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Frequency Conversion in a Dielectric Time-Variant Metasurface via Optical Pumping

Nicholas Karl[1,2], Polina P. Vabishchevich[1,2], Maxim R. Shcherbakov[3], Sheng Liu[1,2], Michael B. Sinclair[1], Gordon A. Keeler[1], Gregory M. Peake[1], Gennady Shvets[3] and Igal Brener[1,2]
[1]Sandia National Laboratories, Albuquerque, New Mexico 87185, USA
[2]Center for Integrated Nanotechnologies, Sandia National Laboratories, Albuquerque, New Mexico 87185, USA
[3]School of Applied and Engineering Physics, Cornell University, Ithaca, NY 14853, USA

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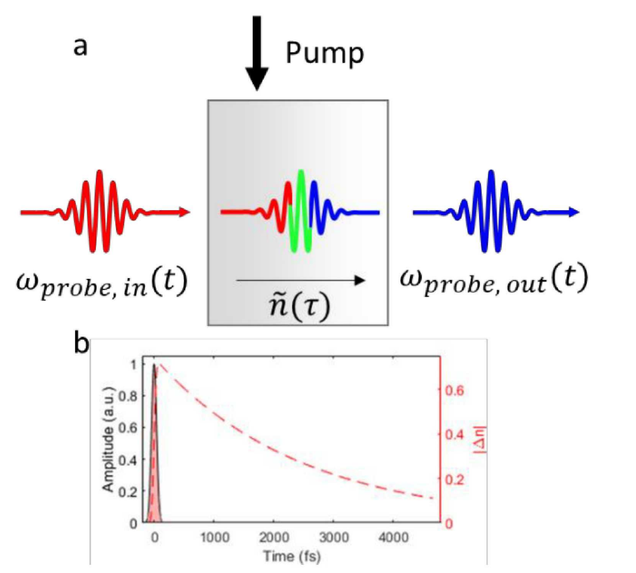
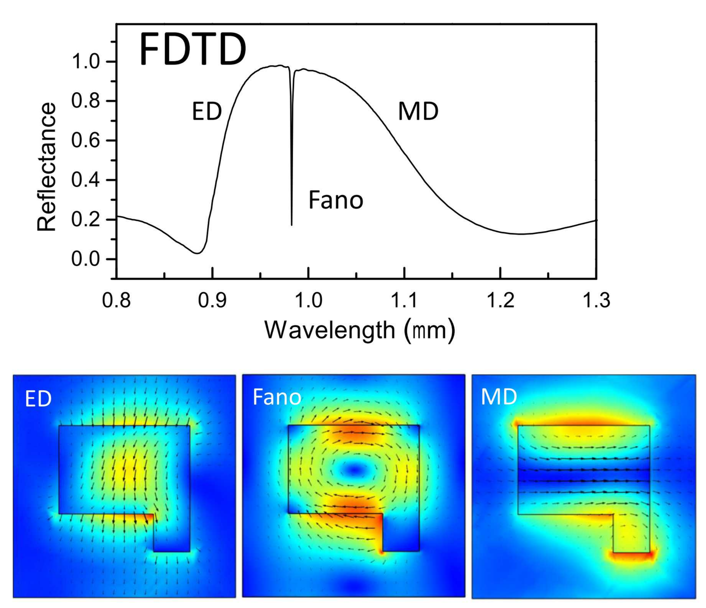
Introduction

Key Information

- Electromagnetic wave propagation in a nano-resonator that has a temporally variant refractive index induces frequency conversion of the confined photons.
- The conversion is dependent on the quality factor (Q) of the resonator.
- All-dielectric metasurfaces give us: low absorption, high damage threshold, tunable via optical pumping, Mie modes for design flexibility.
- Breaking the resonator symmetry allows coupling between bright and otherwise-dark modes that results in Fano resonances of far higher Q than the original modes.
- The frequency conversion is not based on a material nonlinearity and thus may be observed at low fluence.



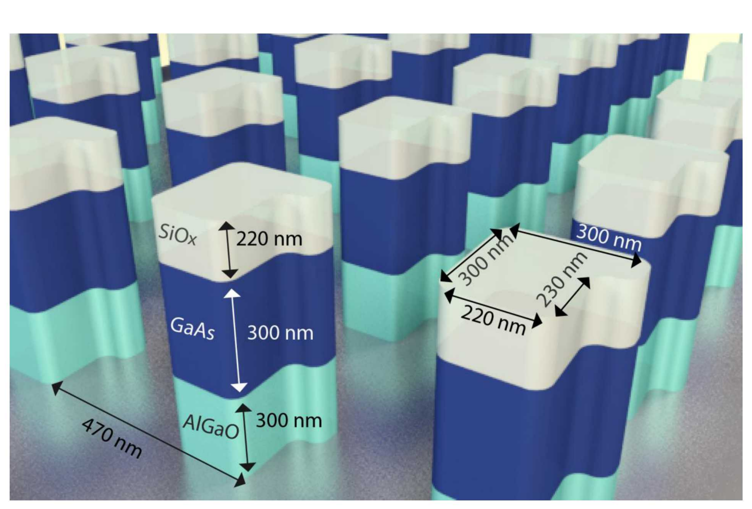
(a) Principle of frequency conversion in a cavity. Probe photons exist in the cavity at t_0 when the pump pulse reduces the index of the cavity as (b) shows. The probe is blue-shifted as the index is reduced.

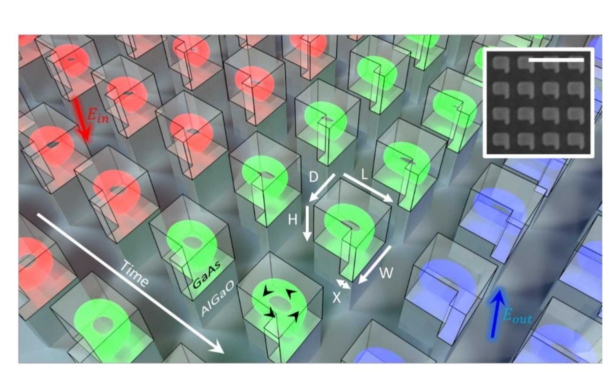


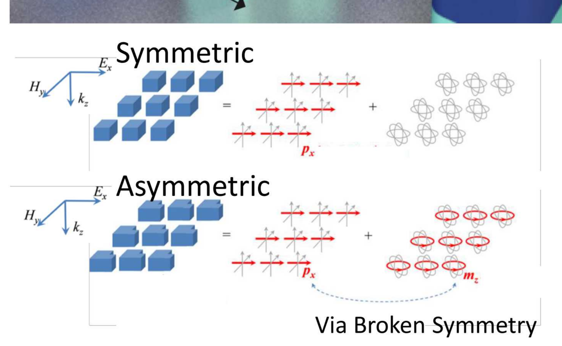
(top) FDTD spectra of the metasurface.
ED & Fano: Color & Quiver show E field
MD: Color shows E field, Quiver shows H field

Karl, N., APL, In Press, (2019);

Device & Resonance

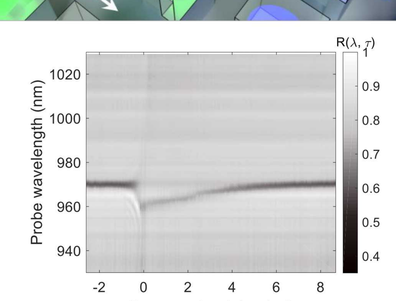


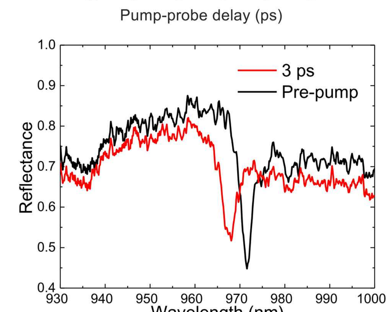




Q ~ 10

Q ~ 500



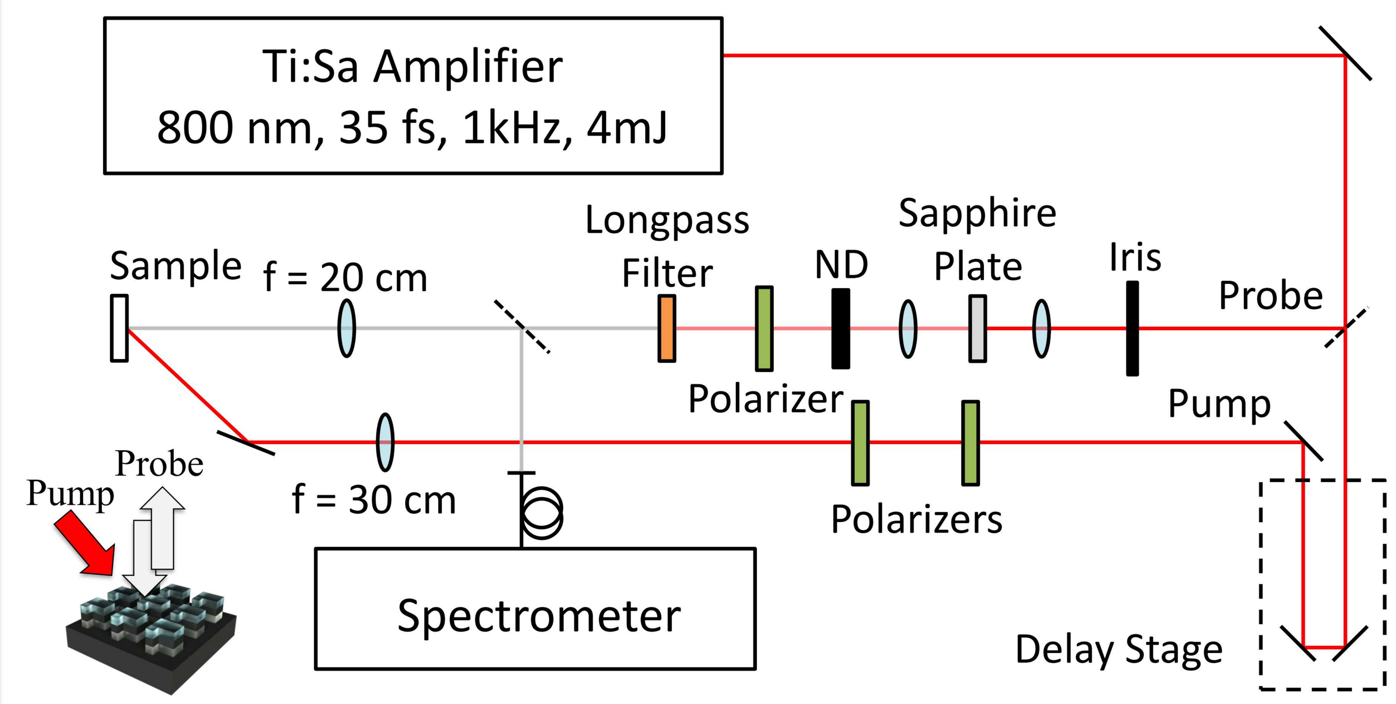


Device Dimensions and SEMs are shown (top). a) shows the transient reflectance dynamics of the Fano resonance as it is pumped and recovers. b) shows the Fano resonance as it is shifted due to pump-induced free carrier generation in the resonator at a pump fluence of 150 μJ·cm^{-2}.

Karl, N., APL, In Press, (2019); Campione, S., ACS Photonics 3 (12), 2362, (2016)

Experimental Setup & Results

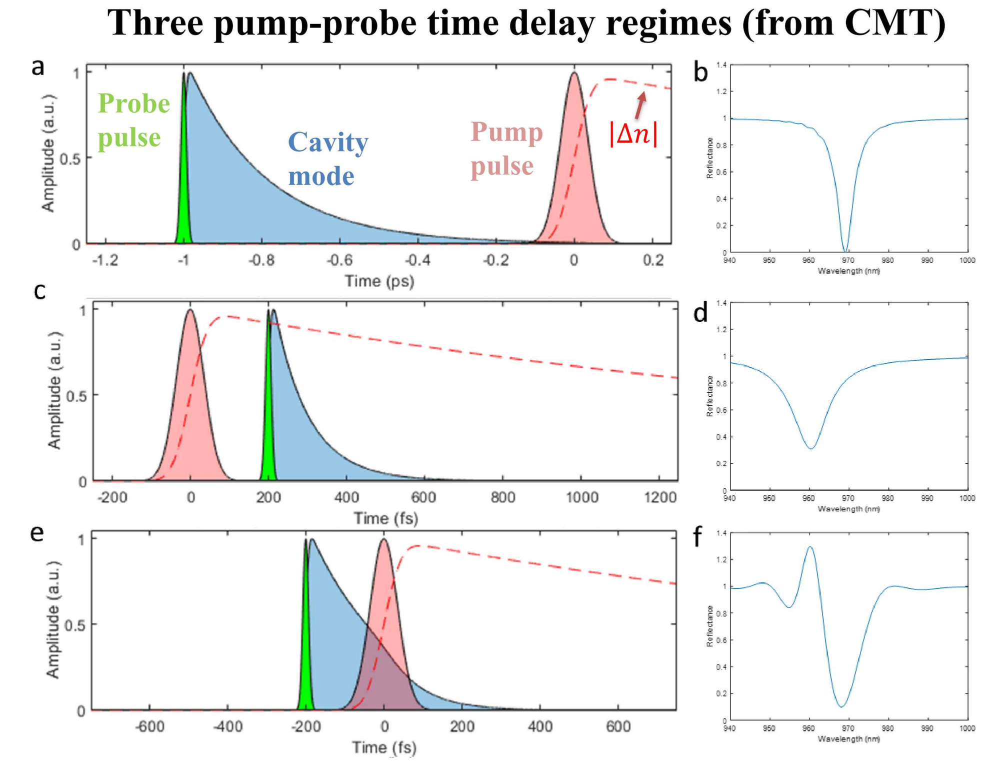
Pump-Probe Reflectance Spectroscopy



A broadband supercontinuum pulse is generated in the sapphire plate which is used as a probe.

Pump-Probe Timing

Three pump-probe time delay regimes (from CMT)



No pump interaction – Probing the default metasurface response

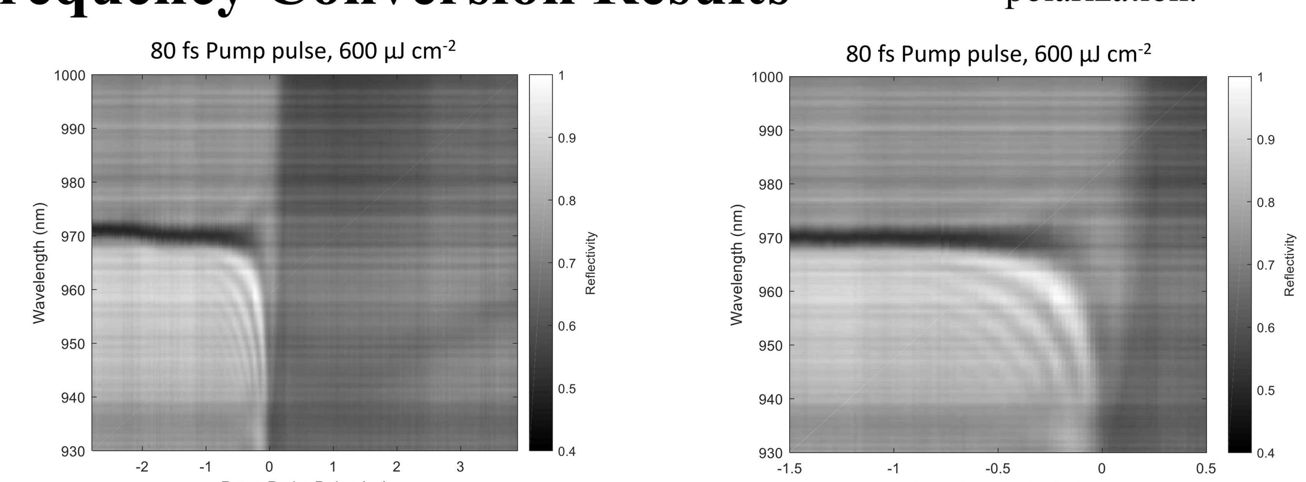
Standard pump-probe spectroscopy – Probing the effect of the pump on the resonator refractive index

Frequency conversion – Probe photons in the cavity when the pump is incident

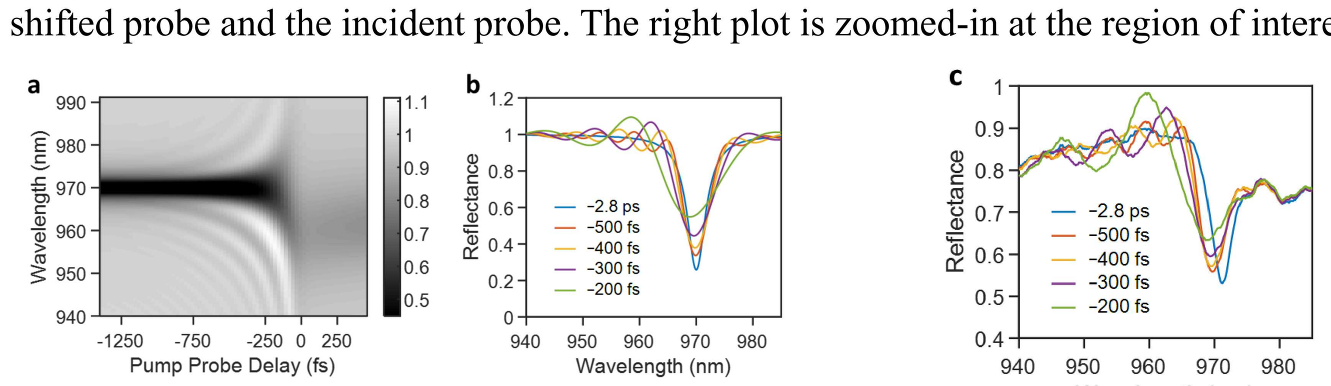
A,C,E) Transient analysis of the modes
B,D,F) Spectra of the reflected cavity mode from CMT

The observed fringes are independent of the relative pump-probe polarization.

Frequency Conversion Results



Experimental transient reflectance spectra as a function of pump-probe time delay. The fringes in the spectra between -1 and 0 ps are due to interference between the blue-shifted probe and the incident probe. The right plot is zoomed-in at the region of interest.



a & b show CMT spectra, with b showing various time delays from a. Right shows experimental spectra from the above experimental maps. The observed fringes are a result of interference between the blue-shifted probe and the incident probe.

Coupled Mode Theory

Time Dependent CMT

- The dynamics of the system are well described by a dynamic coupled-mode theory.
- In this analysis we modify standard coupled mode theory for a single-mode metasurface to include a time dependent central frequency and quality factor (loss).

$$\dot{a}(t) + i\omega(t)a(t) + [\gamma_r + \gamma_{nr}(t)]a(t) = \sqrt{\gamma_r}s_1^+(t),$$

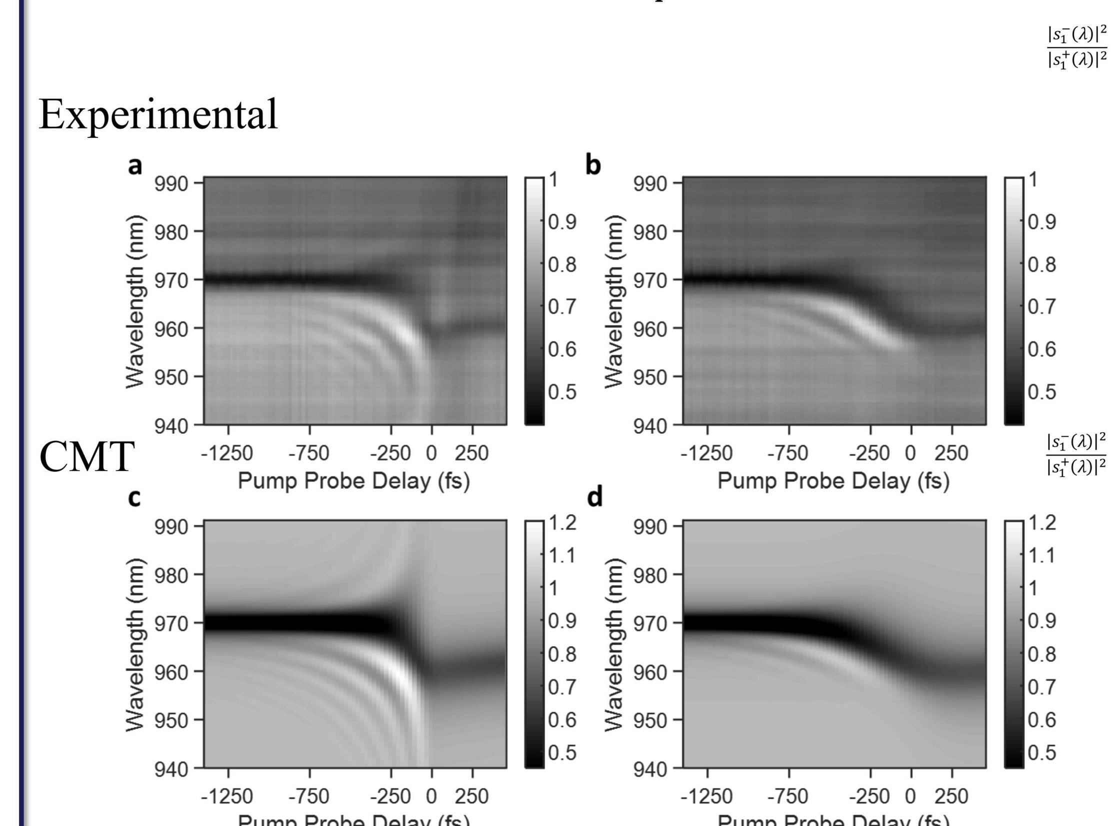
$$s_1^-(t) = s_1^+(t) - \sqrt{\gamma_r}a(t)$$

$$\omega(t) = \omega_0 + \left[\frac{N(t)}{N_{\max}}\right]\Delta\omega,$$

$$\gamma_{\text{nr}}(t) = \gamma_{\text{nr},0} + \left[\frac{N(t)}{N_{\max}}\right]\Delta\gamma_{\text{nr}},$$

$$N(t) = N_{\max}\frac{1 + \text{Erf}[(t-\tau)/\tau_{\text{pump}}]}{2},$$

$a(t)$ – complex mode amplitude,
$\omega(t)$ – mode center frequency,
$\gamma(t)$ – mode damping,
$N(t)$ – carrier concentration, note: $|\Delta n| \propto N(t)$,
$s_1^+(t) = s_0 \exp(-i\omega_0 t - t^2/\tau_{\text{probe}}^2)$ – incident broadband probe.



Experimental vs CMT for two different pump pulse durations, pump fluence = 185 μJ cm^{-2}

Top τ_{pump} = 400 fs, Bottom τ_{pump} = 80 fs.

Shorter pump pulses result in greater $|\Delta n|/\Delta t$ which increases the frequency conversion.

Greater pump fluence also increases $|\Delta n|/\Delta t$ and improves frequency conversion.

Conclusion & Outlook

- We have demonstrated a dielectric time-variant metasurface that exhibits linear frequency conversion at NIR wavelengths.
- The frequency conversion is a result of the probe photons experiencing an ultrafast shift in the refractive index of the GaAs resonator. The quality factor of the resonator must be sufficiently high to observe this effect, here we achieve this by breaking the resonator symmetry.
- The frequency conversion is not based on a material nonlinearity and thus may be observed at low pump and probe fluence.
- The low required pump fluence (<150 μJ cm^{-2}) is also due to the use of direct-gap semiconductors having high linear absorption at 800 nm.
- The observed results indicate that frequency conversion metasurfaces are a novel time-variant nonlinear platform that could be applied towards various applications in ultrafast photonics.

References:
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