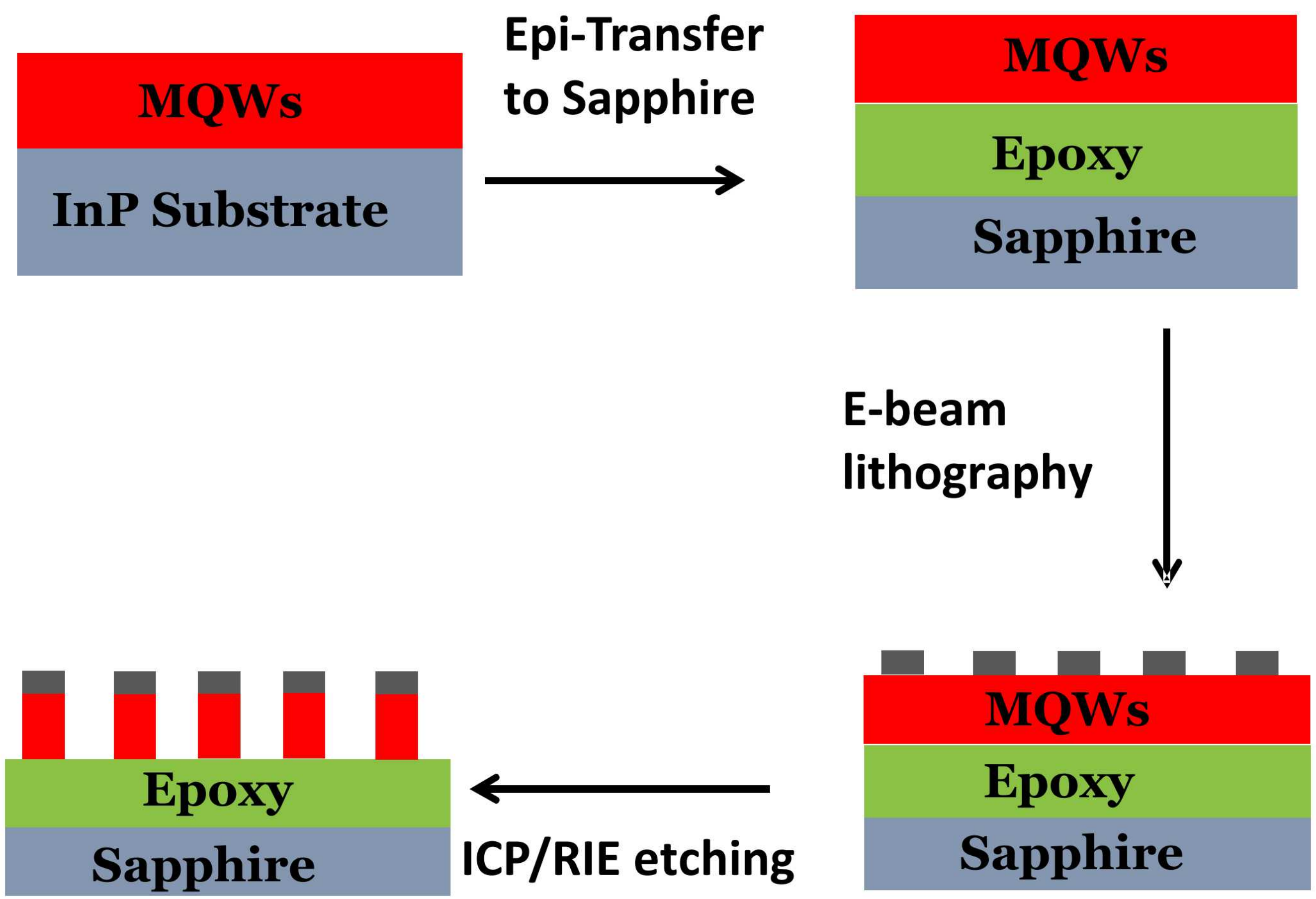


$$\chi^{(2)}(\omega) \propto \frac{N \cdot z_{12} z_{23} z_{13}}{(\omega - \omega_{12} - i\Gamma_{12})(2\omega - \omega_{13} - i\Gamma_{13})}$$

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

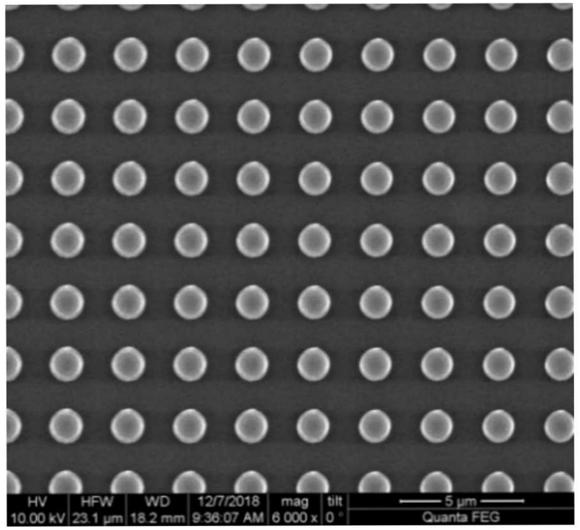
IEEE J. Quantum Electr. 30, 1313 (1994)

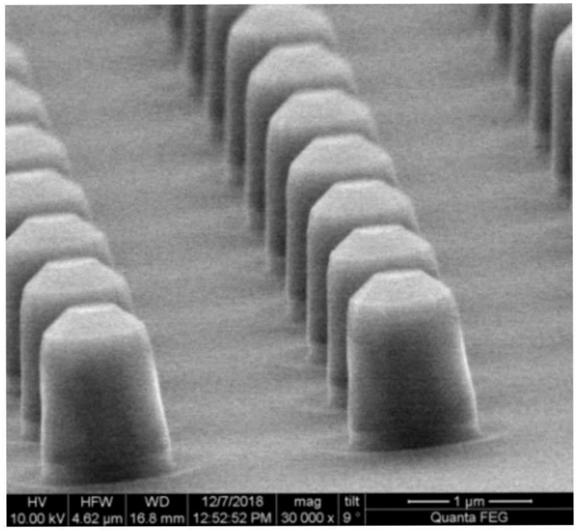
Fabrication of the Polaritonic All-Dielectric Metasurface



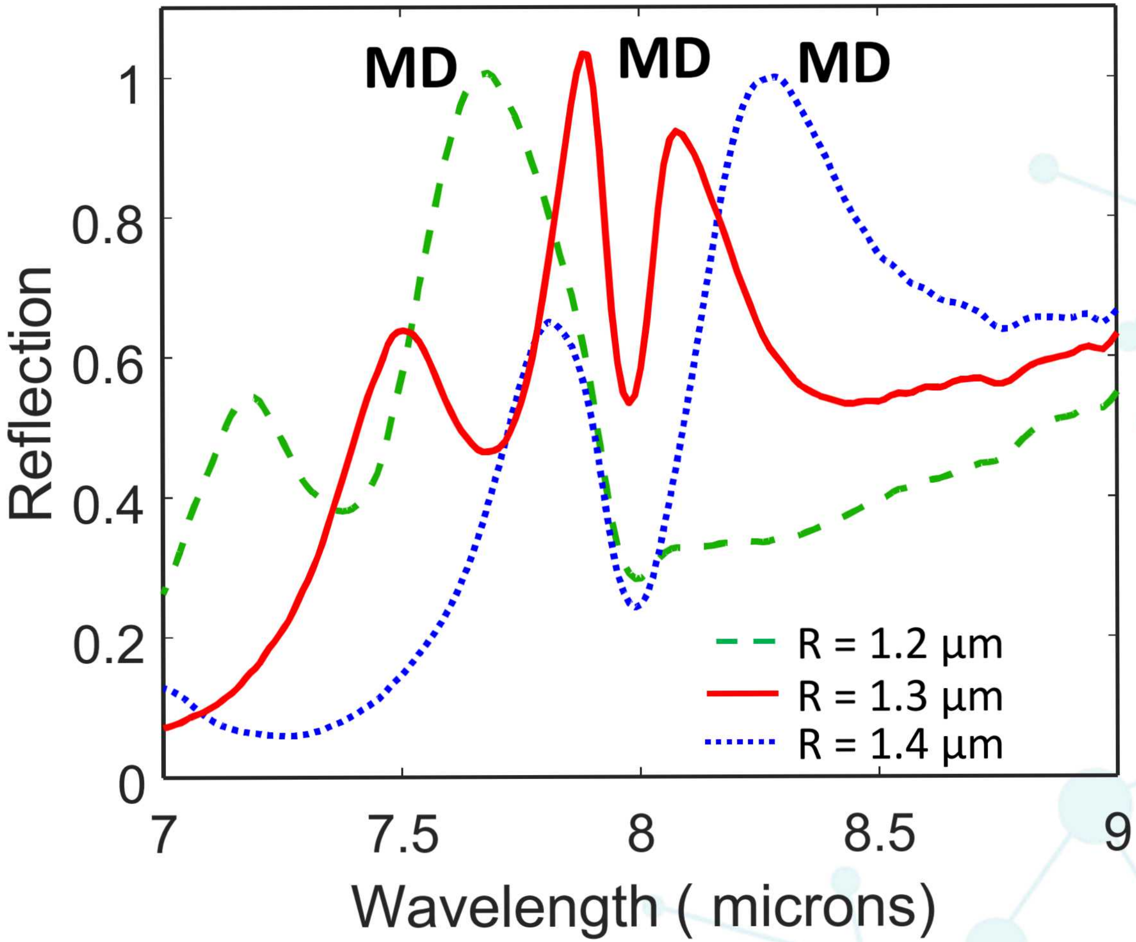
Fabricated Structures and Linear Reflectance Spectra

Scanning Electron Micrographs



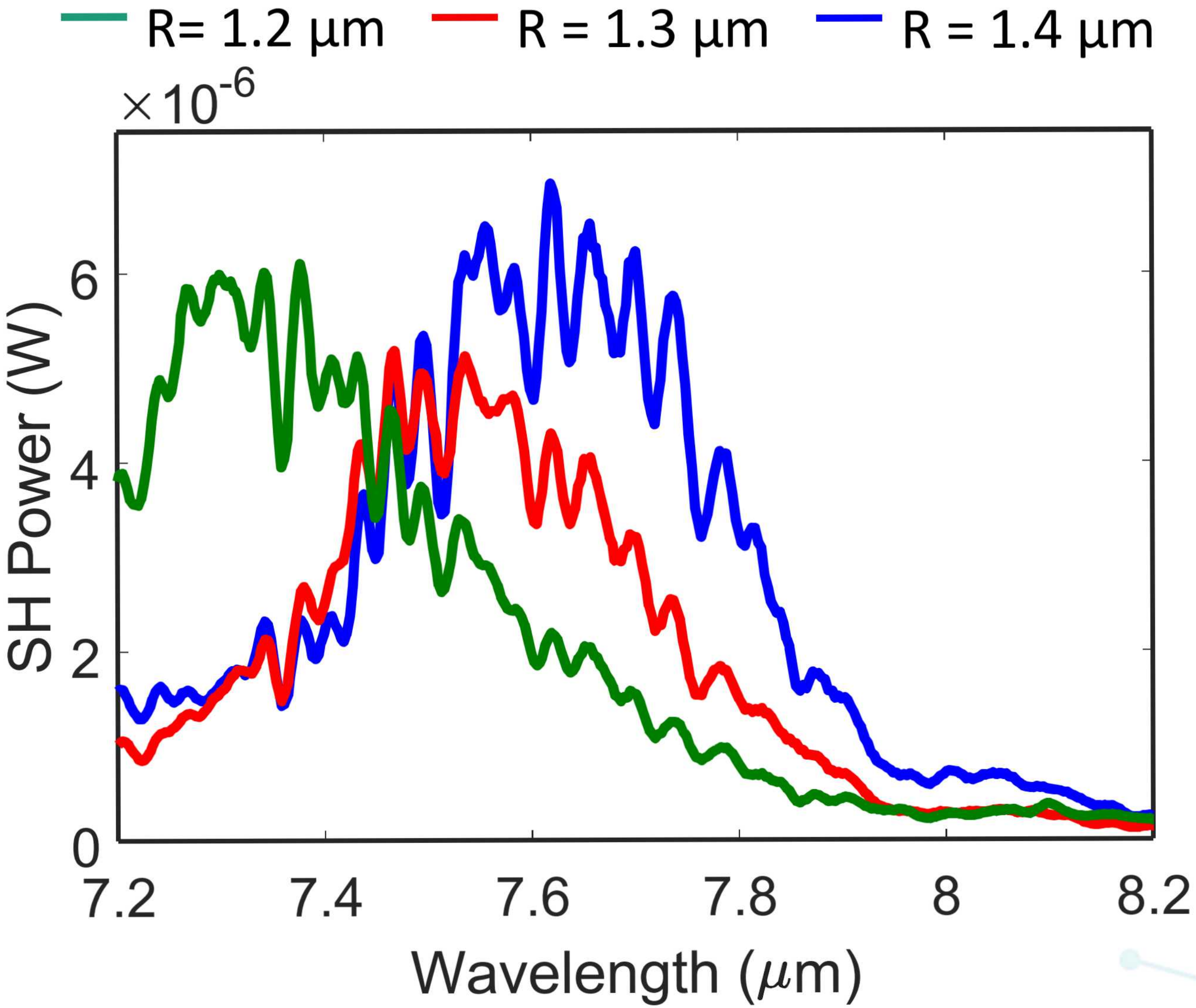


Mie Resonance at 8 microns



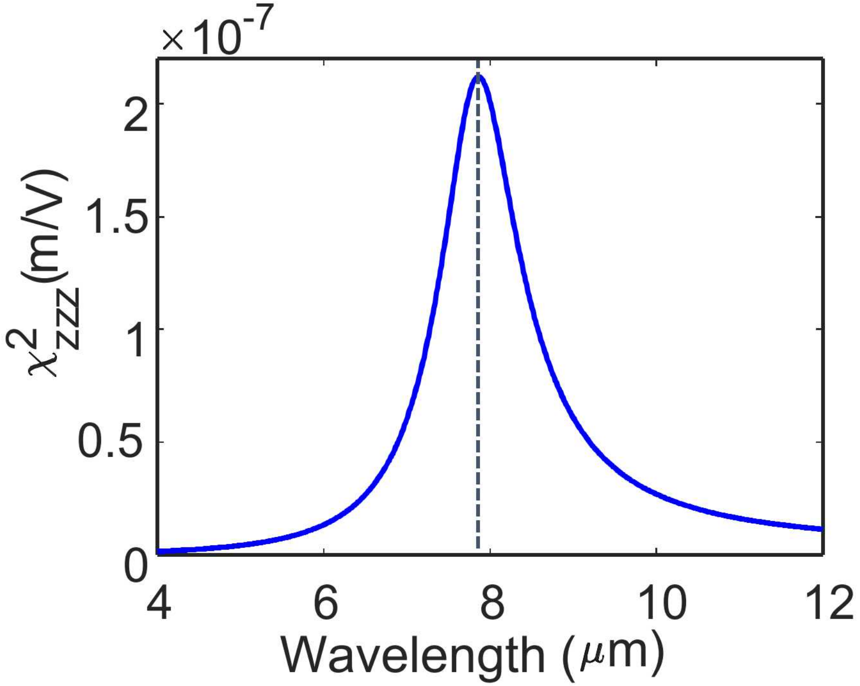
Splitting of Photonic Resonance due to Coupling

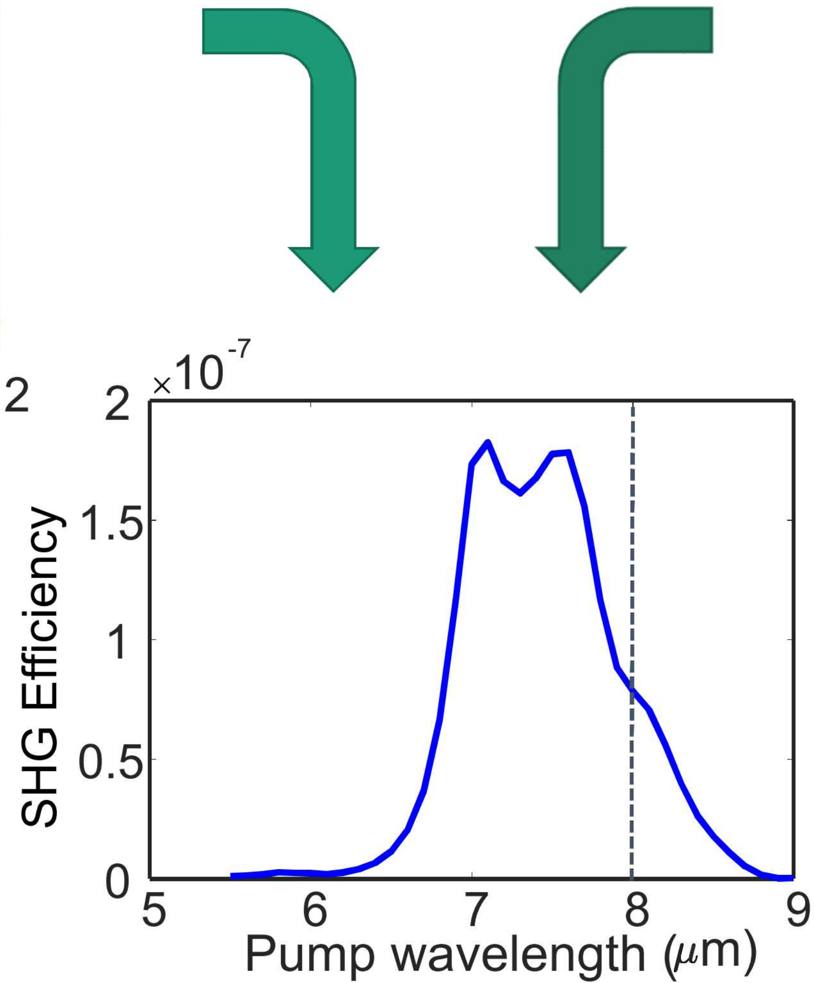
Experimental Second-Harmonic Spectra

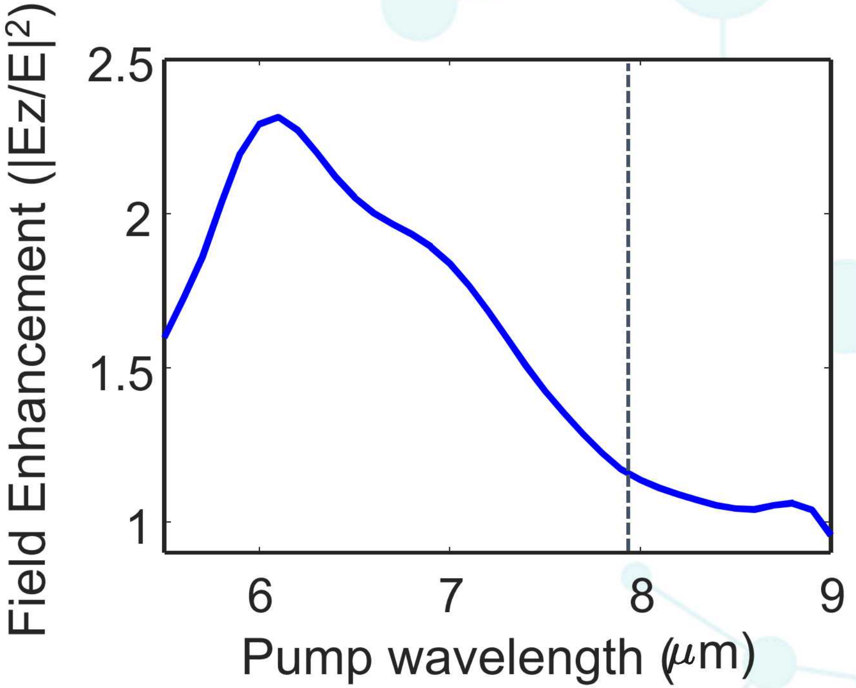


Maximum second harmonic power is observed at wavelengths smaller than 8 microns.

Interplay between Nonlinearity and Field Enhancement

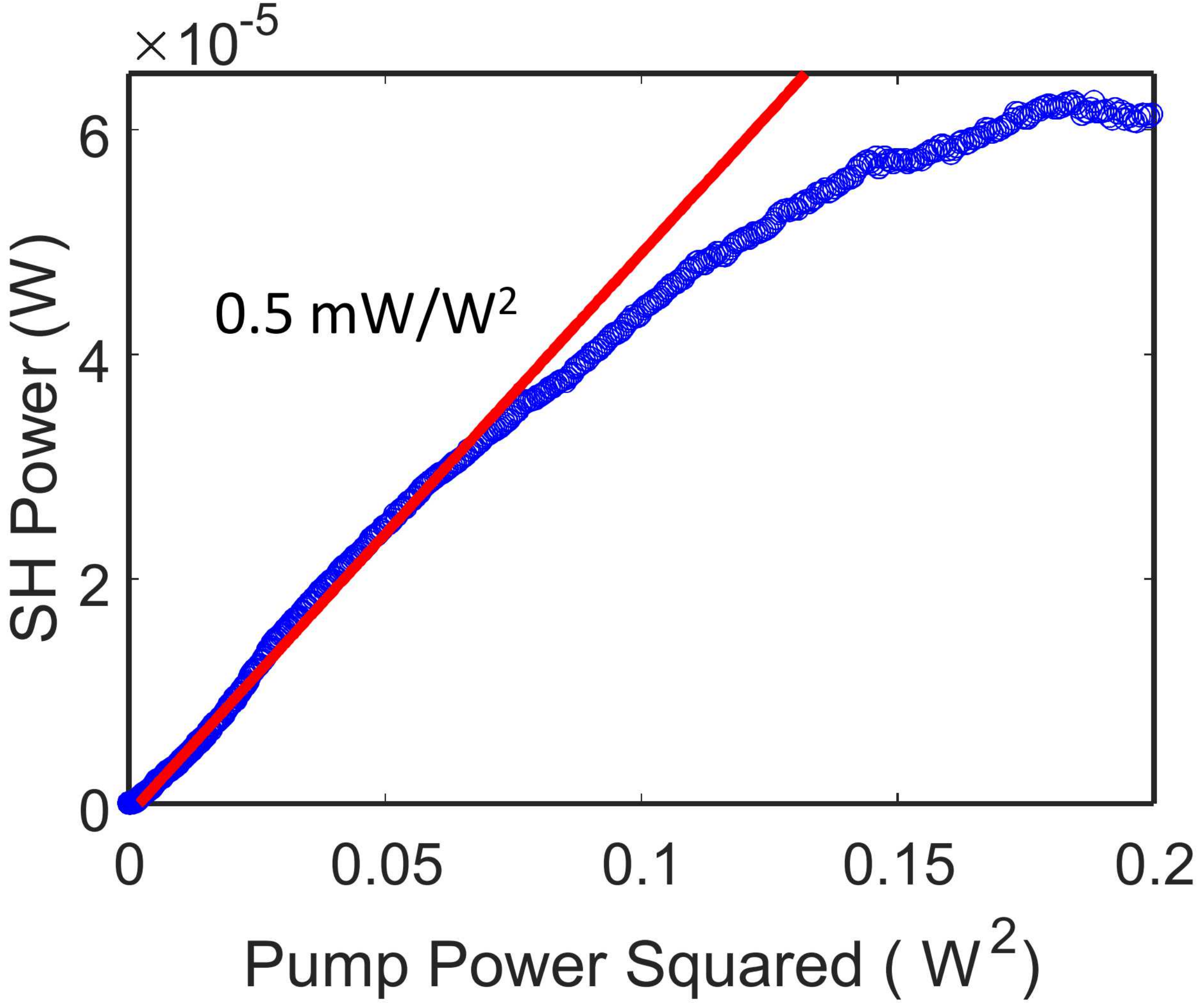


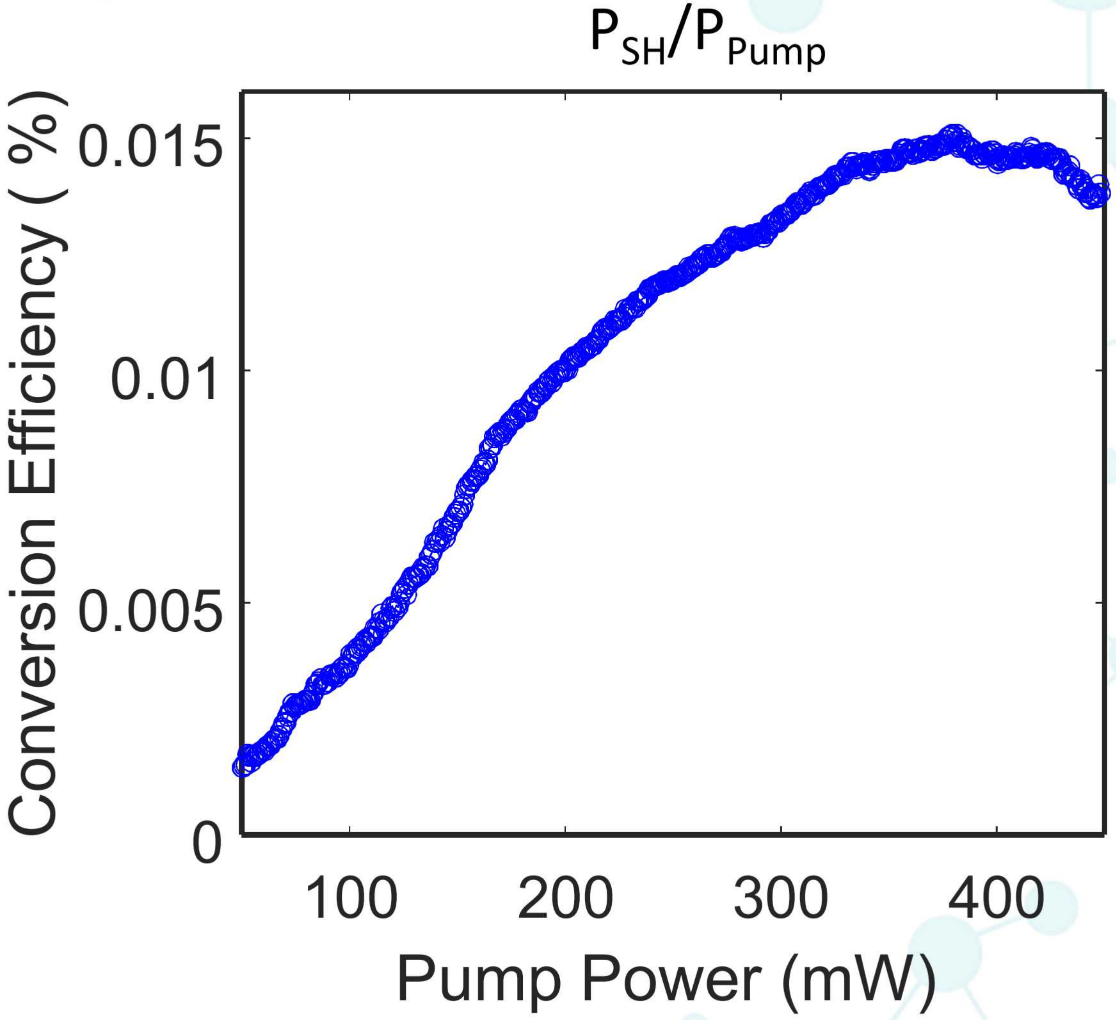




The SHG efficiency is determined by the product $\chi^{(2)}\ |E|^2$ and the peak is at wavelengths shorter than 8 μm.

Experimentally Measured SHG Efficiencies



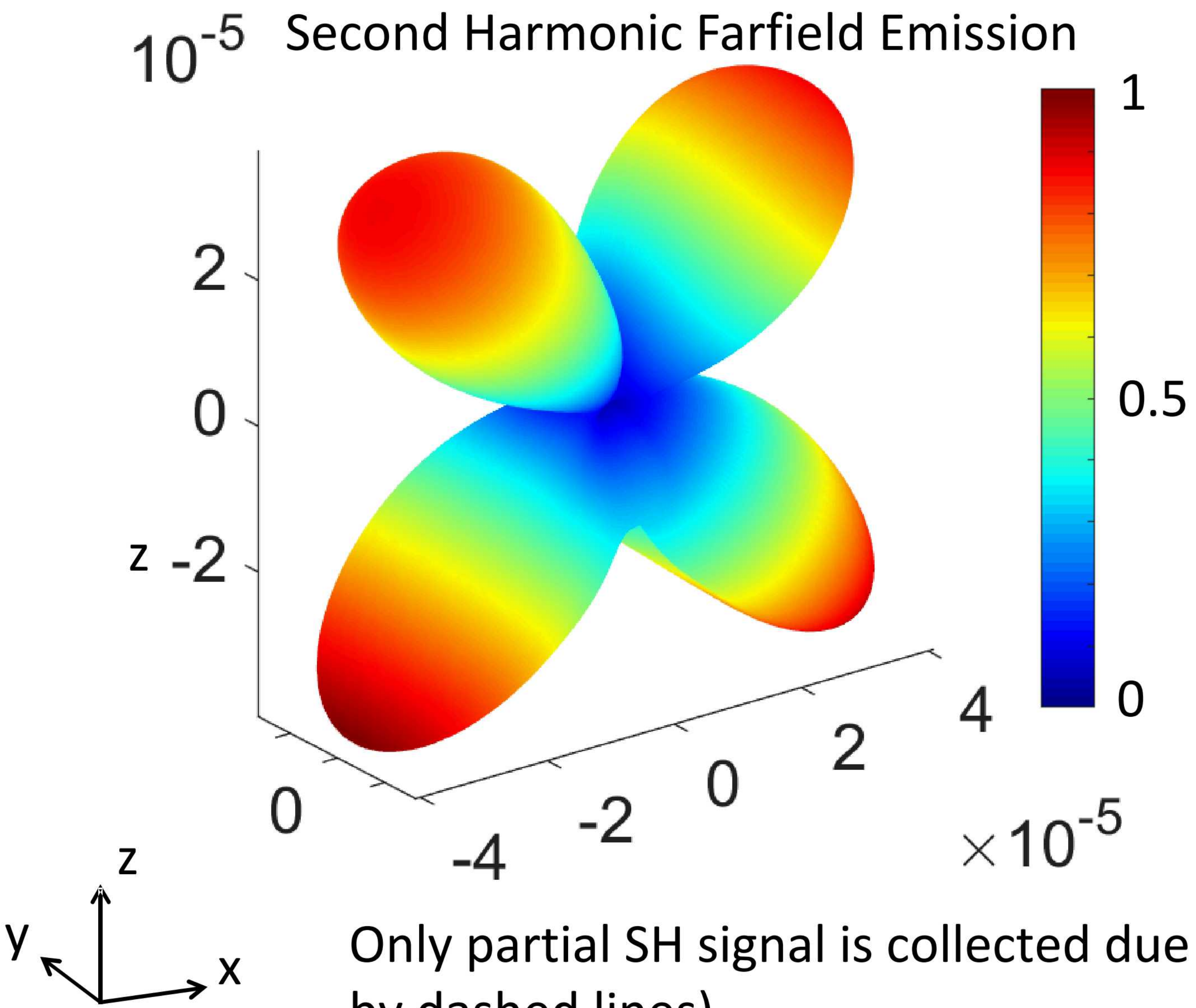


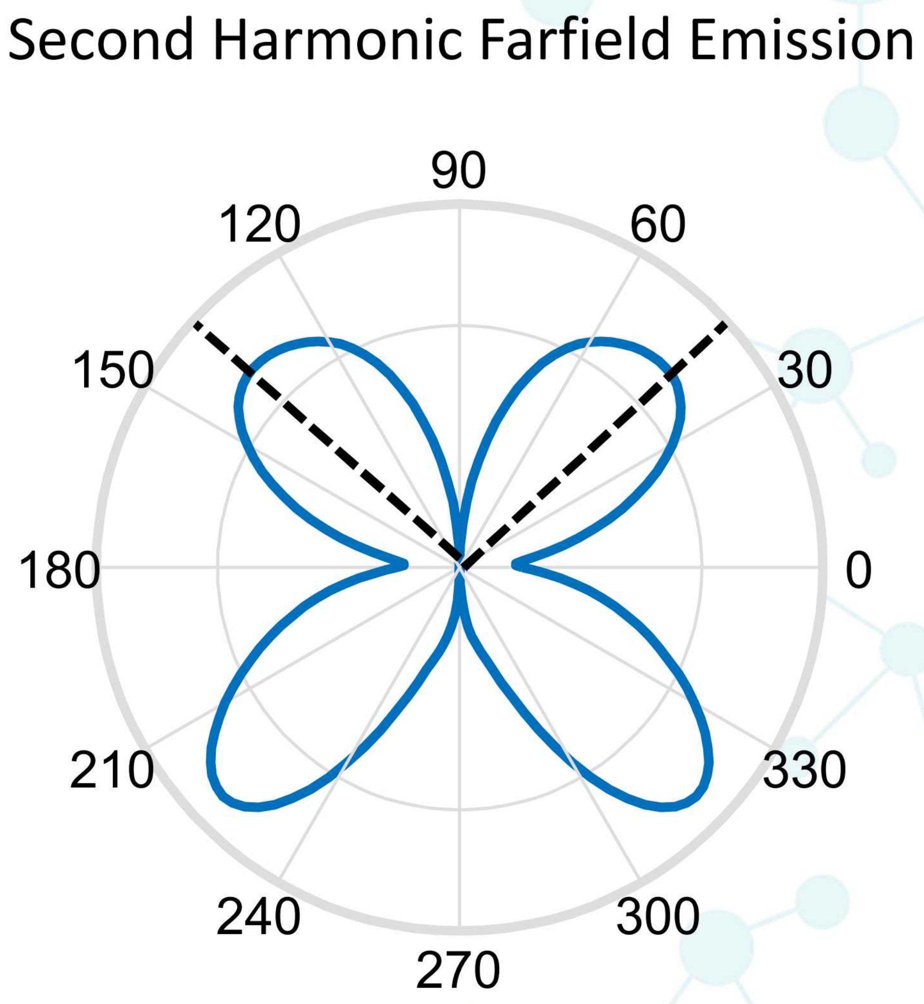
Larger mode volumes compensate lower field enhancements (compared to plasmonic resonators). It increases saturation intensity and gives efficiency ~ 0.015 % (comparable to record highest 0.075 %)

Comparison of SHG Efficiencies using Different Approaches

Nonlinear Metasurface Approaches	**Maximum SHG Efficiency P_{SH}/P_{Pump}**	**Maximum Normalized Conversion Efficiency (mW/W^2)**
Optimized IST + Optimized Plasmonic Resonator + Metal Backplane + Etching of QWs	0.075 % (~ 15 kW/cm^2)	16 (Experimental)
GaAs/AlGaAs nonlinear Mie metasurfaces with optimized BIC resonator and optimized input beam	0.001 % (~ 0.1 GW/cm^2)	~ $1x10^{-3}$ (Experimental)
IST + Mie Resonator (Not optimized !)	**0.015 % (~ 20 kW/cm^2)**	**0.5 (Experimental)**

Factor Limiting Measured Efficiency : Collection Optics





Only partial SH signal is collected due to finite NA (0.8) of the objective (shown by dashed lines).

Summary

- We demonstrate giant second-order nonlinearities in polaritonic all-dielectric metasurfaces.

- Our results are proof-of-concept and the efficiencies can be improved by optimizing the heterostructure, field overlaps, and interplay between field enhancement and nonlinearity.

- Our approach although demonstrated for a particular wavelength, in principle, can be scaled to other wavelengths from visible to near-IR.