# Strong Field Enhancement with the Anapole Mode in Split Dielectric Nanocuboid Metasurfaces

Guanghou Sun,[1,3] Xuejin Zhang,[1,2,*] and Yongyuan Zhu[1,†]
[1]National Laboratory of Solid State Microstructures and Collaborative Innovation Center of Advanced Microstructures and Key Laboratory of Modern Acoustics and School of Physics, Nanjing University, Nanjing 210093, China
[2]College of Engineering and Applied Sciences, Nanjing University, Nanjing 210093, China
[3] School of Science, Jiujiang University, Jiujiang 332005, China
*Corresponding author: xuejinzh@nju.edu.cn
†Corresponding author: yyzhu@nju.edu.cn

***Abstract*—An all-dielectric metasurface composed of a split Si nanocuboid is proposed, in which high-Q resonances and strong near-field enhancements around and inside of dielectric nanostructures are achieved simultaneously with the anapole mode. The Q-factor is up to $4\times10^6$, and the enhancements of the electric and magnetic fields are enhanced to 1450 and 3560, respectively.**

***Keywords*—dielectric; anapole; strong field enhancement; metasurface;**

## I. INTRODUCTION

All-dielectric metasurfaces are currently the subject of intensive research since they can be tailored to produce a variety of optical behaviors. The large near-field enhancement can be obtained by exciting high-Q resonances in all-dielectric metasurfaces because of the suppressed radiative and nonradiative losses [1, 2], which have many fascinating applications in the fields of sensing, spectral filtering and nonlinear optics. Not long ago, the nonradiative anapole mode has been proposed and demonstrated with dielectric nanoparticles [3, 4], where the anapole modes results from the destructive interference of the toroidal and electric dipole moments in the far-field zone. The incident fields are usually confined in the dielectric resonators due to the Mie resonance properties of dielectric particles. This limits the use of dielectric metamaterials for applications in sensing, nonlinear optics and luminescence enhancement. By introducing split gaps, the near-field enhancements can be extended outside of the resonators at the expense of the Q-factor [1, 5]. However, it is hoped that high Q-factor and strong near-field enhancements outside of the nanoparticles are achieved simultaneously.

In this paper, we realize the anapole mode in split dielectric nanocuboid metasurfaces, which have more geometric freedom than disks and square pixel geometries. Furthermore, the Q-factor and near-field enhancements inside and outside of the structures are extremely enlarged using split nanocuboid metasurfaces. Our proposed split dielectric nanocuboid metasurfaces could be useful for many applications such as biosensing, nanolaser, narrow-band filter, and nonlinear optics.

## II. ANAPOLE MODE IN NANOCUBOID METASURFACES

We discuss the optical properties of the Si nanocuboid metasurface by an external plane wave. Figure. 1(a) shows the geometry of the unit cell characterized by the length L, width W and height H. The optical constants of Si are taken from the measured data [6], and the refractive index of the surrounding medium is supposed to be 1.46. This nanostructure is excited by a linearly polarized plane wave. The transmission spectrum is presented in Fig. 1(b) for $L$ = 560 nm, $W$ = 460 nm, $H$ = 270 nm, and the period $p$ = 650 nm. A Fano-like spectral feature is observed around 1493 nm as shown in Fig. 1(b). The near-field enhancements and the field vector distributions at the structural cross sections when the incident wavelength is at the Fano dip are represented in Fig. 1(c), which indicates that a toroidal dipole is exited. The multipolar decomposition in Fig. 1(d) demonstrates clearly the excitation of the anapole mode in the nanocuboid metasurface. The far-field scattering power of both the electric and the toroidal dipole moments have a similar intensity around 1493 nm. Their destructive interference results in the generation of the anapole mode, thereby forming the Fano-like lineshape in the spectrum [3, 4].

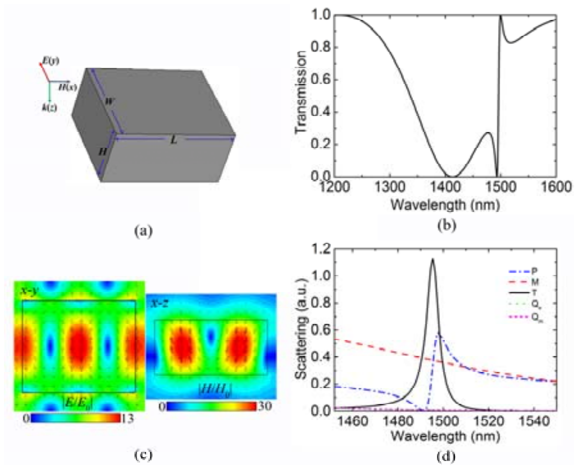


Fig. 1 Optical responses of the Si nanocuboid metasurface. (a) The unit cell and (b) transmission spectrum of the metasurface. (c) The E-field and H-field enhancement at anapole mode respectively, the superimposed arrows indicates the direction of the fields. (d) Multipole expansion results of the scattering spectrum for the metasurface.

## III. ANAPOLE MODE IN SPLIT DIELECTRIC NANOCUBOID METASURFACES

The field enhancement is principally localized in the dielectric nanostructure at the Fano resonance. Previous studies have shown that near-field enhancements outside of the dielectric nanoparticles can be improved by introducing split gaps, and the optical interactions with surrounding environments are strongly enhanced, but the Q-factor is reduced caused by additional radiation losses [1, 5].

We investigate the optical properties of the split cuboid metasurface. The transmission spectra of the split cuboid metasurface with the gap width $G$ = 85 nm are shown in Fig. 2 (b), where the other geometry parameters are identical as that in Fig. 1. The Fano resonance becomes much sharper than that in Fig. 1(b), the Q-factor of which is enlarged to $1.5\times10^5$. In order to better present the effect of the gap width, Figs. 2(c) and (d) show evolution of the line width and field enhancement by changing the line width. With increasing of the gap width from 10 nm to 89 nm，the Q-factor and the enhancements of the electric and magnetic fields increase dramatically at the same time. This is because that the coupling between the electric and toroidal modes is modified by modulating the split gap, leading to the suppression of the radiative loss [1]. On the contrary, the Q-factor is significantly decreased with increasing of the gap width from 91 nm to 150 nm. It is noteworthy that the Fano resonance is eliminated for $G$ = 90 nm, because that the interaction of the toroidal dipole and the electric dipole within its own unit cell offsets that in the adjacent unit cell [1]. Figure 2(e) shows electric (left panel) and magnetic (right panel) field enhancements distributions of the anople mode for the split cuboid array with $G$ = 89 nm. Its enhancements of the electric and magnetic fields are improved to 1450 and 3560, respectively, and the Q-factor increases dramatically up to $4\times10^6$, which are larger than those in the split disk array [7].What’s more important is that the enhanced

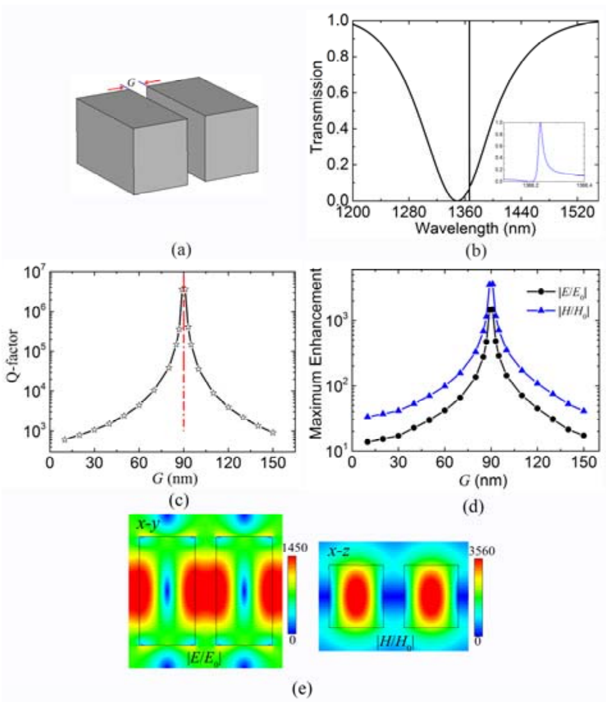


Fig. 2 (a) The geometric schematic of the split Si nanocuboid metasurface unit cell. (b) The transmission spectrum of the metasurface with $G$ = 85 nm, where the inset shows the magnified spectrum around the Fano resonance. (c) Q-factor and (d) Maximum near-field enhancements for the split disk arrays with different gap width. (e) The E-field and H-field enhancement at the anapole mode with $G$ =89 nm, respectively.

electric field is extended outside of the dielectric nanoparticles for the split cuboid arrays, and the enhancement of the magnetic field is significantly improved in the dielectric nanoparticles. The strong enhancements of the electric and magnetic fields would be useful for many applications in photonic devices.

## IV. CONCLUSION

In conclusion, our study shows that the nonradiative anapole mode is excited in dielectric naocuboid and split dielectric nanocuboid metasurfaces. It is important that high-Q resonances and strong near-field enhancements around and inside of the nanoparticles can be achieved simultaneously by using split dielectric nanocuboid metasurfaces. The Q-factor of the anapole mode is markedly improved by modulating the gap width, and the maximum Q-factor is up to $4\times10^6$. And strong electric and magnetic fields enhancements are achieved as 1450 and 3560, respectively. Our proposed split dielectric nanocuboid metasurfaces would contribute to the design of optical devices with excellent performance, such as nonlinear effects, biosensing and nanolasers.


## ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support for this work from the National Key R&D Program of China (Grant No. 2017YFA0303700) and the National Natural Science Foundation of China (Grant Nos 11274159, 11374150 and 11664020).


## REFERENCES


[1] Y. M. Yang, I. I. Kravchenko, D. P. Briggs, and J. Valentine, "All-dielectric metasurface analogue of electromagnetically induced transparency," Nat. Commun., England, vol. 5, pp. 5753, December 2014.

[2] G. H. Sun, L. R. Yuan, Y. Zhang, X. J. Zhang, and Y. Y. Zhu, "Q-factor enhancement of Fano resonance in all-dielectric metasurfaces by modulating meta-atom interactions," Sci. Rep., America, vol. 7, pp. 8128, August 2017.

[3] A. E. Miroshnichenko, A. B. Evlyukhin, Y. F. Yu, R. M. Bakker, A. Chipouline, A. I. Kuznetsov, B. Luk'yanchuk, B. N. Chichkov, and Y. S. Kivshar, "Nonradiating anapole modes in dielectric nanoparticles," Nat. Commun., England, vol. 6, pp. 8069, August 2015.

[4] L. Wei, Z. Xi, N. Bhattacharya, and H. P. Urbach, "Excitation of the radiationless anapole mode," Optica, America, vol. 3, pp. 799-802, July 2016.

[5] J. F. Zhang, W. Liu, Z. H. Zhu, X. D. Yuan, and S. Q. Qin, "Strong field enhancement and light-matter interactions with all-dielectric metamaterials based on split bar resonators," Opt Express, America, vol. 22, pp. 30889-30898, July 2014.

[6] D. Smith, E. Shiles, M. Inokuti, and E. Palik, "Handbook of optical constants of solids," Handbook of Optical Constants of Solids, Academic Press, Inc. Orlando, vol. 1, pp. 369-406, 1985.

[7] S. D. Liu, Z. X. Wang, W. J. Wang, J. D. Chen, and Z. H. Chen, "High Q-factor with the excitation of anapole modes in dielectric split nanodisk arrays," Opt Express, America, vol. 25, pp. 22375-22387, September 2017.