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Dielectric Metasurfaces with High-Q Toroidal Resonances

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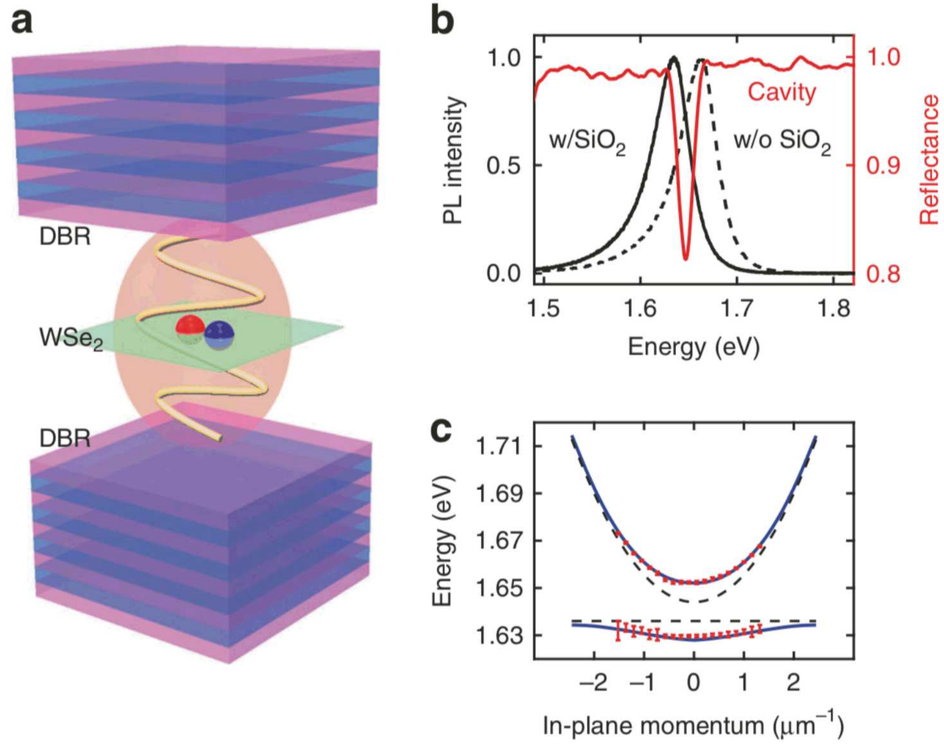
Dielectric Metasurfaces for High-Q Resonances

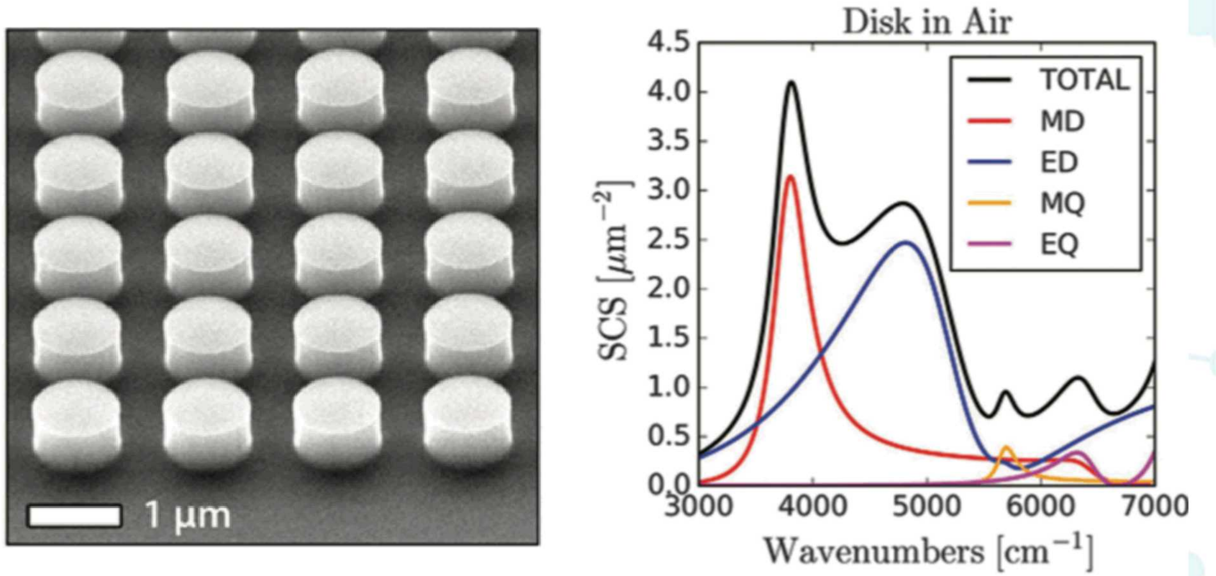
* Higher Q-factor = Strong light-matter interaction

* High-Q resonances in bulky conventional cavities



L. Qiu et al., Nature Commun. 10, 1513 (2019)

* A compact, flexible alternative: dielectric metasurfaces

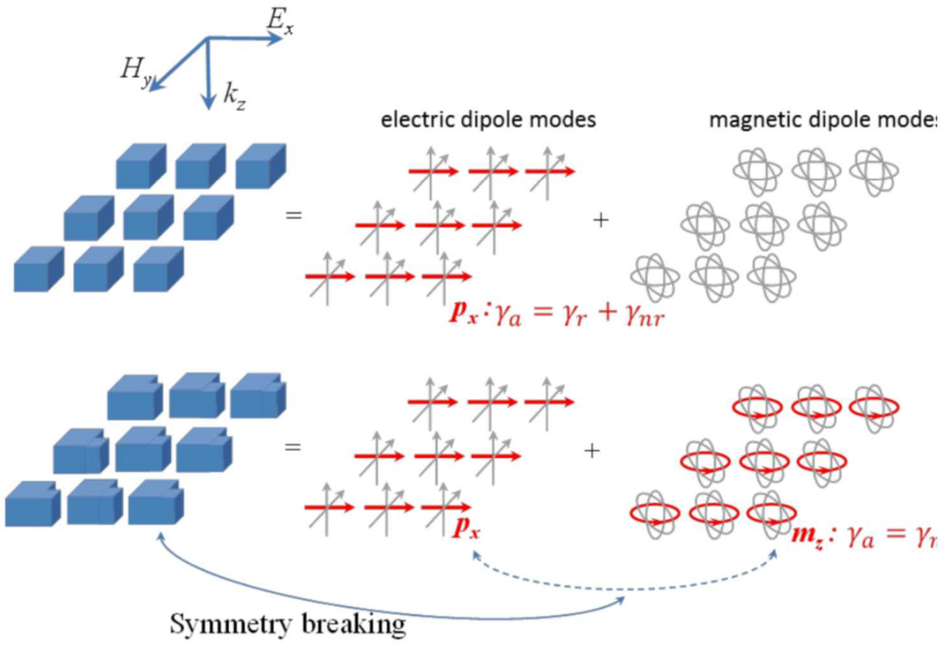


B. Sain et al., Advanced Photonics 1, 024002 (2019)

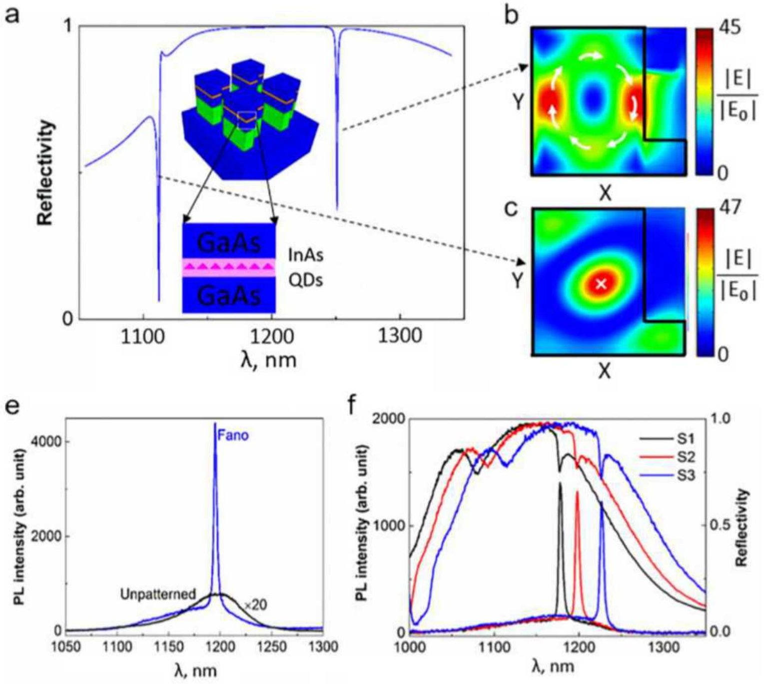
* How to overcome low Q-factors of Mie resonances in dielectric metasurfaces?

Dielectric Metasurfaces for High-Q Resonances

* How to achieve high-Q : start from non-radiating 'dark' mode, and then break the symmetry



S. Campione et al., ACS Photonics 3(12), 2362 (2016)



S. Liu et al., Nano Letters 18, 6906 (2018)

* High Q-factor requires a very small asymmetry

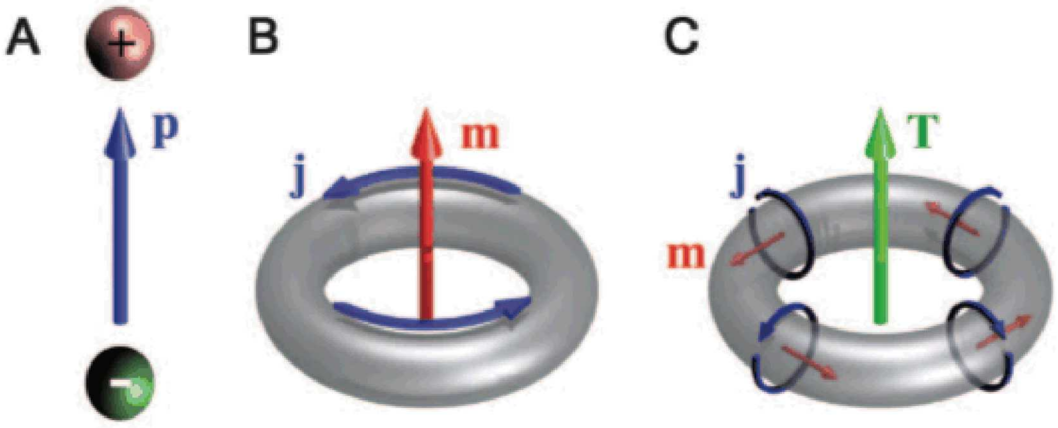
→ hard to fabricate samples

* Field is mostly confined inside, and is ill-defined outside the resonator

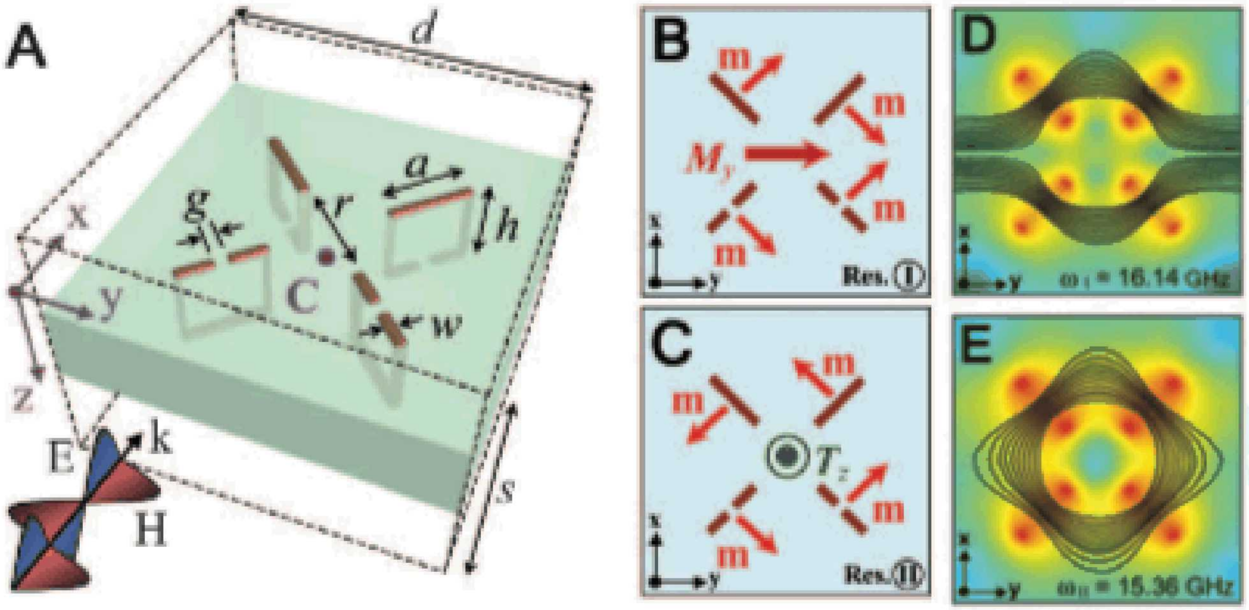
→ limited applications for light-matter interactions

Toroidal Resonances in Metamaterials

* Toroidal dipole: self-closing field profile → inherently weak free space coupling, well-suited for high-Q resonances



T. Kaelberer et al., Science 330, 1510 (2010)



* Toroidal dipoles are 3-dimensional distribution and generally requires complex 3-D structures to observe

* <u>2-dimensional dielectric metamaterials with high quality factor toroidal resonances?</u>

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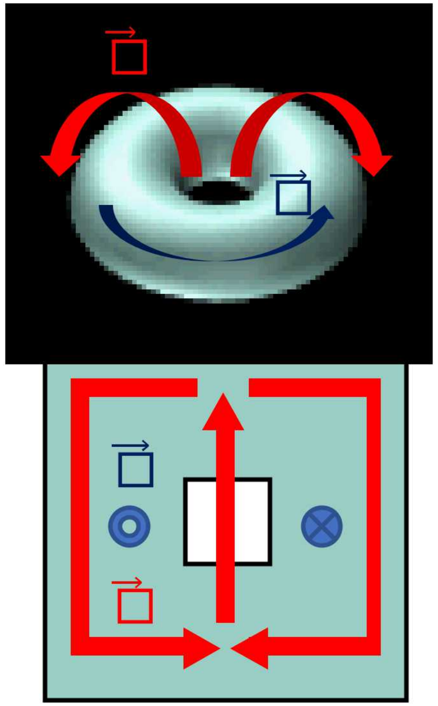
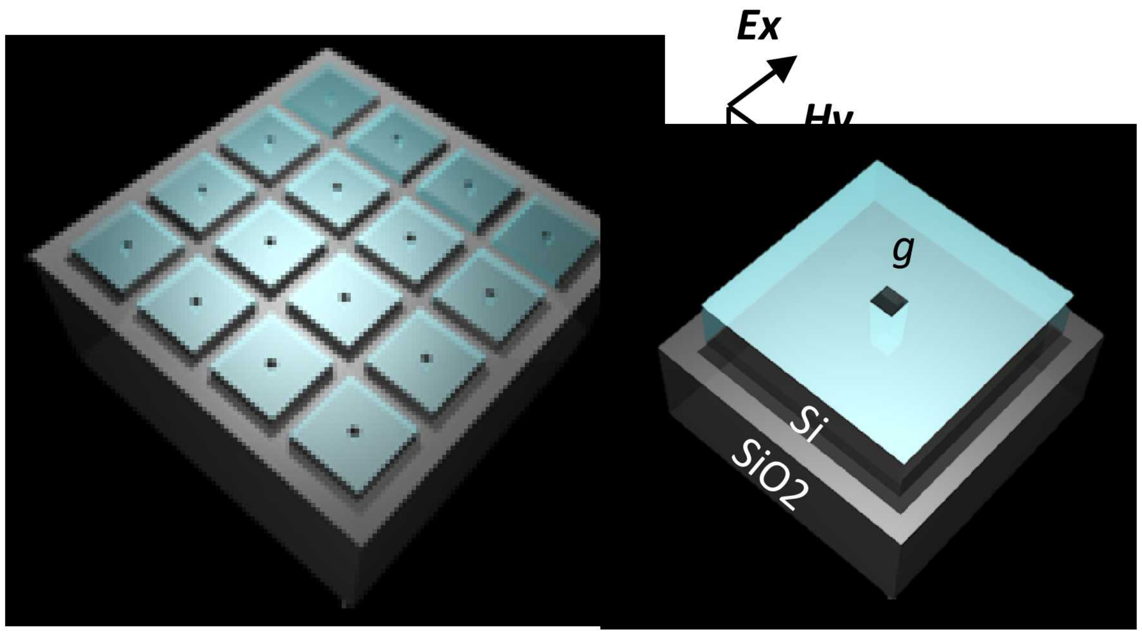
Dielectric Cuboid Arrays for High-Q Toroidal Resonances





Target λ: 1500 nm

Dielectric: Si (n=3.6)

P = 780 nm

l = 630 nm

g = 155 nm

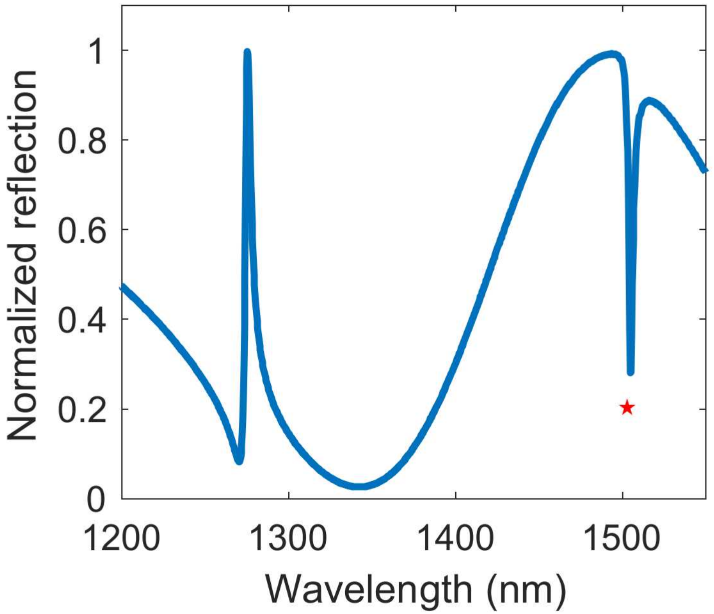
h = 300 nm

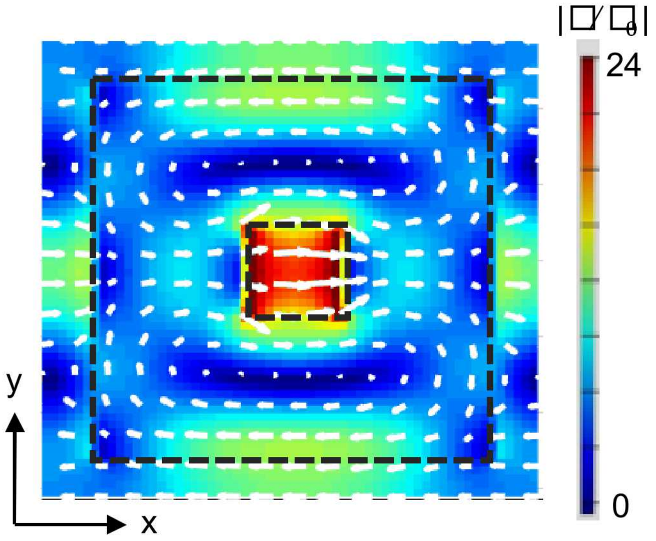
J. Algorri et al., Optics Express 27, 6320 (2019)

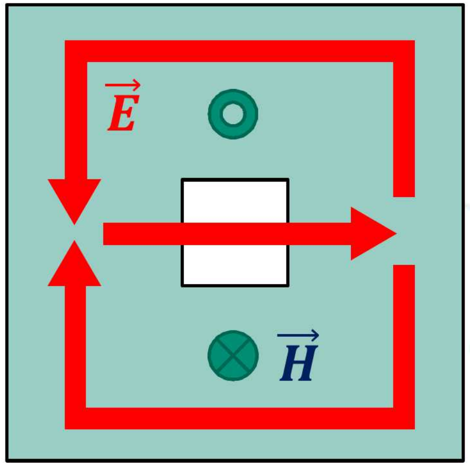
* High index of Si allow strong field confinement and enhancement

* Void in the middle allows a strong in-plane dipolar field to interact with the environment

Simulations and Multipole Decomposition Studies



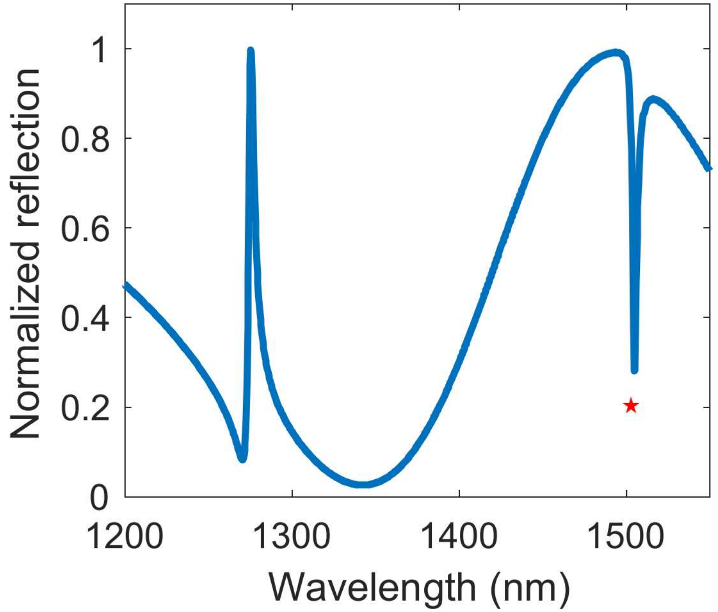


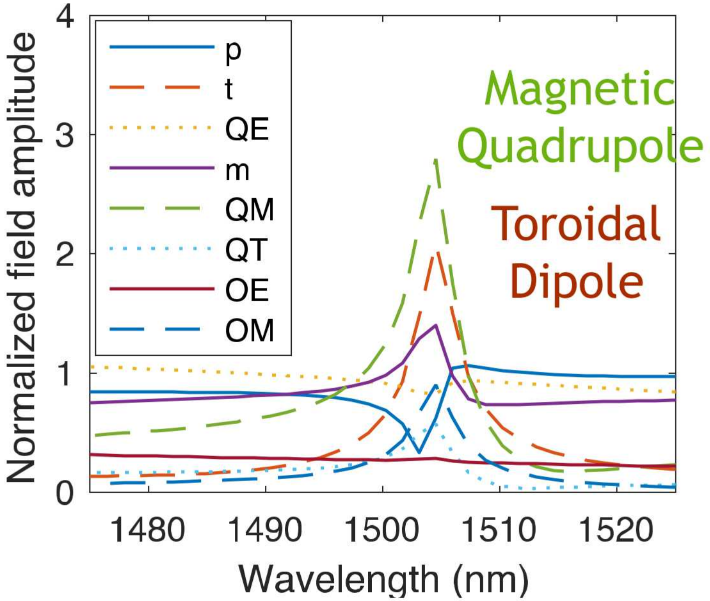


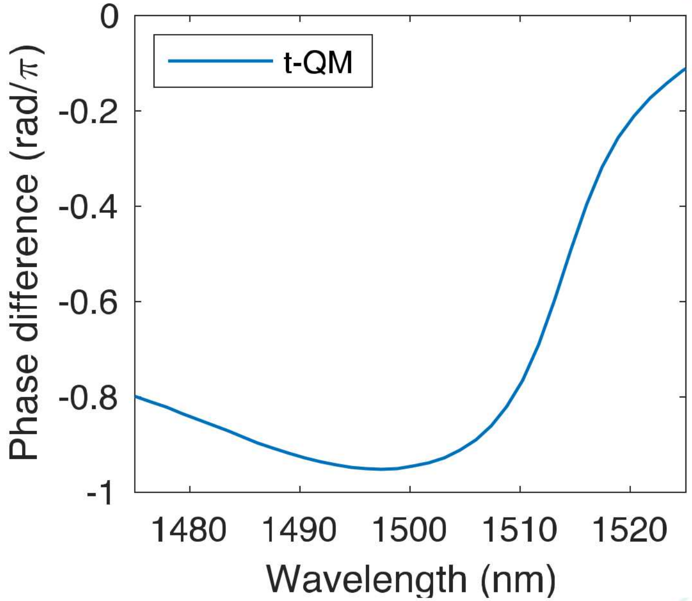
* High-Q resonance with toroidal electric field profile is observed near 1500 nm

* Center void incorporates a strong field enhancement with a well-defined, in-plane dipolar distribution, which should be ideal for coupling to quantum emitters

Simulations and Multipole Decomposition Studies





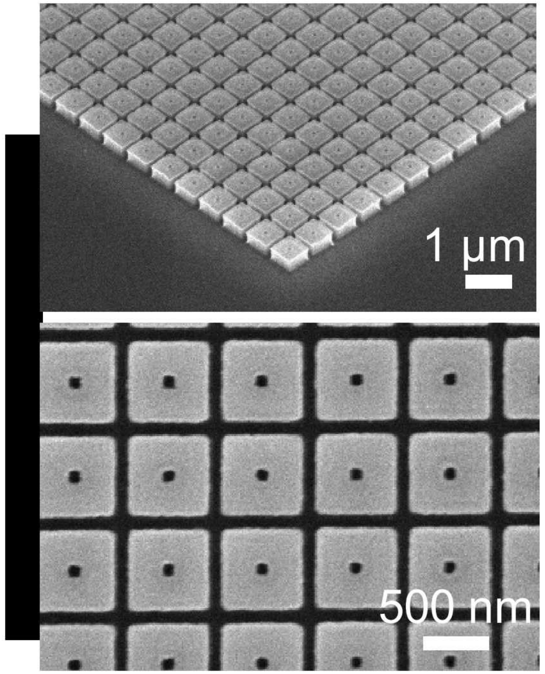


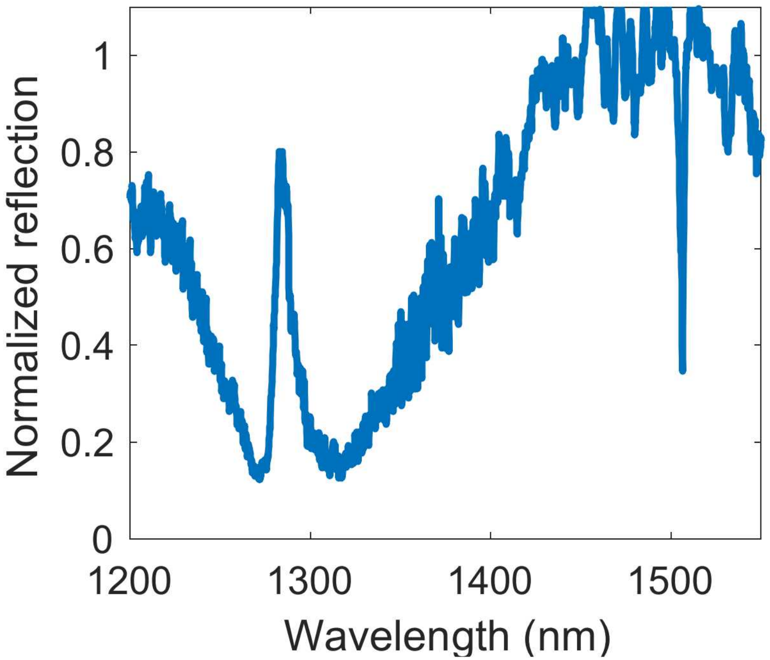
* Large magnetic quadrupole is a consequence of exciting the 3-D toroidal dipole in a 2-D geometry

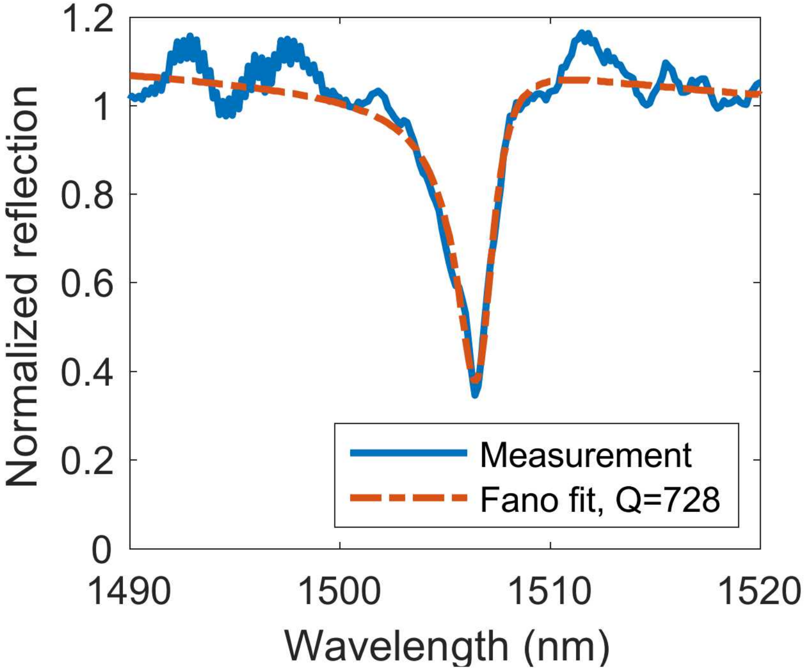
* The magnetic quadrupoles are expelled from the center of the resonance, such that toroidal dipole is still clearly visible in the field distribution

(more discussion on magnetic quadrupoles in A. Basharin et al., Phys. Rev. X 5, 011036 (2015))

Fabrication and Measurement





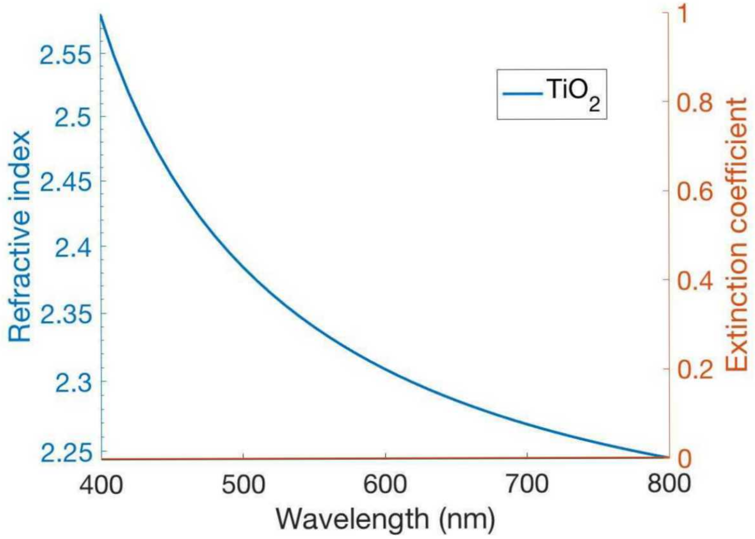


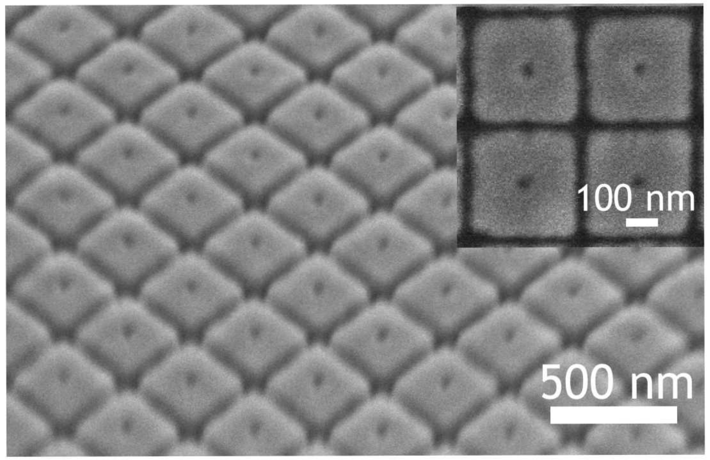
* Fabrication with standard top-down approach on poly-Si on quartz

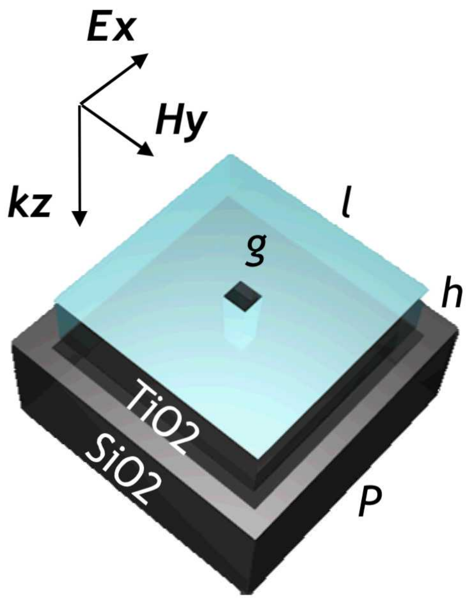
* Experimental Q-factor of 728 is observed

Broadband Application: Visible Wavelength Viable

* High index, low loss dielectrics are very limited in visible wavelengths → few high-Q dielectric metasurfaces







Target λ: 680 nm

P = 450 nm

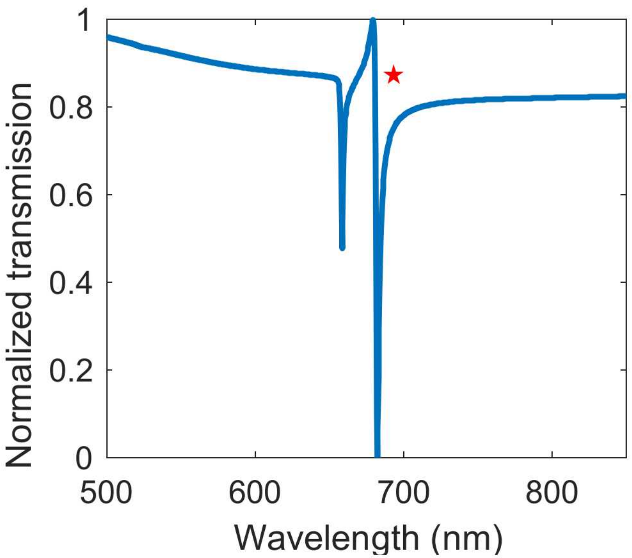
l = 400 nm

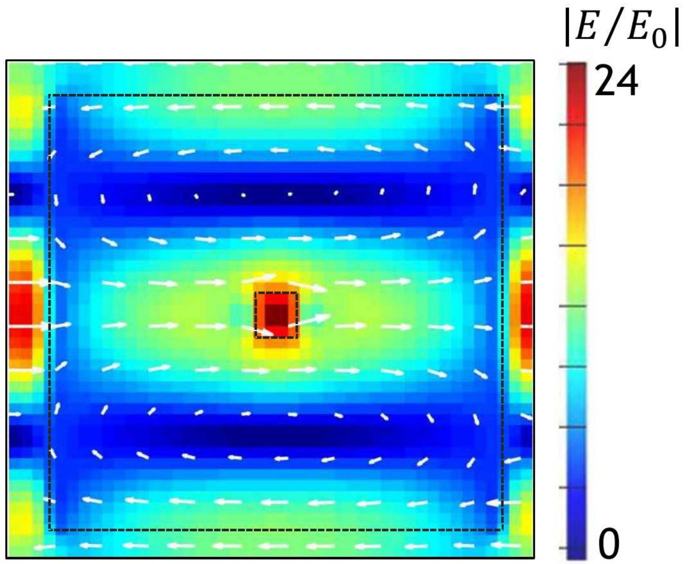
g = 35 nm

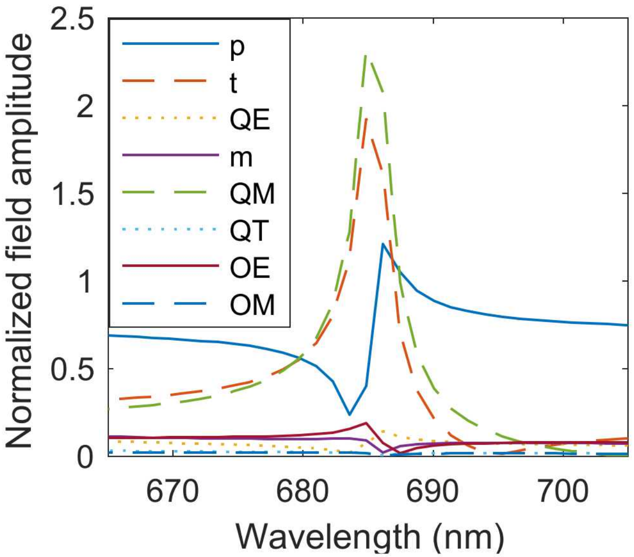
h = 100 nm

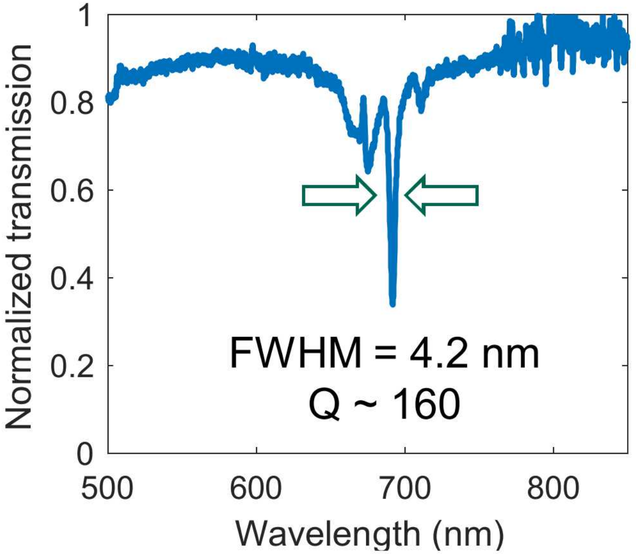
* Cuboids can support toroidal resonances even with dielectrics of a moderate index

Broadband Application: Visible Wavelength Viable









* Same physics can be observed in visible wavelengths

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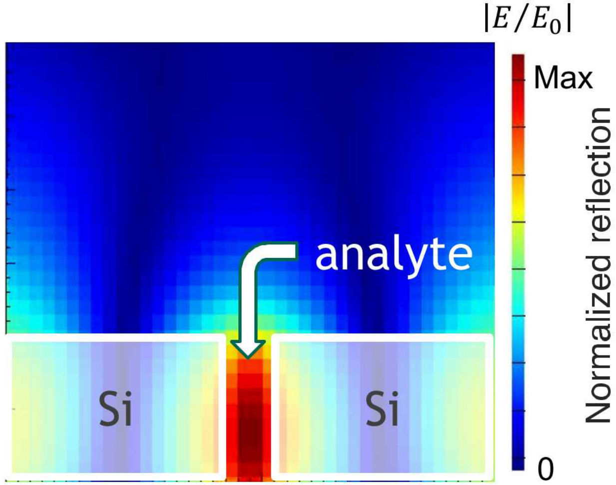
Application #1: Refractometric Sensing



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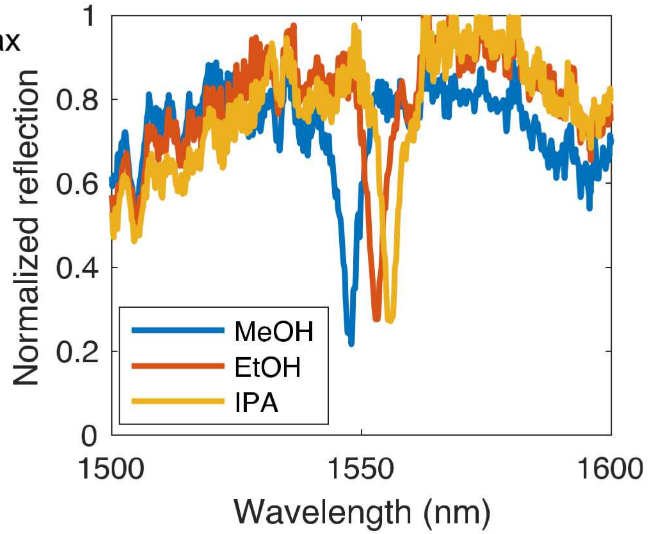
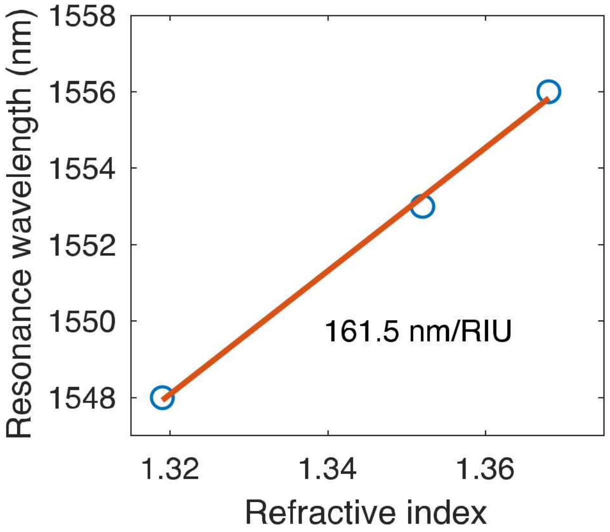
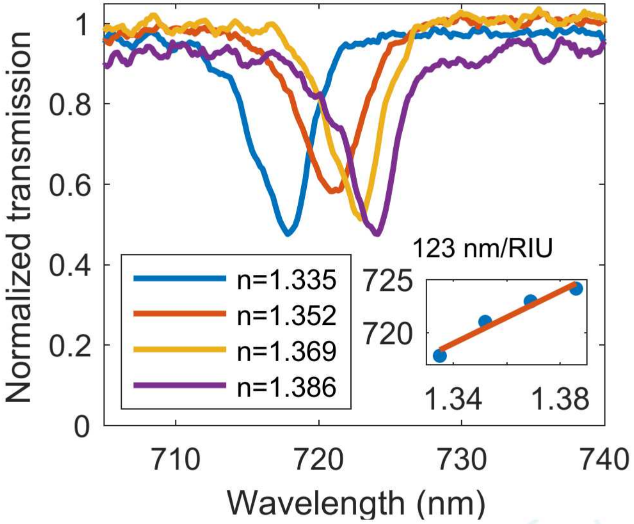




<Visible>



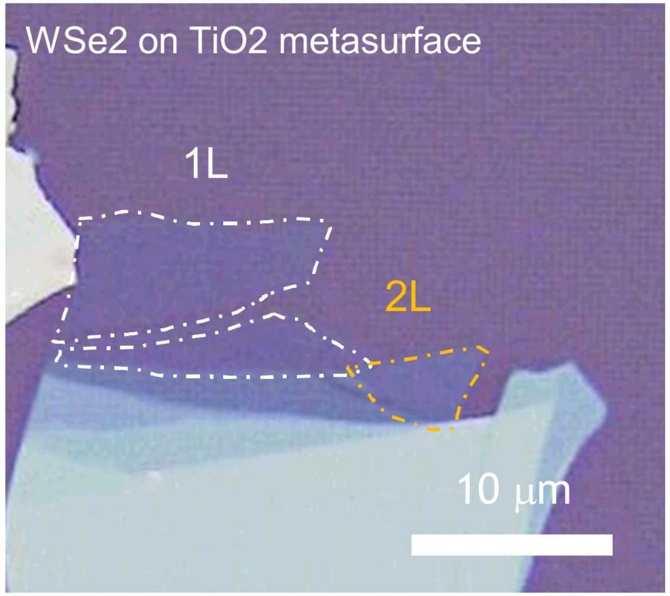
* Strong field enhancement at the void allows efficient refractometric sensing

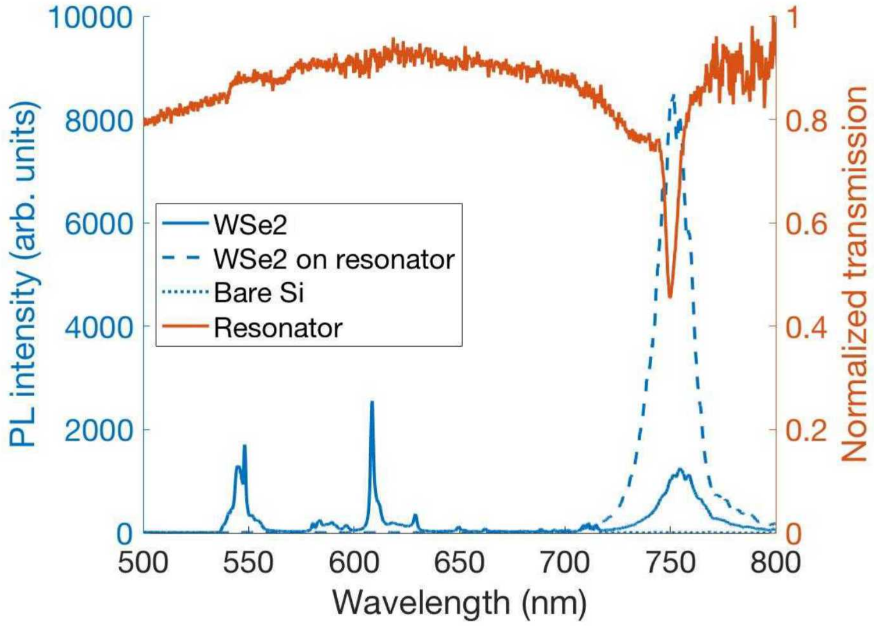
* State-of-the-art for dielectric metasurface (NIR): ~300 nm/RIU,[1] conventional Mie resonators: ~30 nm/RIU[2]

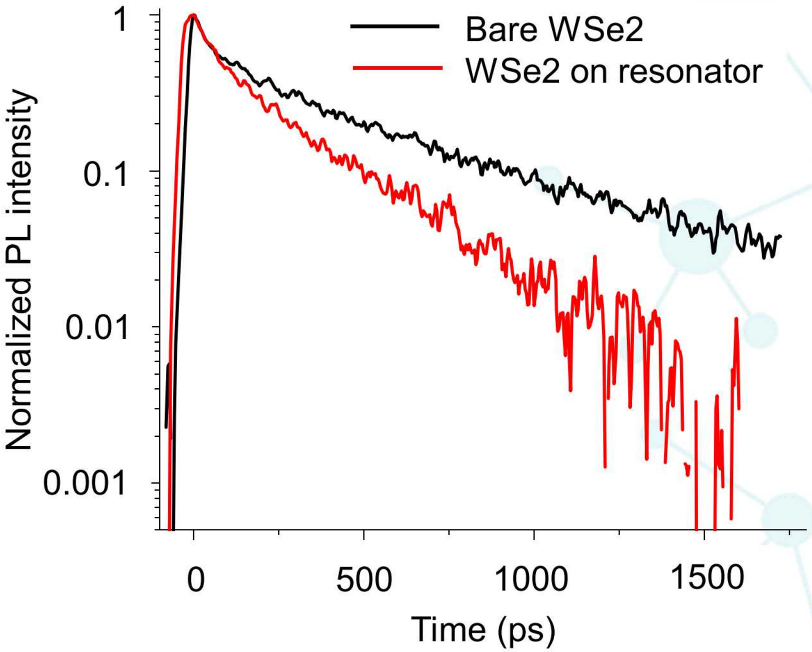
[1] Y. Yang et al., Nature Communications 5, 5753 (2014)

[2] N. Bosio et al., ACS Photonics 6, 1556 (2019)

Application #2: Coupling to 2-D Materials







* Toroidal metasurfaces can modify emission from 2-D materials placed atop via Purcell effect

Summary

* Dielectric metasurface with high Q-factor toroidal resonances are demonstrated in near-infrared and visible wavelengths.

* Cuboid arrays allow formation of high-Q toroidal resonance without very small gaps or precisely controlled asymmetry in the structure of the resonator.

* Center void allows a strong in-plane dipolar electric field to couple to free space, allowing an efficient refractometric sensing and a potential strong coupling to quantum emitters integrated onto the resonator.

Thank you!

Questions welcome: pajeong@sandia.gov

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