

Probing Ultrafast Transient Electric and Magnetic Fields in Silicon Metasurfaces

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Abstract: We conduct ultrafast broadband spectroscopy on an all-dielectric Si metasurface to understand how their nanoscale transient electric and magnetic fields modify dynamically the overall optical resonance response of our system.

1. Introduction

Manipulating electromagnetic fields at the nanoscale has gained significant interest in the last decade as they can enhance device efficiency in the energy, telecommunication and medical sectors. Both plasmonic and all-dielectric metasurfaces can be used for controlling light at the nanometer length and femtosecond time scales. However, the dielectric metasurfaces have shown more versatility over their metallic counterparts in controlling light thanks to their low loss^[1] and simpler geometric structure. Silicon has been the main choice of dielectric material because of its high refractive index in the visible and since it forms the backbone of microelectronics and on-chip photonics. Moreover, its indirect bandgap allows for low absorption losses while generating strong nanoscale electric and magnetic fields thanks to its Mie resonances^[2]. In addition, silicon's high third-order susceptibility^[2] provide strong nonlinear properties^[3] and it has been recently demonstrated that Si nanodisks can exhibit strong third harmonic generation^[4-6].

While much studies have focused on the linear optical properties of either single dielectric nanostructure or in a two-dimensional lattice configuration, also referred to as metasurfaces, here we compare the linear properties of large-size array ($1 \times 1 \text{ mm}^2$) of silicon nanodisks to their femtosecond optical properties. Using three-dimensional full-field finite-difference time-domain electromagnetic simulations, coupled to a population model, we provide an understanding of the physical origins of these complex, transient resonances.

2. Discussion of Fabrication and Experimental Results

We fabricated the $1 \times 1 \text{ mm}^2$ Si nanodisk array, each of diameter around 160 nm and height of 230 nm with period of 1000 nm using electron-beam lithography (EBL) technique. First, we spin-coated a glass substrate with poly methyl methacrylate (PMMA) in anisole and annealed at 180°C for 3 minutes. EBL was then performed at an accelerating voltage of 100 kV at the working distance of 10 mm. After development, silicon was deposited by thermal deposition using electron-beam evaporation to a thickness of around 230 nm. After the silicon was deposited, the PMMA film was removed via standard liftoff procedure.

We then performed the linear extinction spectroscopy on the sample using a home-built Kohler-illumination microscopy setup. For ultrafast transient absorption spectroscopy, we pump our sample at a wavelength of 900 nm and probe the metasurface response using a white-light broadband supercontinuum (Fig. 1a). We observe that there is strong resonance near 680 nm that broadens and last for few 100s of picoseconds while the two other resonances in the near-infrared (at 720 nm and 780 nm) are short lived (< 10 ps). To understand the complex dynamics of these resonances, we plot the spectral slices at specific time delays (1 ps, 100 ps and 1 ns) and compare those spectra to the extinction (linear) measurement as shown in figures 1(b) and 1(c), respectively. We can see the close match of the

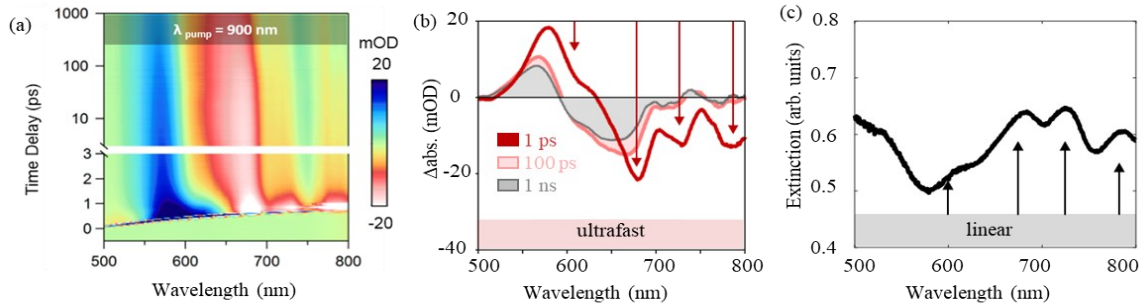


Fig. 1. (a) Ultrafast broadband measurement of Si nanodisk arrays excited at wavelength of 900 nm; (b) Ultrafast snapshots at 1ps, 100 ps and 1 ns of Si nanodisks; (c) Linear extinction result of Si nanodisks.

resonances between linear and ultrafast measurements for our Si metasurface. In the ultrafast data, we see spectral blueshift of about 10 nm for all the resonances. From our dynamical modelling, these blueshifts are caused by lattice heating due to a change in the thermo-optic coefficient. Simulations were done using finite-difference time-domain (FDTD) technique using Lumerical Solutions® for silicon metasurfaces, with comparable refractive index and similar nanodisk structural parameters. The extinction spectra computed for our simulated structures showed a similar optical response as linear extinction graph.

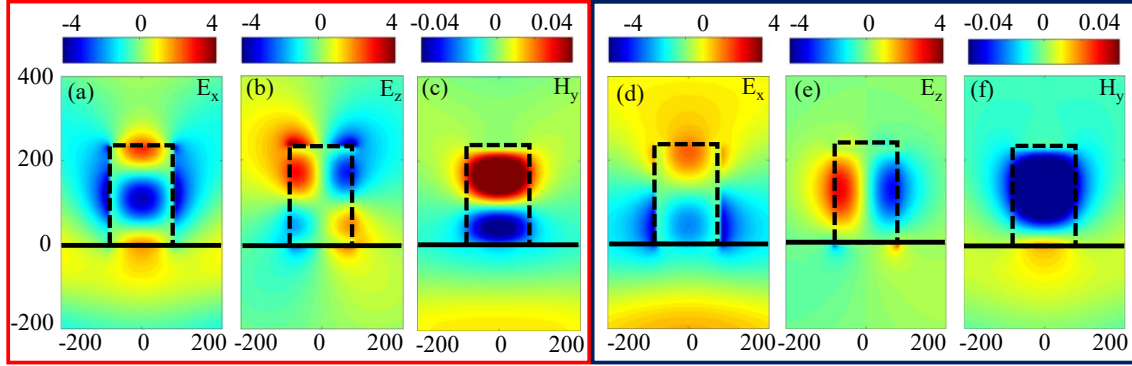


Fig. 2. Electric and magnetic field in the silicon nanodisks. The red box (left) represents the resonance at 680 nm and the blue box (right) represents the resonance at 780 nm. Scale in x- and y-axis are in nanometers.

To understand the origins of these resonances, we plot cross-sectional maps of electric fields when light (x -polarized and propagating in z -direction) was incident from the top of the nanodisk as seen in Fig. 2(a, b) for the resonance near the experimental 680 nm and Fig. 2(d, e) for the resonance near the experimental 780 nm. Similarly, plots of the magnetic fields are shown in figure 2(c) for 680 nm and 2(f) for 780 nm resonances respectively. From these plots, we infer that the resonance at 680 nm is an electric dipole and the one at 780 nm is a magnetic dipole. We note that when simulations are conducted for a single nanodisk, when compared to the metasurface, the resonance at 720 nm can only be seen for the latter, thus suggesting a resonance arising from the metasurface periodicity.

3. Conclusions

We have fabricated a Si metasurface on transparent glass substrate with disk diameter size of 160 nm to understand their ultrafast optical properties. Furthermore, we have demonstrated that the arrays have complex linear spectral signatures that match their corresponding ultrafast ones. Critically, we found that for certain resonances, electric or magnetic, there are significant optical modulation within the first 100 ps which could allow the separation of the electric and magnetic near-field modes at nanometer spatial resolution and sub-picosecond timescales.

4. References and Acknowledgments

- [1] Khurgin JB, Sun G. "Practicality of compensating the loss in the plasmonic waveguides using semiconductor gain medium", *Applied Physics Letters* **100**, 011105 (2012).
- [2] Shcherbakov MR, Liu S, Zubyuk VV, Vaskin A, Vabishchevich PP, Keeler G, et al. "Ultrafast all-optical tuning of direct-gap semiconductor metasurfaces", *Nature Communications* **8**, 17 (2017).
- [3] Shcherbakov MR, Shorokhov AS, Neshev DN, Hopkins B, Staude I, Melik-Gaykazyan EV, et al. "Nonlinear Interference and Tailorable Third-Harmonic Generation from Dielectric Oligomers", *ACS Photonics* **2**, 578-82 (2015).
- [4] Liu S, Sinclair MB, Saravi S, Keeler GA, Yang Y, Reno J, et al. "Resonantly Enhanced Second-Harmonic Generation Using III-V Semiconductor All-Dielectric Metasurfaces", *Nano Letters* **16**, 5426-32 (2016).
- [5] Shorokhov AS, Melik-Gaykazyan EV, Smirnova DA, Hopkins B, Chong KE, Choi D-Y, et al. "Multifold Enhancement of Third-Harmonic Generation in Dielectric Nanoparticles Driven by Magnetic Fano Resonances", *Nano Letters* **16**, 4857-61 (2016).
- [6] Shcherbakov MR, Neshev DN, Hopkins B, Shorokhov AS, Staude I, Melik-Gaykazyan EV, et al. "Enhanced Third-Harmonic Generation in Silicon Nanoparticles Driven by Magnetic Response", *Nano Letters* **14**, 6488-92 (2014).

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