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High quality factor anapole resonance in dielectric metasurfaces

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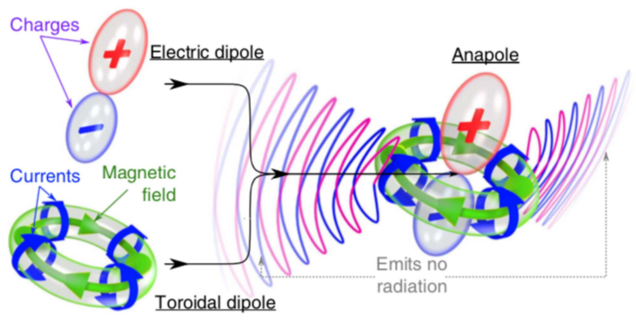
Abstract

Anapole is a non-radiating source realized by destructive interference of electric and toroidal dipole radiation, with its origin in nuclear physics. Recently it started to gain attention in the field of nanophotonics for its superior ability to confine and enhance the electromagnetic energy within a resonator. Yet, non-radiative nature of the anapole mode has so far constrained most of the experimental studies to the near field regime, especially at visible and near-infrared wavelengths. Here, we report a high quality factor anapole resonance in visible and near-infrared frequencies, realized in dielectric nanocubiods metasurfaces. Coupling between resonators are maximized due to the rectangular shape of the resonator and the metasurface configuration, resulting in a high quality factor resonance delocalized over a wide area of resonators. We experimentally observe Q-factors of 500 and 160 at near-infrared and visible frequencies, by using silicon (n=3.6) and titanium oxide (n=2.3) as the dielectric, respectively. Numerical simulations indicate that the hole in the middle cause the field to be enhanced by a factor of ~20 at the resonance, which would be ideal for refractometric sensing or strong light-matter interaction.

Anapole – a new class of non-radiating sources

Anapole: toroidal dipole + electric dipole

- Far-field radiation patterns of an electric dipole and a toroidal dipole are identical, perfectly cancelling each other when the two dipoles overlap (image from [1]).



- The anapole mode can be most conveniently described with multipole decomposition. [2]

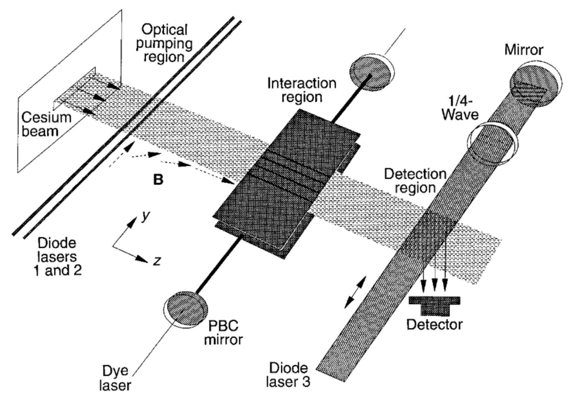
$$p = \frac{1}{-i\omega}\int J(r)dr$$

$$m = \frac{1}{2c}\int r\times J(r)dr$$

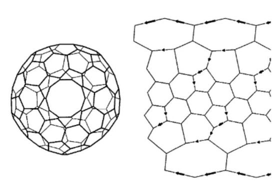
$$t = \frac{1}{10c}\int [(r\cdot J(r))r - 2r^2 J(r)]dr$$

$$C^p_{sca} = \frac{k^4}{6\pi}|p|^2, \quad C^t_{sca} = \frac{k^6}{6\pi}\left|t + \frac{k^2}{10}R_t^2\right|$$

Anapoles in nature



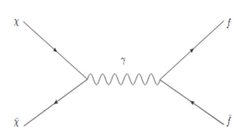
- Parity non-conserving transition requires a toroidal dipole moment, which was measured in 6S→7S transition of cesium. [3]



- Some molecules with toroidal symmetry support static anapoles. [4]

	$\vec{\sigma}$	$\vec{E}$	$\vec{B}$	$\vec{J}$
C	+	−	−	−
P	+	−	+	−
T	−	+	−	−
CPT	−	+	+	−

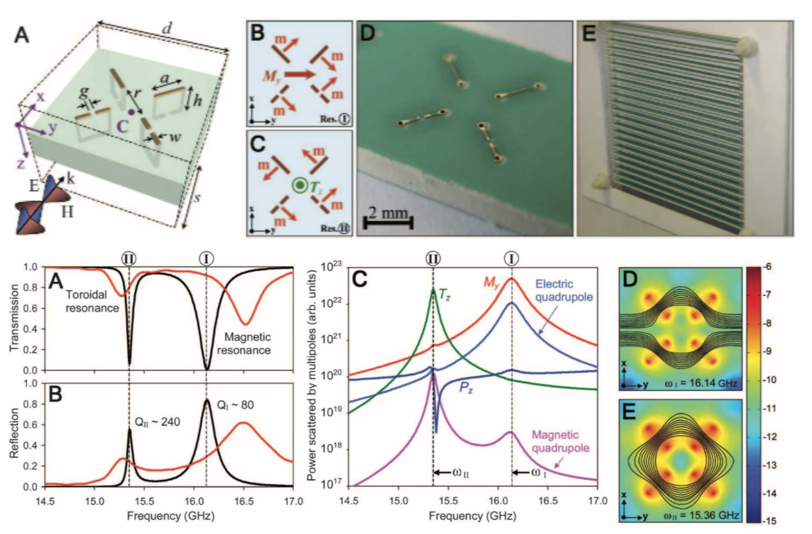
$$\mathcal{H}_I = -\frac{g}{\Lambda^2}\vec{\sigma}\cdot\vec{J}$$



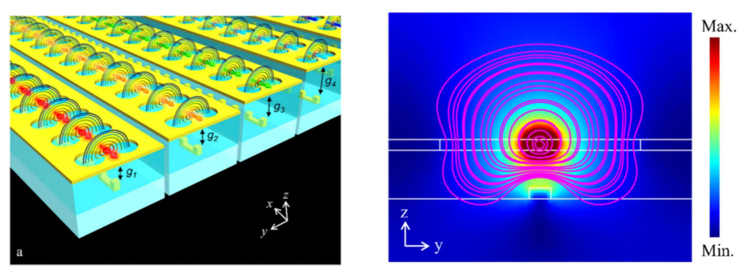
- Anapole is the only allowed electromagnetic form factor of Majorana fermions, which might relate to the dark matter. [5]

Anapoles in photonics

Anapole moments in metallic metamaterials

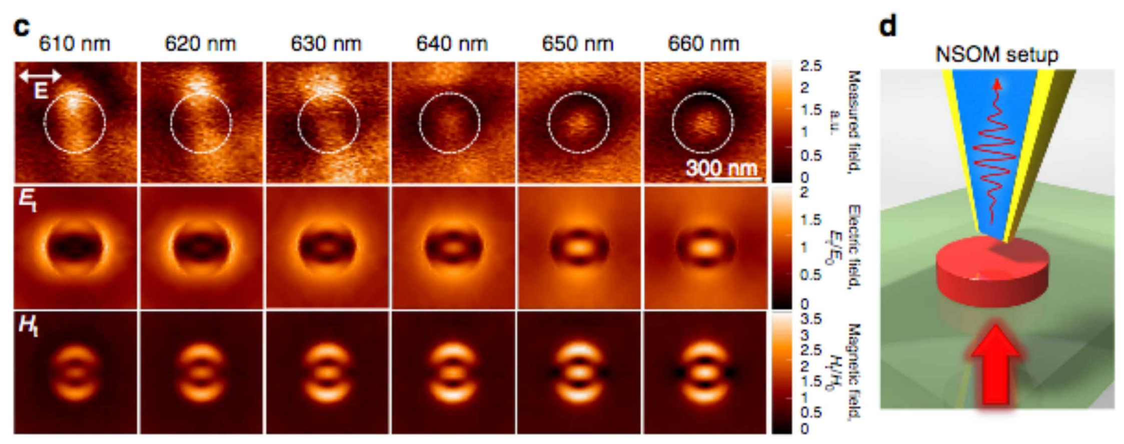


- The first realization of toroidal dipole excitations in photonics was made at microwave frequencies. [6]

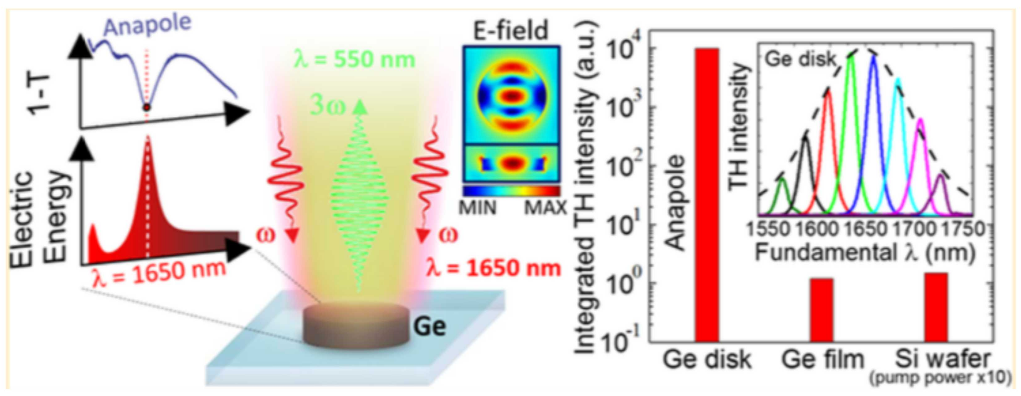


- Hybrid aperture-split ring resonator supports anapole mode at near-infrared (IR) wavelengths. [7]

Anapoles in a single dielectric disk



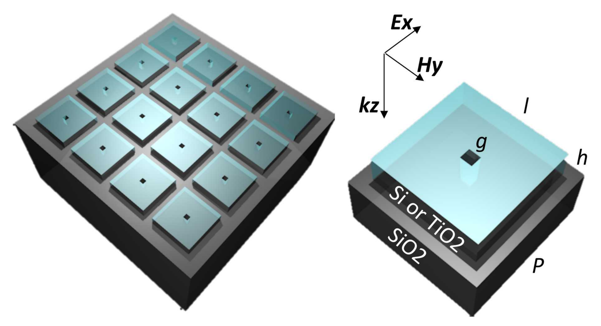
- Near-field measurement of anapole field profile was made on a silicon nanodisk at visible wavelengths. [8]



- The highly concentrated electric energy at anapole resonance can be beneficial in enhancing third harmonic generation. [9]

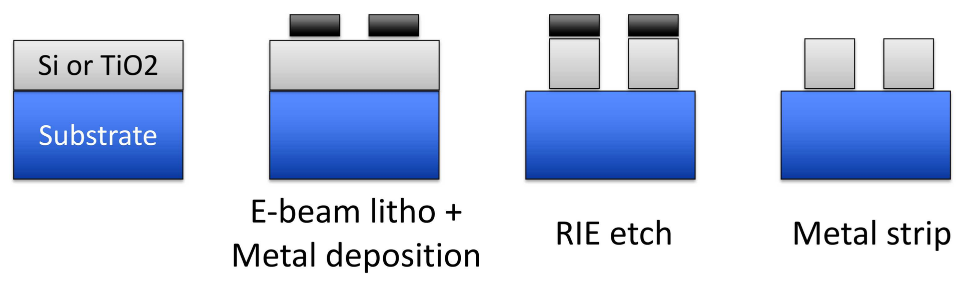
Result – high-Q anapole resonances in visible & near-IR

Dielectric nanocuboid metasurfaces for anapole resonance

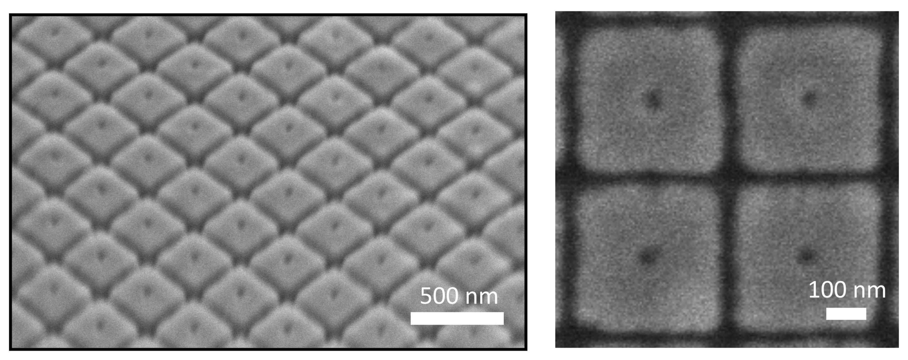


Near-IR	Visible
Si (n = 3.6)	TiO2 (n = 2.3)
P = 780 nm,	P = 450 nm,
l = 630 nm,	l = 400 nm,
g = 140 nm,	g = 35 nm,
h = 300 nm	h = 100 nm

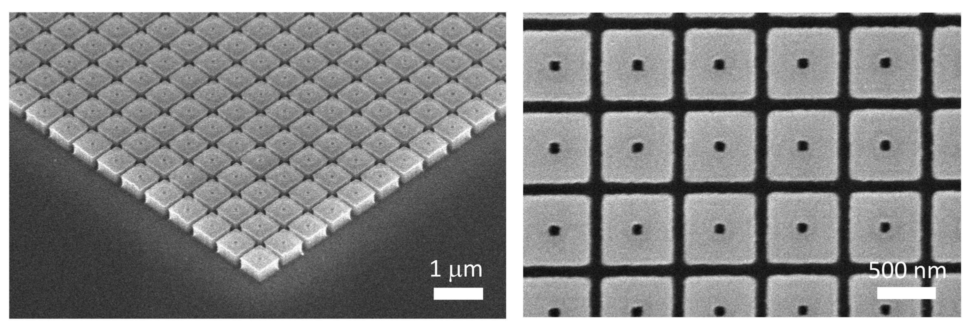
Sample fabrication



Sample images (TiO2)

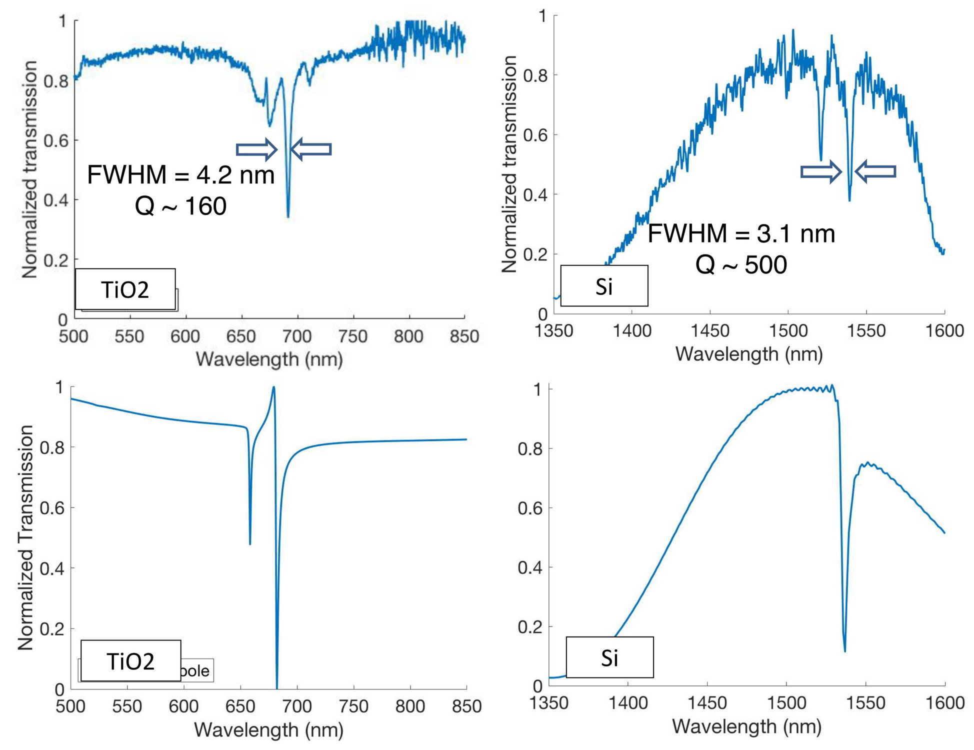


Sample images (Si)



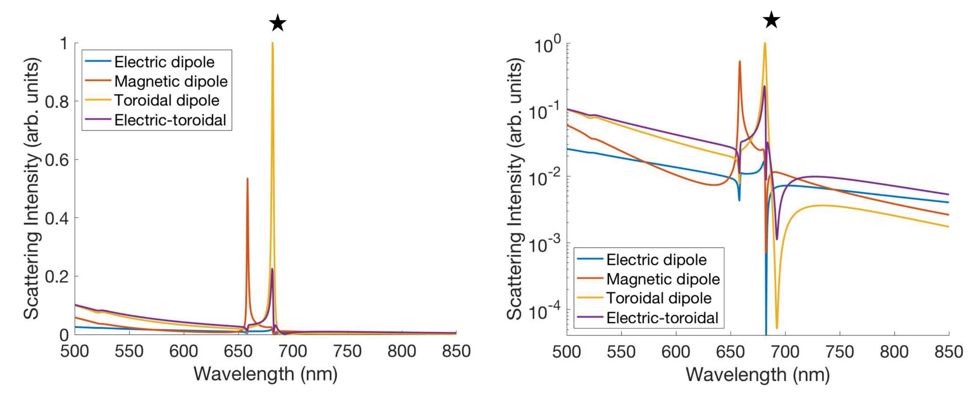
- Feature sizes down to ~35 nm is successfully realized.

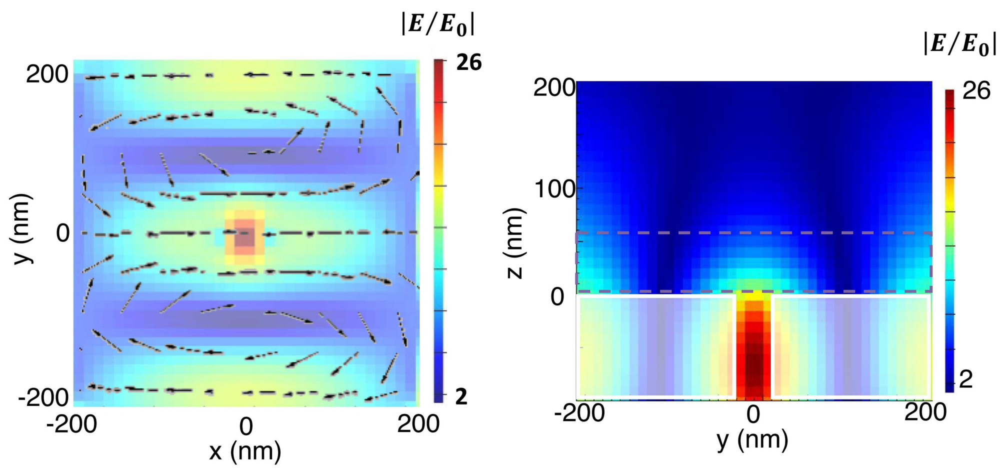
Measurements w/ Calculations



- The additional dip in Si measurement is possibly due to asymmetry in the structure.

Simulations and multipole decomposition (TiO2)





- Strong toroidal response and field enhancement at/on the gap is observed.

Conclusion and outlook

- With dielectric metasurfaces of nanocuboids, high quality factor anapole resonance could be achieved at visible and near-IR.
- Dielectrics with a relatively low refractive index (n < 2.5) are also capable of supporting the anapole, with a well-designed structure and good fabrication.
- The large field enhancement at the gap, together with the high quality factor, is expected to be beneficial in strong light-matter interactions, refractometric sensing and nonlinear phenomena.

References

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