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All-dielectric ellipsoid for hybrid anapole observation

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Abstract. We investigate all-dielectric flattened ellipsoid particle on dielectric substrate for demonstration of hybrid anapole mode. We find that such particle could support first and second order electric and magnetic anapole modes that manifesting fully eliminated scattering of the structure. We demonstrate scattering properties of high index all-dielectric ellipsoid particle and provide multipole decomposition on the scattering minimum.

Keywords: multipoles, scattering properties, anapoles, hybrid anapole modes, ellipsoid.

1. INTRODUCTION

Resonance subwavelength effects are promising for light- matter interaction in novel photonic technologies including nanoantennas, biosensing/detecting devices, beam splitting and invisible theory[1]. Therefore, resonant nonradiating states for strong field localization with minimized far-field scattering are strongly demanded for high quality open resonator implementations[2]. For this purpose, modern nanophotonics are dedicated to study of interference effects between electromagnetic multipoles and to reveal optimized conditions for experimental implementation from microwave to optics. The vast majority of these studies concern interference between electric and magnetic multipoles providing well-known Fano-type resonance, EIT effects and others. One should consider Fano resonance as overlapping of two interacting channels referred to as bright and dark modes providing narrow spectral line. This leads to scattering in forward direction while total invisibility is provided by anapole mode excitation due to toroidal multipoles family.

The concept of toroidal multipoles received great attention in the field of nanophotonics and metamaterials due to possible realization of nonradiating anapole. The toroidal moment and effects of toroidal electrodynamics have been theoretically studied [3-7] and experimentally observed in conducting to all-dielectric particles and metamaterials in microwave and optical ranges. Special attention delivered to anapole state that can be excited in toroidal objects and known for establishing a nonradiating configuration owing to destructive interference between electric and toroidal dipole interactions in the same structure. However, static anapole (in Greek, without poles) introduced by Ya. Zeldovich for the description of static current configuration in the nuclear system and long time later interpreted as dynamic anapole for classical case in microwave metamaterials and in all-dielectric nanodisks. Due to nature of electric and toroidal multipoles interaction, these anapoles also referred to as nontrivial electric anapole mode and possess suppressed scattering of electric type[8].

Recently, the technique for magnetic anapole mode excitation is proposed and analytically investigated[9]. The mechanism for such magnetic nonradiating state is different from electric anapole excitation and aimed at extinguishing magnetic response by means of excitation of so-called magnetic mean square radii moments (MSR) interfering with magnetic dipole moment. On the other hand, one pursues the idea of coexistence of both electric and magnetic anapole modes for creation of purely nonradiating sources also known as hybrid anapole.

The main advantage of hybrid anapole is that the scattering cross section of electric and magnetic multipoles tends to zero and hybrid anapole supporting particle appears invisible. Indeed, the scattering cross section of object is describing by terms multipoles[10] :

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$$\sigma_{scat} = 2\frac{\sqrt{\frac{\mu_0}{\varepsilon_0\varepsilon_d}}}{|\boldsymbol{E}_{inc}|^2}\left\{\frac{k^4\sqrt{\varepsilon_d}}{12\pi\varepsilon_0{}^2c\mu_0}\left|p_i+\frac{ik\varepsilon_d}{c}T_i+\frac{ik\varepsilon_d}{c}T_i^{<2>}\right|^2+\frac{k^4\sqrt{\varepsilon_d}}{12\pi\varepsilon_0 c}\left|m_i+\frac{ik\varepsilon_d}{c}M_i^{<2>}\right|^2 + \frac{k^6\varepsilon_d\sqrt{\varepsilon_d}}{160\pi\varepsilon_0{}^2c\mu_0}\left|Q_i^e+\frac{ik\varepsilon_d}{c}Q_i^T\right|^2+\frac{k^6\varepsilon_d{}^2\sqrt{\varepsilon_d}}{160\pi\varepsilon_0 c}\left|Q_i^m+\frac{ik\varepsilon_d}{c}Q_i^{m<2>}\right|^2 \dots\right\} \quad (1) \qquad (1)$$

In our study, we use Cartesian multipole expansion of p_i- electric dipole, m_i- magnetic dipole, T_i - toroidal dipole moments, their quadrupoles Q_i^e, Q_i^m, Q_i^T of electric, magnetic and toroidal type and moment of mean-square radii (MSR) of magnetic $M_i^{<2>}$, toroidal $T_i^{<2>}$, and magnetic quadrupole $Q_i^{m<2>}$. This series sufficiently describes the scattering properties of the object discussed below; however, the full series of higher order multipoles is presented in Ref.[11]. One can conclude, that several lower anapole effects can be classified by formula (1) [10] and[12]. In order to illustrate the difference between anapoles, we combine them depending on triviality nature, interacting channels and definitions for anapole conditions[13].

Table 1. The classification of electric and magnetic type anapole modes and their formulas.

Non-trivial	Trivial	Nontrivial
Electric anapole		$p_i = -\frac{ik\varepsilon_d}{c}T_i$
Magnetic anapole	$m_i = -\frac{ik\varepsilon_d}{c}M_i^{<2>}$	
Toroidal anapole	$T_i = -\frac{ik\varepsilon_d}{c}T_i^{<2>}$	$p_i = -\frac{ik\varepsilon_d}{c}T_i^{<2>}$
Electric quadrupole anapole		$Q_i^e = -\frac{ik\varepsilon_d}{c}Q_i^T$
Magnetic quadropole anapole	$Q_i^m = -\frac{ik\varepsilon_d}{c}Q_i^{m<2>}$	

Here, trivial anapoles are result of interaction between multipoles and their MSR of the same families and nontrivial anapoles, in contrast, can be excited by multipoles of different families.

The most familiar electric anapole (1 in Table 1) is nontrivial nonradiating configuration, while destructive interference between electric and toroidal quadrupoles produces nontrivial electric quadrupole anapole of next order (4 in Table 1). Destructive interference between magnetic moment and MSR of magnetic moment provides trivial magnetic anapole configuration (2 in Table 1). Hybrid anapole of both electric and magnetic anapole excitations suppress scattering of electric and magnetic origin. Since the theory of hybrid anapoles have emerged a short time ago, there are a just few works on its theoretical investigation. One of its first theoretical demonstration is high refractive index (high-index) dielectric spherical nanoparticle have been proposed by Luk'yanchuk et al[9].

The first term in (1) shows that toroidal MSR (contributes to total electric anapole and) condition $p_i + \frac{ik\varepsilon_d}{c}T_i + \frac{ik\varepsilon_d}{c}T_i^{<2>}$ should be satisfied.

Toroidal anapole (3 in Table 1) appears to be in both nontrivial and trivial states. Indeed, interaction in destructive manner of toroidal moment and its MSR interaction is trivial due to interaction between dipoles of the same family. In contrast, nontrivial toroidal anapole can be emerged due to interaction of electric dipole moment with toroidal MSR. Magnetic quadrupole anapole is trivial configuration of interacting of magnetic quadrupole with its mean square radius (5 in Table 1).

From Table 1, we can expect that trivial and nontrivial anapole configurations excited in particle by external wave lead to invisibility due to almost suppressed scattering (1) provided by several anapole types in the same frequency range.

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2. The design of the structure. In this paper, our purpose is to demonstrate theoretical model based on all-dielectric ellipsoid particle, which can scatter the plane wave in hybrid anapole manner. Therefore, we endeavor to show the tunability of different type anapoles in ellipsoid particle by interplay of its geometrical parameters, which may indicate on physical nature of the multipole as a whole.

The fundamental mode of a high-index dielectric sphere or cube is usually of the magnetic dipole type and it occurs at a different frequency from the electric one. The same occurs for dielectric pillars, where the diameter and height aspect ratio is almost unity. Consequently, there is an open challenge to tailor resonant spectral position of the electric and magnetic modes in high-index dielectric nanoparticles. On the other hand, spheroidal nanoparticles possess several geometrical parameters that could serve as additional degrees of freedom for resonant overlapping of electric and magnetic Mie mode by simple adjusting the spheroid large to small radii aspect ratio. Recently, the optimum forward light scattering by spheroidal nanoparticle due to aspect ratio tuning have been theoretically demonstrated[14].

An extra degree of freedom is delivered by ellipsoidal particles. Actually, we can show how tuning of each of three radii of an ellipsoid enables adjusting the contribution of various multipoles in the system and especially anapoles. We demonstrate for the first time nonradiating hybrid anapole excitation in terms of electric and magnetic dipoles and quadrupoles suppressed by their corresponding mean-square radii in all-dielectric ellipsoid particle. We theoretically conclude the excitation channels for tuning the spectral overlap of electric and magnetic anapoles by changing ellipsoid parameters.

In order to demonstrate generalized hybrid anapole approach we perform numerical simulation of electromagnetic scattering by ellipsoidal particle by a commercial version of CST Microwave Studio and using Time domain solver with open boundary conditions. The particle is illuminated by plane wave (Figure 1). The parameters of the particle are as follows: the major axis is b = 1.85 μm the minor axes are a = 0.7 μm and c = 1 μm, dielectric permittivity is ε_p=30. An external linearly polarized wave incident on the ellipsoidal particle in normal direction so that wavevector is co-directed with minor axis c. Another minor axis a corresponds to the electric component and major axis b, respectively, corresponds to the magnetic component of the wave. We characterize the electromagnetic response of particle by the scattering cross section spectrum (Figure 2). We observe almost zero scattering at q = 0.85, which implies that the nonradiating state of the particle is excited, where both generalized dipole modes and electric quadrupole mode are suppressed. We plot scattering cross section via independent parameter q = 2πR/λ and normalized on ellipse cross-section S = πab. The total scattering is limited by magnetic quadrupole mode. However, the scattering beyond this range is very high ∼ 10.

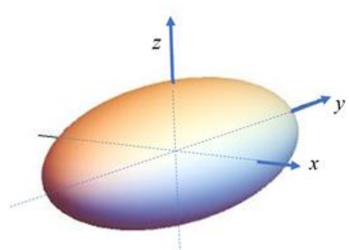

Fig. 1. Illustration of all-dielectric ellipsoidal particle placed on the vacuum medium. Wavevector **k** is directed along *z* axis and electric field **E** directed along *x* axis.

3. The results. We characterize the electromagnetic response of particle by the scattering cross section spectrum. We observe almost zero scattering at f = 80.77 THz implying on the nonradiating state of the particle, where both dipole modes and electric quadrupole mode are suppressed. The total scattering is limited by magnetic quadrupole mode.

However, the scattering beyond this range is very high ~ 10 um^2. Therefore, it is proved by near field distribution maps at this frequency demonstrating unperturbed wave front propagation through the particle (Figure 3 a, b and c for electric field and d, e, f for magnetic field). Thus, the particle at frequency f = 80.77 THz is implied to be invisible. We were not able to reach simultaneously local minimum for magnetic quadrupole, which is situated at higher frequencies, f = 86 THz. However, this magnetic quadrupole mode can be also suppressed for the particle on substrate as it is shown further.

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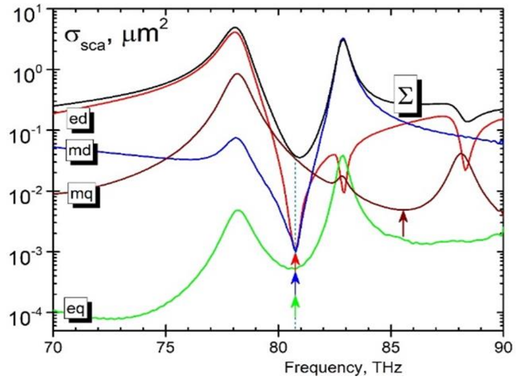

Figure 2. Scattering cross section and contribution of basic multipoles in Table 1. Electric dipole contribution ("ed" first term in Eq. (1)) – red line. Magnetic dipole contribution ("md" second term in Eq. (1)) – blue line. Electric quadrupole contribution ("eq" third term in Eq. (1)) – green line. Magnetic quadrupole contribution ("mq" fourth term in Eq. (1)) – wine line. Sum of four terms Σ – black line.

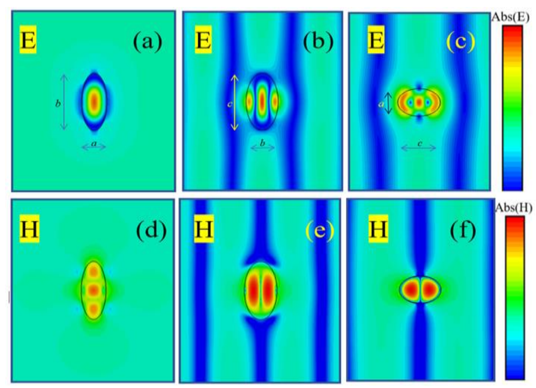

Figure 3. Electric and magnetic fields distribution in *xy*-plain (a, d), *yz*-plain (b, e), and *zx*-plain (c, f) of ellipsoid particle with axis: a = 0.71602 μm, b = 1.85 μm, c = 1 μm at f = 80.77 THz.

For considered particle parameters, one can see resonant behavior of multipoles intensities at f = 80.77 THz, their dipole moments and quadrupole, as well as mean-square radii. Namely, the interference of electric type dipoles, i.e. electric and toroidal dipoles, as well as toroidal MSR (red curve in Figure 2) perfectly coincides with the position of interference of magnetic type dipoles – magnetic dipole and magnetic MSR (blue curve in Figure 4 (a)). Therefore, these suppressed intensities are accompanied by deep lying (10-3 um^2) electric type quadrupoles (electric and toroidal quadrupoles, green curve at Figure 4 (a)). The intensity of magnetic type quadrupoles (magnetic quadrupole and MSR of magnetic quadrupole) is nearly zero (0.02) and exceeds other kind of multipoles. However, it does not strongly affect no scattering pattern of particle.

As for an individual contribution of each multipole, at f = 80.77 THz the overlapping between electric and magnetic moments and their mean square radii is observed (Figure 2b). Although, toroidal and electric moments coincide in intensities at f = 80.77 THz forming electric anapole, while magnetic moment interferes destructively with magnetic MSR forming magnetic anapole. Similar regime is observed for electric quadrupole anapoles. As a total, the contribution of three type of anapoles of electric, magnetic, and electric quadrupole anapoles constitutes hybrid anapole at f = 80.77 THz.

Conclusion. In conclusion, we proposed and theoretically studied a novel class of all-dielectric ellipsoidal particle that exhibit a resonant hybrid anapole response. We demonstrated excitation by means of four anapole channels which can be "manually" tuned by changing of axes of ellipsoid and presented substrate. This particle possesses almost zero scattering due to electric, magnetic and their quadrupoles anapoles excitation. This technic can be promising for practical realization of invisible nanophotonics and strong field localization devices.

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