Anapole Mode Sustaining Silicon Metamaterials in Visible Spectral Range

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This paper is dedicated to a type of perforated silicon metamaterials, possessing anapole mode in visible spectral range due to destructive interference between electric and toroidal dipole moments. The proposed structure gains both in attainable material and simplified fabrication. Such a material exhibits a desirable physical effect and has obvious practical application: it supports the anapole mode without complicated 3D toroidal geometry and can be processed in one step by nanofabrication methods. The metamaterial paves the way for advanced optical devices on the base of all-dielectric metamaterials. Besides inherently low dissipative losses and strong anapole response, such an optical metamaterial can demonstrate subtle sensing, nonradiative data transfer, Aharonov-Bohm effect and other tempting applications in nanophotonics.

1. Introduction

Metamaterials are composite media consisting of arranged subwavelength building blocks called metamolecules. These artificial structures are popular for their unnatural properties such as negative refractive index, strong field localization, cloaking, strong magnetic response, superlensing effect and others. Metamaterials are of high technological demand since their electromagnetic properties can be tuned easily by changing geometrical sizes and shapes.[1–4] Although metallic metamaterials are promising candidates for light manipulation, they inherently possess high dissipative losses. Since nanoscale devices gained popularity, there is another obstacle for metallic metamaterials in their size scaling limit in optical range.[5,6]

On the other hand, all-dielectric metamaterials are widely used due to several advantages over metallic metamaterials. The main difference between metallic and all-dielectric metamaterials is in the nature of induced currents. An illuminated electromagnetic wave induces displacement currents in all-dielectric metaparticles, which possess low dissipative losses. Additionally, all-dielectric metamaterials are scalable in optical frequency range and their resonances can be controlled by means of tailoring the permittivity and sizes of metaparticles. All-dielectric metamolecules provide strong magnetic response similar to those of plasmonic Split-Ring Resonators (SRR), but features less dissipative losses in visible and near IR range. Due to different resonance order of dielectric materials, all-dielectric metaparticles firstly exhibit magnetic dipole resonance in visible spectral range, and makes it possible to create "magnetic" light.[7–11]

Among other dielectric materials, silicon is extensively investigated due to number of reasons. Specially arranged silicon metasurfaces and metamaterials are used for phase retardation, overcoming chromatic aberration for multiwavelength devices, Huygen's surfaces, beam shaping, biosensing and other. Additionally to their optical properties, silicon nanostructures are mechanically, electrically, optically and thermal robust.[12–16]

Comprehensive experimental investigation of silicon nanoparticles in visible spectral range revealed the possibility of anapole mode establishment in such metamaterials. The term static anapole firstly introduced by Y. B. Zel'dovich in nuclear physics for description of weak interactions in nucleus.[17] In electrodynamics, dynamic anapole mode is destructive interference of electric and toroidal multipoles, resulting in extermination of far-field radiation. Here, toroidal multipole is the next term of multipole decomposition of currents and represents toroidal configuration of poloidal currents with corresponding closed head-to-tail magnetic loop. Toroidal response of this configuration oscillates in perpendicular to the magnetic loop surface.[18–20] The engineering challenge of anapole mode sustaining metamolecule is the realization of toroidal geometry that support dynamically induced and spatially confined magnetic loop. Especially, this problem is acute at optical frequencies as well as engineering of any other 3D structures in general. On the other hand, anapole mode is in the spotlight due to a number of features. Primarily, because of the ability to concentrate strong electromagnetic fields inside a point nonradiating source or scatterer and ensuring the suppression of radiation in an external field. Therefore, metamaterials with anapole mode demonstrated

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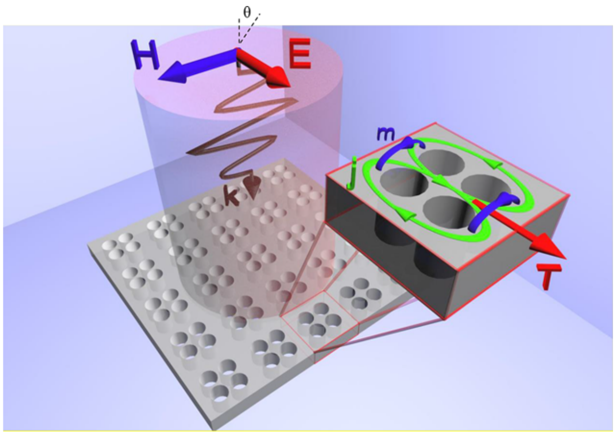

Figure 1. Illustration of the proposed optical metamaterial supplemented with current and mode distribution within each metamolecule. Inset shows toroidal mode excitation; here **m** stands for magnetic dipole moment, **j** – electric current loops, **T** – toroidal dipole moment.

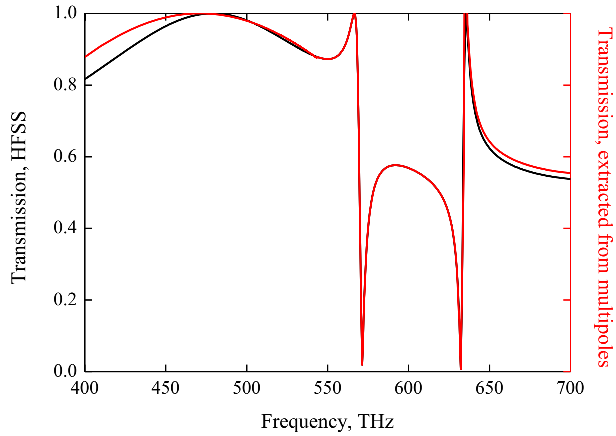

Figure 2. Simulated and reconstructed from multipoles transmission spectrum for metamolecule depicted on Figure 1. Sharp transparency peak corresponds to f = 566.5 THz.

extremely high Q-factor so that manifested themselves as perfect resonator.[21–30]

All these properties lead to extensive research of all-dielectric and, particularly, silicon metamaterials and their many applications. 2D metamaterials or metasurfaces stand out due to the simplicity of fabrication and exhibits desirable optical properties.[11,22,31–39] Nevertheless, we should mention the ref. [40], in which the possibility of an anapole excitation in 3D plasmonic toroidal metamaterials of the optical range has been shown. Commonly exploited technique is electron-beam lithography with subsequent reactive ion etching (RIE), carving procedure or femtosecond lasers.[41] Although most experimental works are based on this technique, their use is limited for spherical and ellipsoidal shaped nanodisks.[42,43] Alternative techniques are laser printing of nanospheres and chemical vapor deposition. Both techniques are very sophisticated since nanosphere fabrication demands high precision and multi-step realization.

In this paper, we demonstrate novel anapole mode sustaining silicon metamaterials in visible spectral range. Therefore, this type metamaterial is promising since it does not require high-tech implementation.

2. The Structure of the System

Our metamaterial consists of arranged metamolecules (i.e. unit cells) that are clusters of four throughly perforated holes in silicon slab. The edges of metamolecule have the similar length 200 nm and thickness 100 nm. The diameter of each hole is 45 nm, period of cluster is 200 nm and center-to-center distance between holes is 55 nm. We assume linearly polarized incident wave normally directed onto top of metamaterial.

As can be seen from **Figure 1**, metamolecule is illuminated from the top facet and both electric and magnetic counterparts of impinging wave propagates perpendicular to holes' axis. Tailored geometrical sizes and dielectric permittivity of metamaterial together with polarization and angle of incident wave leads to desirable form of displacement currents. In turn, these currents cause resonant electromagnetic scattering also called Mie resonance.[44] This Mie resonance explains accurately electromagnetic properties of dielectric nanoparticles, especially the appearance of strong magnetic modes. Mie resonance also provides essential for toroidal response current distribution form. Displacement currents **j** take the form of meridians on the toroidal surface, resembling poloidal currents, and generates magnetic mode confined within the gedanken torus. This configuration creates electromagnetic analogue of toroidal moment in all-dielectric metamaterials. According to Figure 1, the front of incident wave propagates along the holes' axis and its electric component **E** oscillates along holes. Consequently, displacement currents **j** circle holes and creates two loops of current: counterclockwise and clockwise. These current loops create circulated magnetic mode **m** restricted within these loops. This configuration expectedly creates toroidal response **T** oscillating in the direction of electric component of incident wave. The antiphase oscillation of toroidal **T** and electric **P** modes configuration in the relation of $\mathbf{P} = ik\mathbf{T}$ creates anapole mode at resonant frequency.[19]

3. Results

The electromagnetic properties of silicon slab is calculated by commercial Maxwell's equation solver HFSS using standard modeling approach, where the properties of whole structure represented by the parameters of their unit cell with correctly applied boundary conditions. **Figure 2** depicts transmission spectrum of perforated along its thickness silicon slab as well as reconstructed from multipoles transmission spectrum near their resonant frequency with full transmission peak at f = 566.5 THz of amplitude $|T| = 1$. **Figure 3** provides field maps of absolute value and cutplane in the direction of wave propagation of both electric and magnetic component at resonant frequency f = 566.5 THz. Thus, the electric field strongly concentrates between pairs of holes and preconditions formation of displacement current loops **j** mimicking poloidal currents of the gedanken torus (Figure 3a). These currents create magnetic fields circulated above and below holes (Figure 3b). Moreover, magnetic field strongly

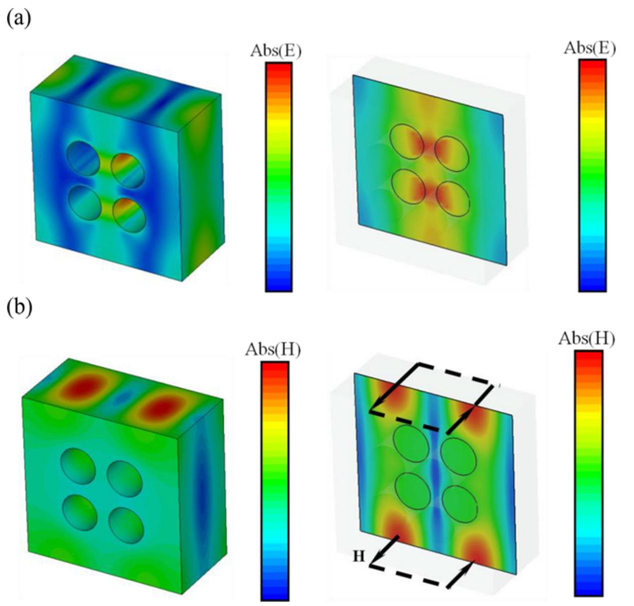

Figure 3. Field maps of a) absolute value of electric field and in cross-section of silicon perforated slab and b) absolute value of magnetic field intensities field and in cross-section of silicon perforated slab.

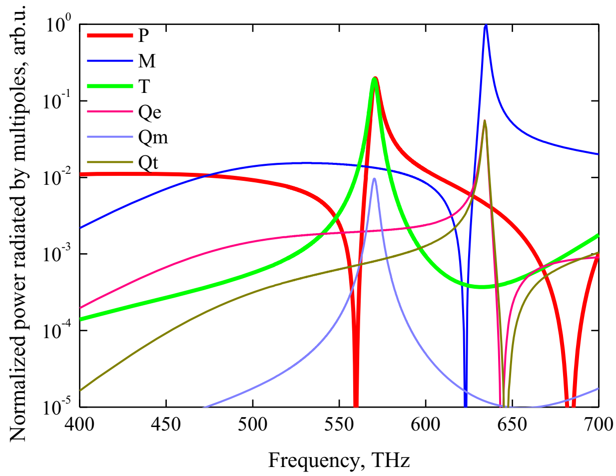

Figure 4. Normalized power radiated (scattered) by metamaterial of near-field distribution of metamolecule up to second order multipoles.

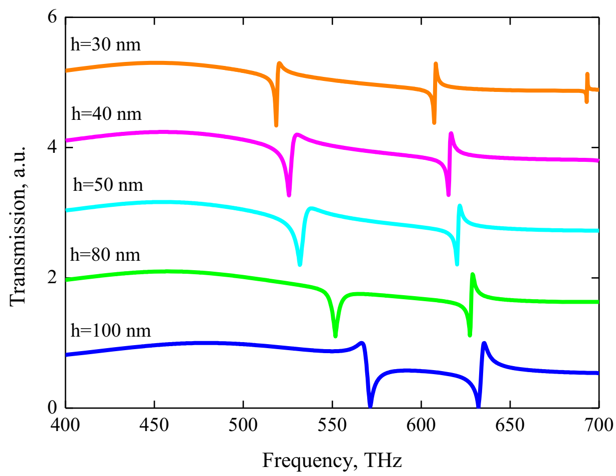

Figure 5. Transmission versus frequency for various depths h of silicon slab at resonant frequency.

concentrates on top and bottom facets of metamolecule and rotates clockwise (Figure 3b). Accordingly, we expect that such electromagnetic configuration of displacement currents and fields induce toroidal response **T** within metamolecule oscillating up and down on the direction of electric component **E**.

The electric and magnetic fields at resonant frequency appear due to Mie-type modes and such fields configuration corresponds to anapole mode excitation, which features strong electric field localization between holes and magnetic fields concentration above and below holes with low radiation into far-field that intrinsic for anapole mode excitation owing to destructive interference of electric and toroidal moments.

To confirm our assumption, we carry out multipole decomposition of displacement currents in terms of six strongest multipoles: electric **P** and magnetic dipoles **M**, toroidal dipole **T**, electric **Qe** and magnetic **Qm** quadrupoles as well as toroidal **Qt** quadrupoles illustrated in **Figure 4**. Thus, close to resonant frequency there is compelling electric dipole **P** and toroidal dipole **T** which at resonant frequency f = 566.5 THz come into oscillation of $\mathbf{P} = ik\mathbf{T}$ so that establish anapole mode. Additionally, we can see rather high value of magnetic dipole as well as electric **Q**e, magnetic **Q**m and toroidal **Q**t quadrupoles throughout a given range, which are below 10 times. These multipoles contribute to widening of transmission peak so that suppress of Q factor due to radiating losses. This multipoles family sufficiently contributes to transmission of the system. Reconstructed from these multipoles transmission curve perfectly matches simulated by HFSS transmission curve (see Figure 1).

Furthermore, we consider different depth of holes and study how the anapole mode disappears. In **Figure 5**, we provide transmission spectra of metamolecule at depths of h = 30 nm, 40 nm, 50 nm, 80 nm and 100 nm. Thus, the shortening of hole depths leads to redshift of resonant frequency. It also accompanied by widening of transmission peak for low value of depth h. **Figure 6** illustrates multipole decomposition of near field for all presented cases of depth h. In particular, for deeper holes in Figure 6b–d anapole mode disappears due to magnetic dipole accompaniment on resonant frequency. For h = 30 nm resonance distinguished by dominating electric dipole moment. Multipolar decomposition for throughly perforated metamaterial presented in Figure 4.

In addition, we estimated transmission spectrum evolution in terms of hole diameter d and incident angle θ. In **Figure 7**a, we present transmission spectra for diameters d = 30 nm, 45 nm, 50 nm, 60 nm, 70 nm. Obviously, larger diameters lead to blueshift of transmission peak. Therefore, larger diameters d = 50 nm, 60 nm, 70 nm provides widening of transmission maximum, i.e. decrease of Q-factor. The case of small diameter (d = 30 nm) corresponds to blueshift of resonance frequency. Although d = 30 nm shows the sharpest transmission peak, this case obstacles difficulties in fabrication. Figure 7b enables to compare how the angle of incidence affects transmission

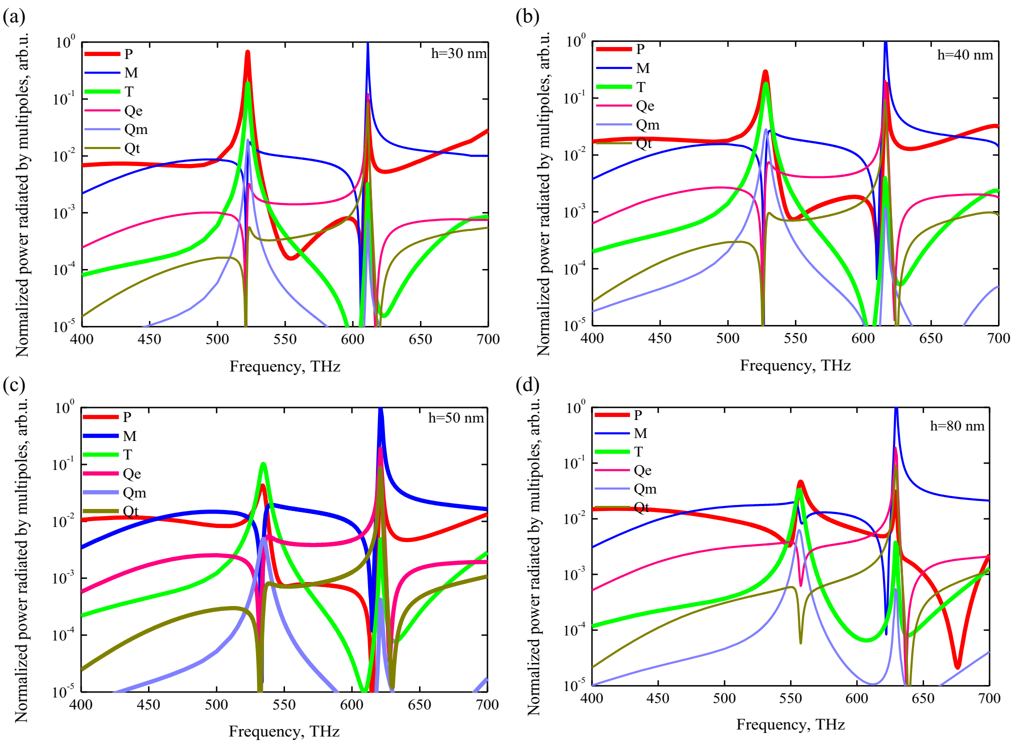

Figure 6. Contributions of the six strongest multipoles excitations to the normalized power radiated by metamaterial for various depths a) h = 30 nm, b) 40 nm, c) 50 nm, d) 80 nm of silicon slab at resonant frequency.

spectrum. We consider the case of incidence angles $\theta = 0^0, 20^0, 40^0, 60^0, 80^0$. The graph shows that gradually increase of angle of incidence leads to redshift of transmission peak and narrowing its resonance.

4. Discussion

In this work, we propose novel type of anapole mode sustaining metamaterial in optics. This metamaterial awaited to exhibit fascinating effects in visible spectral range. Papers of recent years report more and more effects on anapole mode establishment in metamaterials. They have a great potential for application as near-field cloaking sources/sensors so that embodies ambitions of invisible movement. Such metamaterials makes foundation for dynamic Aharonov-Bohm demonstration in visible spectral range, which makes secure communications one step closer.

The main purpose of our work is to propose simple realization of all-dielectric anapole metamaterial. Our metamaterial apparently advantages in fabrication: holes perforation can be easily made by means of, for example, FIB (Focused Ion Beam) method, which is applicable in nanoscale. Silicon is the most preferable material in optics and useful for well-pronounced effects demonstration. Besides, silicon is reasonably cheap and easy to obtain. Since silicon particles are electrically and thermal robust, it is convenient for nonlinear optical effects.

Since FIB fabrication takes place in one step, this kind metamaterial benefits both in time and fabrication price. On the other hand, our structure is promising for application in optical bio/cloaked sensing. Any liquid poured inside such cluster takes form of holes and shifts spectral response of metamaterial. This simplifies specification of liquid nature so that advances biosensors. On the other hand, this metamaterial can be used as a part of anapole cloaking due to field localization within a slab. Integration of metamaterial concept with planar waveguide theory is expected to extend waveguide application in the field of transparency phenomena. Our approach can be adapted for cloaking waveguides. Indeed, perforated silicon waveguide can be considered as transparent system. Accordingly, side wave obliged waveguide transparent through the waveguide due to anapole mode excitation. Therefore, such anapole mode sustaining metamolecule is useful for future of nonradiating sources and subwavelength resonators with extremely high Q factor.

5. Conclusion

In this paper, we innovatively demonstrated anapole mode sustaining all-dielectric metamaterial in visible spectral range. Furthermore, this type metamaterial advantages in fabrication, i.e. in time and price among other known nanoscale metamaterials. Our metamaterial can be easily made by holes perforating in solid silicon slab. Besides, our metamaterial features considerably high Q and strong field localization which makes it outstanding candidate for perfect resonator. Field distribution at resonant frequency showed inherent to anapole mode strong field localization within metamolecule. In confirmation of our assumption, we carried out multipolar decomposition of displacement

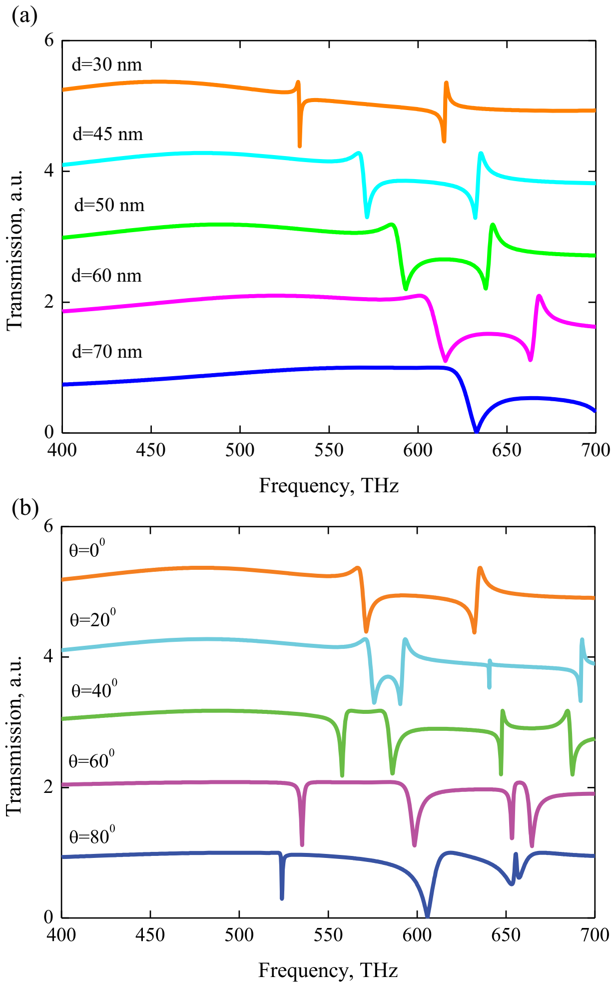

Figure 7. Transmission versus frequency for various a) diameters d of holes and b) angles θ of incidence.

currents in the frame of six strongest multipoles. Our results proved that transparency effect at given resonant frequency, indeed, underpinned by anapole mode excitation. Therefore, we provided transmission spectra for various diameters of holes and angles of incidence and observed their evolution on shift of transmission peak. Our metamaterial paves the way for advanced optical devices on the base of all-dielectric metamaterials. Besides inherent low dissipative losses and strong anapole response, such optical metamaterial supposed to demonstrate subtle sensing, nonradiative data transfer, Aharonov-Bohm effect and other tempting applications in nanophotonics.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

anapole mode, multipolar decomposition, optical metamaterials, silicon metamaterials, toroidal mode

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