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Dielectric metasurfaces with high-Q toroidal resonances

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Abstract: Toroidal dielectric metasurface with a Q-factor of 728 in 1500 nm wavelength are reported. The resonance couples strongly to the environment, as demonstrated with a refractometric sensing experiment.

1. Introduction

Toroidal moment is an electromagnetic excitation that is independent from the familiar electric and magnetic multipole moments. It recently started to gain attention in the field of nanophotonics and metamaterials, for its ability to efficiently confine and enhance the electromagnetic energy within a resonator. Among extensive studies on the toroidal resonances in metamaterials and nano-resonators, high Q-factor toroidal resonances are so far experimentally demonstrated only in a very limited set of geometries and wavelengths. [1–3] Especially, dielectric metasurface configuration in visible and near-infrared wavelengths will open vast possibilities in nonlinear optics and strong light-matter interaction studies.

In this work we demonstrate a dielectric metasurface that supports a high Q-factor toroidal resonance in near-infrared wavelengths. Nano-cuboids are chosen to efficiently support the toroidal mode and to maximize the inter-resonator coupling, to achieve a high-Q resonance. Also, thanks to the hole in the middle, the toroidal resonance in cuboids couples very efficiently to the environment, which is demonstrated in a refractometric sensing experiment. With the versatility and robustness that dielectric metasurface configuration provides, the toroidal resonances are expected to be a powerful tool to investigate strong light-matter interaction and nonlinear phenomena at nanoscale.

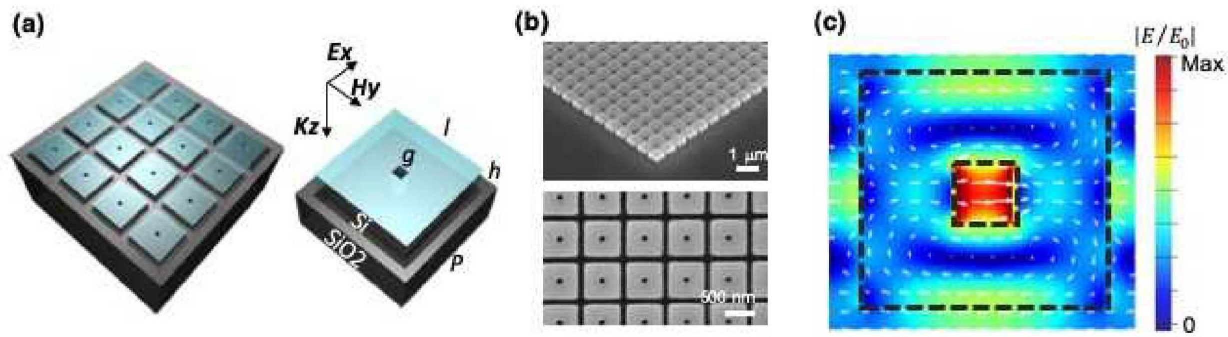

Fig. 1. Dielectric nano-cuboids for toroidal metasurfaces. (a) Schematics of the sample. (b) SEM images of the sample. (c) Simulated electric field profile at the toroidal resonance. Black dashed lines denote the boundary of the cuboid.

2. Results and discussions

We use an array of nano-cuboids for the metasurface geometry (Fig. 1(a)). The parameters are: P = 780 nm, l = 630 nm, g = 155 nm, and h = 300 nm. The samples are fabricated with electron beam lithography and dry-etch processes, starting from an amorphous silicon film on a quartz substrate (Fig. 1(b)). The cuboids support toroidal dipole

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moment in a similar way as a circular disk does, but with a stronger inter-resonator coupling and a strong electric field enhancement at the center hole (Fig. 1(c)).

The far-field spectrum and the near-field distribution of the metasurface is simulated with a commercial finite-difference time-domain solver (Lumerical). In the simulated spectrum of Fig. 2(a), two sharp resonances are visible – the one at 1280 nm is a magnetic dipole resonance, and the one at 1500 nm is a toroidal dipole resonance, whose near field profile is shown in Fig. 1(c). The measurements match the calculation excellently, and shows a linewidth of 2.01 nm and a Q-factor of 728, which is among the highest value reported in dielectric metasurfaces in near-infrared. [4]

The hole in the middle incorporates a strong electric field enhancement and also allows a direct interfacing of the toroidal mode with an external system. This will be useful in realizing strong light-matter interaction, especially with the strongly dipolar field within the hole. As a proof-of-concept demonstration, we perform refractometric sensing with the sample, using methanol (n=1.319), ethanol (n=1.352) and isopropanol (n=1.368). As shown in Fig. 2(c), the sensing is very efficient with a sensitivity of 161.5 nm/RIU and a figure of merit $FOM = S/\Delta f = 78$, where S is the sensitivity and Δf is the linewidth of the resonance.

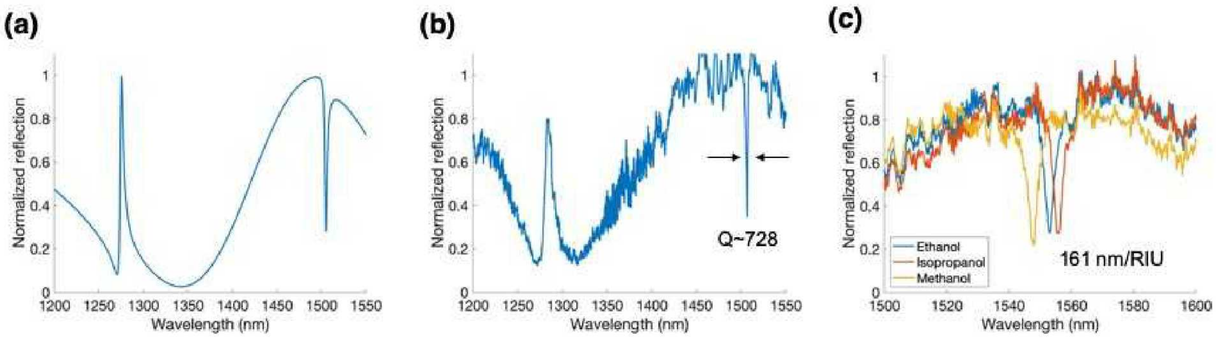

Fig. 2. (a) Simulated and (b) measured reflection spectra of the metasurface. (c) Refractometric sensing experiment.

3. Conclusion

We have experimentally realized a toroidal resonance in near-infrared from a metasurface of nano-cuboids. The resonance shows a very large Q-factor, which is an outcome of the interplay between the inherently weak scattering intensity of toroidal dipole moment, and the low fabrication threshold of the structure compared to other asymmetry-based high-Q resonators. Also, the middle hole of the cuboid incorporates a strong field enhancement, coupling sensitively to the environment. Upon integration with quantum systems, the metasurface is expected to open a new venue in nonlinear optics and strong light-matter interaction studies.

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