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Optical Tuning of Fano Resonances in Dielectric Metasurfaces

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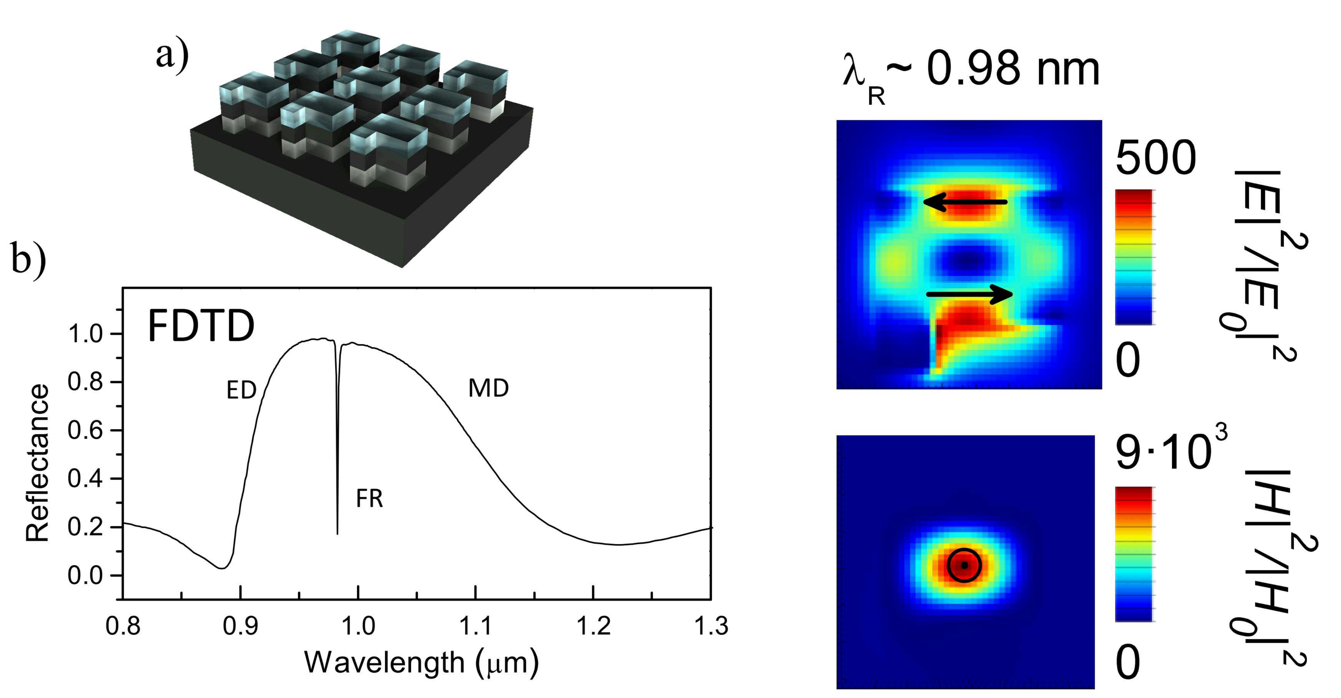
Introduction

Photonic nanostructures that support Fano resonances have attracted growing interest in recent years due to their promising sharp spectral features and the subsequent applications these features can support. For example, plasmonic Fano resonance demonstrations include applications of sensing and enhanced non-linear interaction. As an alternative, dielectric metasurface based Fano resonances supported via Mie modes are an interesting platform for non-linear processes because of their higher non-linear efficiencies. These Fano resonances can be realized with a variety of metasurface designs, and through engineering the resonator geometry the Fano resonance frequency can be adjusted. However, typically dielectric metasurfaces are no longer tunable after fabrication, and an open challenge remains to demonstrate fast and efficient spectral tuning. Here we showcase ultra-fast tuning of a Fano resonance in the near infrared via optical pump.

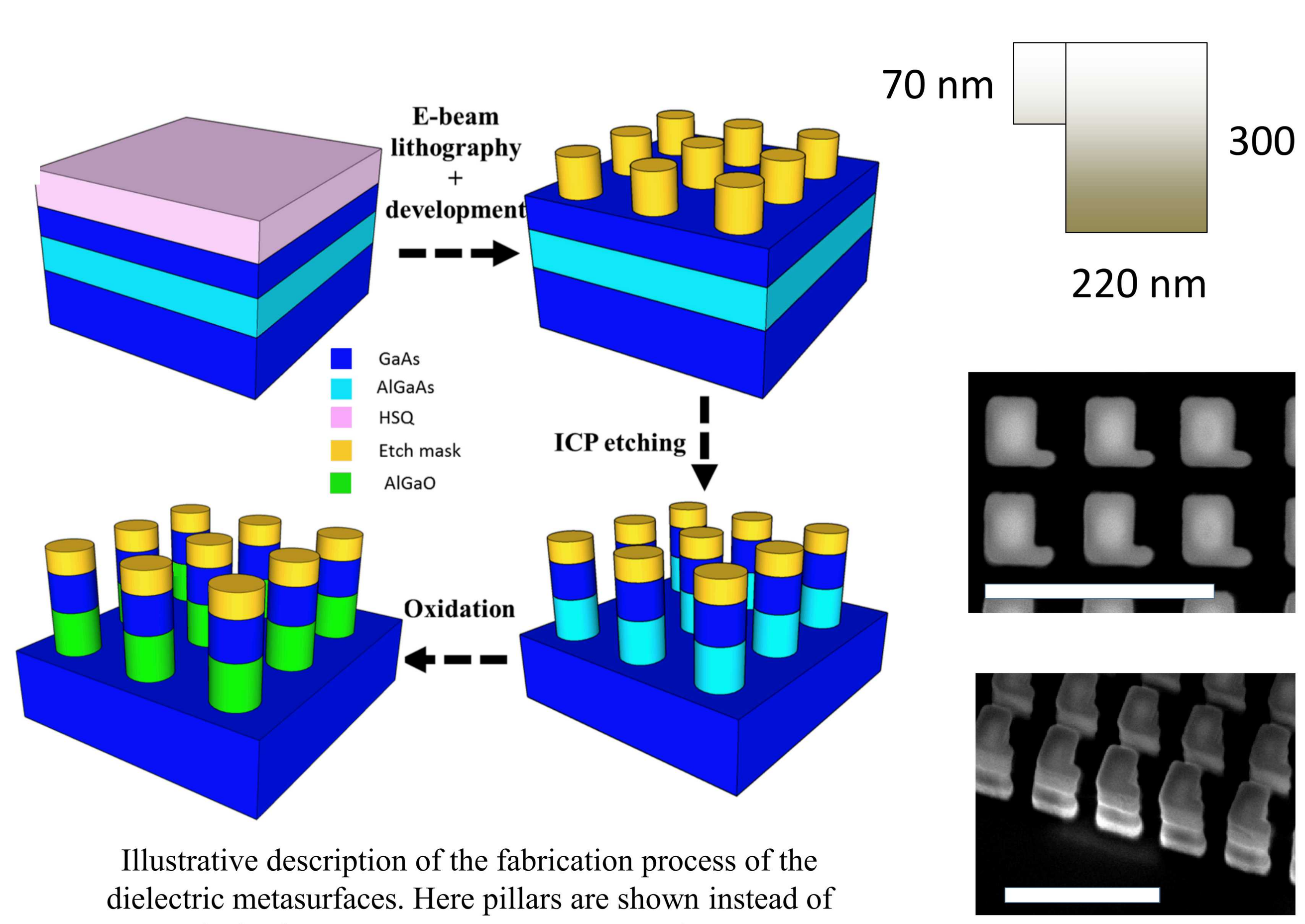


a) Fano dielectric metasurface with 9 resonators.
b) Simulated Fano spectrum, showing modes and the resonance.

Mode field patterns

Vabishchevich, P., et al. *ACS Photonics*, **2018**

Fabrication

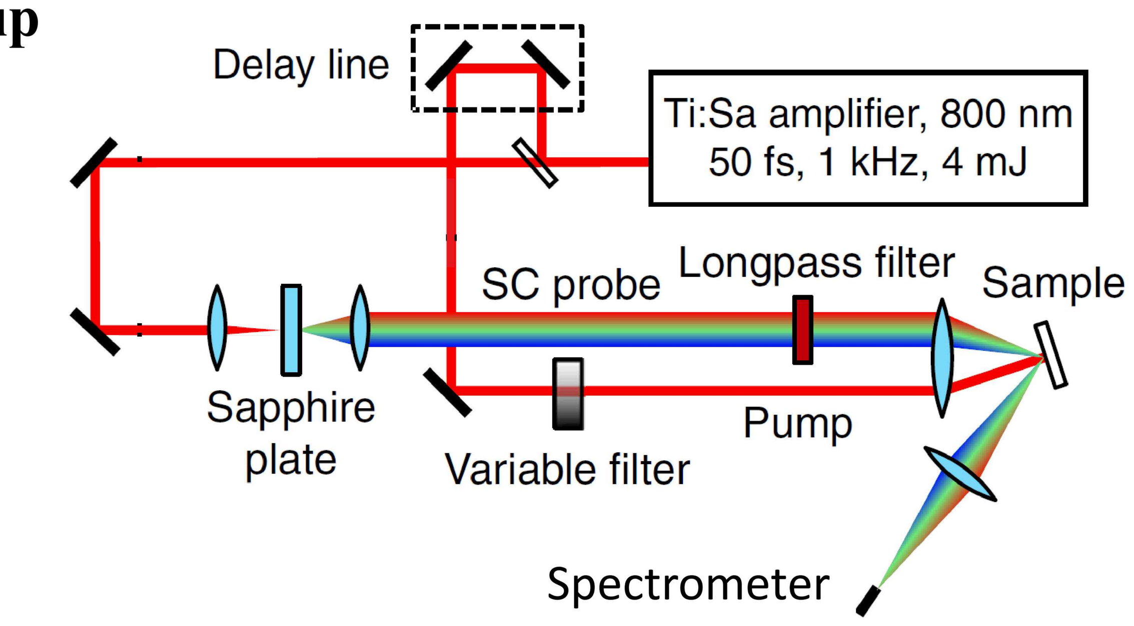


Illustrative description of the fabrication process of the dielectric metasurfaces. Here pillars are shown instead of the broken symmetry Fano resonator shape.

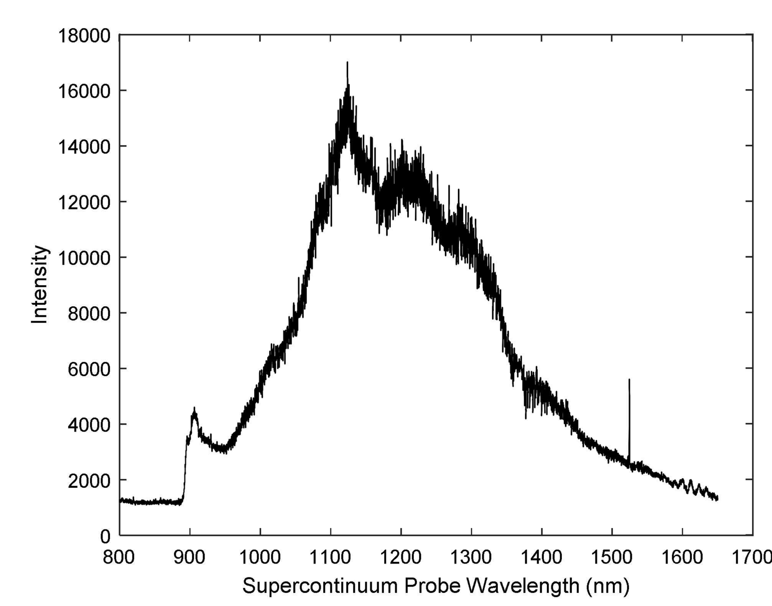
Liu, S. et. al. *Nano letters* 16.9: 5426-5432, **2016**

Experimental Setup & Results

Setup

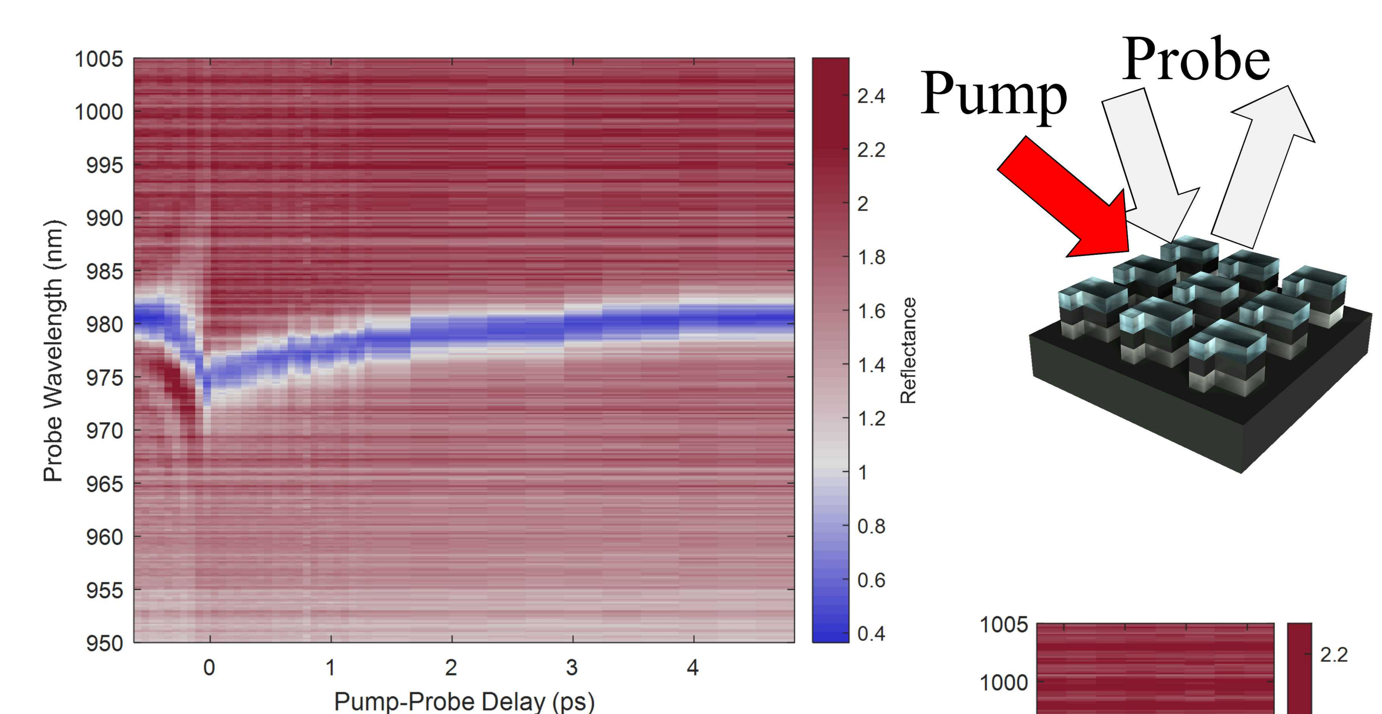


- Schematic of the broadband pump probe spectroscopy setup.
- A supercontinuum is generated in the sapphire plate which is used to probe the Fano resonance.



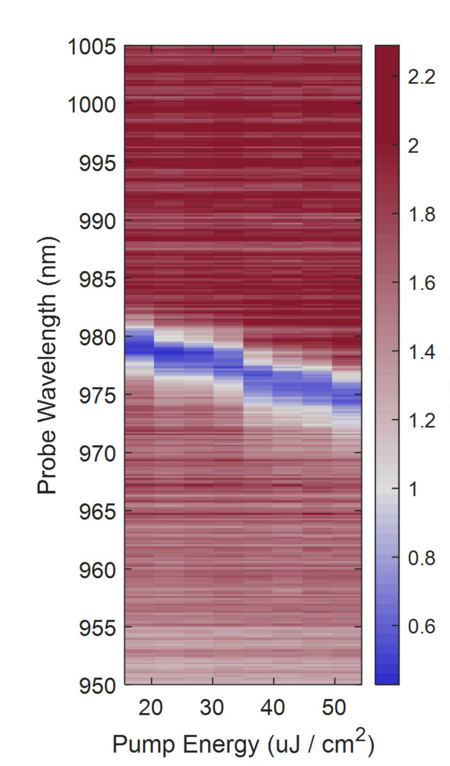
The bandwidth of the supercontinuum probe with 900 nm long pass filter to block the 800 nm pump.

Results



Transient reflectance spectra showing the ultrafast tuning of the Fano resonance on a picosecond timescale. The resonators are pumped with a fluence of 52 μW / cm²

Reflectance spectra as a function of pump fluence. Data obtained at pump probe time delay t = 0.2 ps.



Full wave simulations

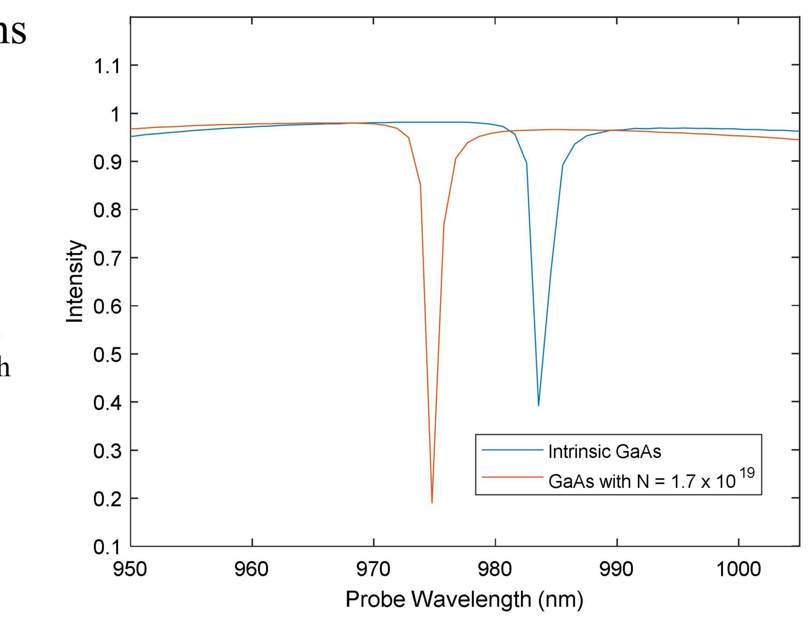
Mechanism of the mode tuning

$$\Delta n_{\mathrm{D}}(N,E) = -\left(\frac{N_{\mathrm{e}}}{m_{\mathrm{e}}} + N_{\mathrm{h}}\frac{m_{\mathrm{hh}}^{0.5}+m_{\mathrm{lh}}^{0.5}}{m_{\mathrm{hh}}^{1.5}+m_{\mathrm{lh}}^{1.5}}\right)\frac{\hbar^2 e^2}{2n\varepsilon_0(E^2+\hbar^2\gamma^2)}$$

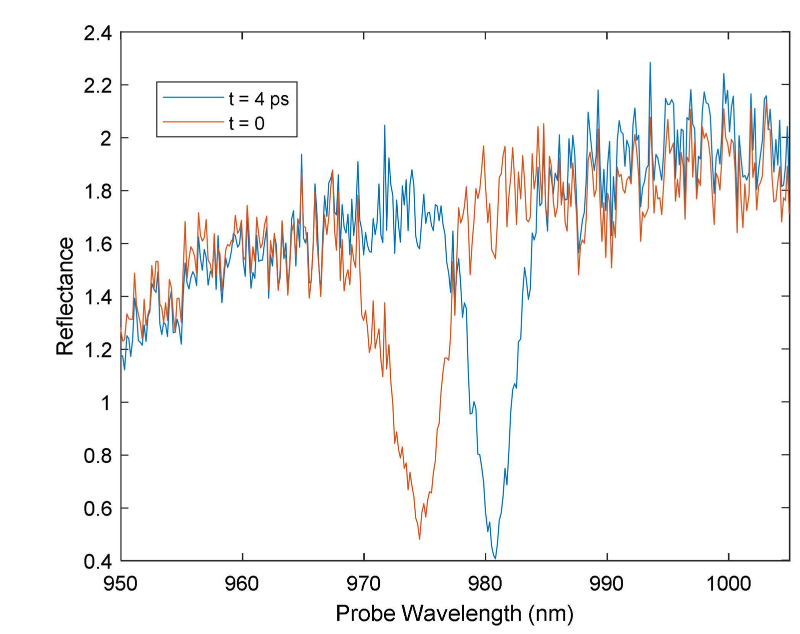
Drude term

N_e – electron density
N_h – hole density
m_e – electron effective mass
m_{hh} – heavy hole mass
m_{lh} – light hole mass
γ – damping factor

- Lumerical FDTD simulations
- Spectra are calculated as a function of time with the GaAs index modified as described above by the free carrier concentration $N_e = N_h$



- Experimental pump-probe spectra
- Spectral results at separate pump-probe delays, each with pump fluence of 52 μW / cm².
- The experimental value at t = 4 ps is reproduced with FC density of 1.7 × 10¹⁹.



Conclusion & Outlook

- We demonstrated an actively tunable Fano resonance through the ultrafast injection of free carriers in a direct-gap semiconductor metasurface.
- Low-power all-optical tuning was achieved at picosecond timescales.
- Key to the high efficiency is the use of direct-gap semiconductors, which offers higher absorption, and more efficient recombination, allowing for tuning at a fluence of just 52 μW / cm².
- Continued research work will focus on the non-linear processes in these metasurfaces, e.g. SHG, and studying how the broken symmetry design influences efficiency.
- The utility of this concept could be applied towards a variety of devices such as ultrafast wavefront control for beamsteering, beamshaping, polarization manipulation, or imaging.

References:

Campione, S. et.al *ACS Photonics* 3 (12), 2362− 2367, **2016**
Vabishchevich, P., et al. *ACS Photonics*, **2018**
Liu, S. et. al. *Nano letters* 16.9: 5426-5432, **2016**
Shcherbakov, M. et. al. *Nat. Comm.* 8, 1 **2017**.

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