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Metamaterial engineered transparency due to the nullifying of multipole moments

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Here we propose, to the best of our knowledge, a novel transparency effect in cylindrical all-dielectric metamaterials. We show that the cancellation of multipole moments of the same kind leads to almost zero radiation losses in all-dielectric metamaterials due to the counter-directed multipolar moments in metamolecule. The nullifying of multipoles, mainly dipoles, and suppression of higher multipoles, results in the ideal transmission of an incident wave through the designed metamaterial. The observed effect could pave the road to the new generation of light-manipulating transparent metadevices such as filters, waveguides, and cloaks.

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The narrow transmission peak called a "transparency window" in the optical spectral range [1] is one of the most promising effects in nanophotonics. This effect provides a new field in electronic and optical applications, namely, slow light propagation and long pulse delays for the storage of optical data in matter, frequency selectivity for narrow-band filters, enhanced nonlinear effects, and strong light-matter interaction in photonics [2]. Recently, this well-known quantum phenomena imitated in classical systems. Experimentally, classical electromagnetically induced transparency (EIT) obtained in metamaterials in a microwave frequency range [3]. At the same time, metamaterials are manmade materials exhibiting unnatural properties such as negative refraction, cloaking, and strong field localization [4–8]. Since metamaterials are free for geometrical modifications, they may be tuned to reach a narrow-band transparency window corresponding to a high Q-factor. Thus, the next challenge is to create suitable structures with proper interactions for EIT-like phenomena.

One can demonstrate a "transparency window" by inducing the overlapping of electric and magnetic multipoles in plasmonic and all-dielectric particles [9]. This phenomenon, called Fano-resonance, arises due to the interference between different parts of the constituent metamolecules [10,11]. Another technique to observe the EIT in metamaterials is "trapping" an incident electromagnetic wave and exciting destructive interference between the same multipoles in metamaterials [12,13]. In addition, an anapole mode can be defined as the third principal method of transparency produced by destructive interference between electric and toroidal multipole moments of the same amplitudes and angular momentum [14–16]. All aforementioned systems possess low radiative losses and exhibit transparency due to destructive interference of the main two multipoles of the same order and suppressing other multipoles. However, in this Letter, we propose a metamaterial transparency effect due to the nullifying of the main excited dipole moments, leading to almost zero radiative losses in all-dielectric metamaterials.

The unit cell of proposed metamaterial consists of clusters containing four identical subwavelength high-index dielectric cylinders with rhombic shapes. For the demonstration of well-pronounced effect in terahertz frequency range, we choose the cylinders made of $LiTaO_3$. This ionic crystal is known to exhibit a strong polaritonic response in the terahertz frequency range and can be practically realized by means of methods of crystal growth [17,18]. Complex dielectric permittivity of $LiTaO_3$ shows Lorenz-type dispersion $\varepsilon = \varepsilon_\infty \frac{\omega^2-\omega_L^2+i\omega\gamma}{\omega^2-\omega_T^2+i\omega\gamma}$. Here $\omega_T/2\pi = 26.7$ THz stands for the frequency of the transverse optical phonons, $\omega_L/2\pi = 46.9$ THz is the frequency of longitudinal optical phonons, $\gamma/2\pi = 0.94$ THz is the damping factor due to dipole relaxation, and $\varepsilon_\infty = 13.4$ is the limiting value of the permittivity for frequencies much higher than ω_L. At frequencies lower than phonon resonance, one can consider permittivity of $LiTaO_3$ to be ~41.4. At these frequencies, $LiTaO_3$ crystals have negligible dissipation losses.

The height of each cylinder is assumed to be infinitely elongated. The electromagnetic response of our system is characterized by the displacement currents induced in each cylinder by an incident electromagnetic wave. Displacement currents cause electromagnetic scattering that becomes resonant due to the accurately chosen radius and permittivity of the cylinders

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and the polarization of the incident electromagnetic wave. This resonant behavior corresponds to Mie resonance emerging on cylindrical all-dielectric particles. In our case, a parallel-polarized electromagnetic wave excites the resonant electric dipolar moment in each high-index dielectric cylinder, as can be seen in Fig. 1 [19,20]. This gives an opportunity to use dielectric metamaterials as unique structures for artificial magnetism, magnetic and toroidal dipolar excitation, as well as an anapole mode [20–26]. The incident electromagnetic wave with E-field polarized parallel to the cylinder axis induces counter-directed **P** electric moments in opposite cylinders (1 and 3, 2 and 4) and forms two pairs of displacement current loops in each metamolecule (Fig. 1). Each pair of loops creates two magnetic dipole ($2'$ and $4'$) moments **m** directed out of center. Another pair of magnetic dipole moments emerges between the cylinders from different pairs ($1'$ and $3'$) and is directed to the center of the unit cell. All magnetic moments of the studied system are orthogonal to the cylinder axis. Each pair of magnetic dipolar moments **m** has the opposite direction and eliminates the other. Therefore, the total magnetic response of the system disappears. In addition, the total electric dipolar response of the metamolecule damped as well. This can be explained by the cancellation of displacement currents of neighboring cylinders from different current loops.

In previous works, transparency was suggested as a consequence of destructive interference between multipole moments, as in [10,11,15]. However, our findings presented here show that transparent metamaterials can be designed without any dipolar response just due to the nullifying of each kind of dipole moment. This provides zero radiation losses, and such a metamaterial becomes transparent in the optical frequency range.

Our proposed system demonstrates strong electromagnetic interaction due to the near-field coupling of closely located high-index dielectric cylinders. The unit cell scaled to obtain a pronounced dipolar response at the expense of higher order multipoles. Each cylinder has a radius $r = 5$ μm and center-to-center distance with neighboring within metamolecule cylinders of $l = 12$ μm. The period between clusters is $d = 60$ μm. The clusters are surrounded by air or vacuum media. We assume indefinitely elongated height h of cylinders allowing the consideration of two-dimensional structure. The electromagnetic properties of metamaterial are calculated by the commercial Maxwell's equation solver HFSS using a standard modeling approach, where the whole structure is described by replicating unit cell properties using periodic boundary conditions.

The transmission spectrum of our metamaterial is depicted on Fig. 2. The sharp narrow transmission peak at 2.2446 THz corresponds to the emergence of the transparency effect. This resonance has an amplitude of 1 and width of 0.0017 THz and due to $Q = f_0/\Delta f$ one can obtain a very high Q-factor value of 1320. The field map at this value shows opposite distributed electric field strengths in every neighboring cylinder, indicating an occurrence of displacement current loops in each pair of cylinders [Fig. 3(a)]. The direction of field strength of cylinder 1 coincides with the direction in the cylinder 3, while both 2 and 4 cylinders have opposite field distribution directions. This means that these cylinders, let us say pairs 1 and 2, 2 and 3, 3 and 4, 4 and 1, form four loops of displacement currents in every unit cell of the system. In turn, two loops generate two magnetic dipolar responses directed out of the center of the unit cell [$2'$ and $4'$ of Fig. 3(b)]. The other two loops of displacement currents generate another pair of magnetic dipole moments that are directed toward the center [$1'$ and $3'$ of Fig. 3(b)]. The field map on Fig. 3(b) shows magnetic field distribution in the unit cell. The strong magnetic field

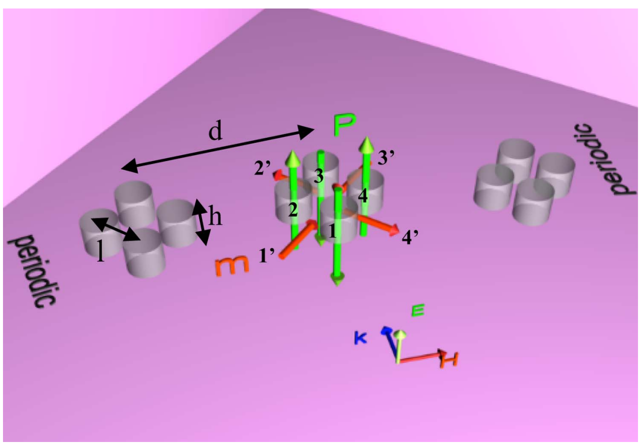

Fig. 1. Illustration of the proposed metamolecule, consisting of four identical parallel dielectric cylinders. Electric component of the incident wave polarized parallel to the cylinder axis; induces counter-directed electric moments in each neighboring cylinder. The loops excite four magnetic dipolar moments that are directed to and from the center of the metamolecule.

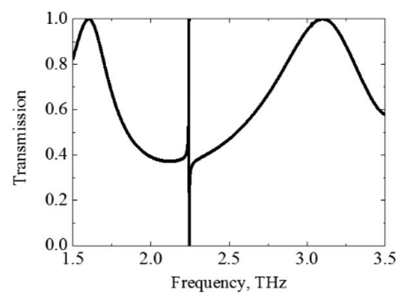

Fig. 2. Transmission spectrum for the metamolecule in a terahertz frequency range. The narrow sharp transparency peak corresponds to $f = 2.2446$ THz with $Q = 1320$.

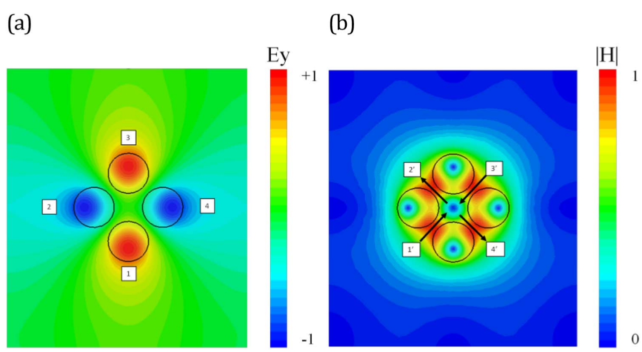

Fig. 3. Field maps of (a) the y-component (along the cylinder axis) of the electric field and (b) the absolute values of the magnetic field intensities.

localization between cylinders indicates the near-field coupling between them. These oppositely directed magnetic dipole moments have zero contribution in the metamolecule dipolar response. In addition, there is a zero total electric dipolar response, since the electric field strength of cylinders 1 and 3 cancels the electric field strength of cylinders 2 and 4.

To confirm our assumption on nullifying the same kind of multipoles, we carried out multipolar decomposition up to the second order of multipoles scattering by metamolecule at a resonant frequency value from the HFSS transient solver method simulated displacement currents in each cluster with periodic boundary conditions [22]. Figure 4 shows normalized power of the near-field distribution of a metamolecule up to second-order multipoles. The resonant frequency corresponds to the second peak of the transmission spectrum. At the resonant frequency $f = 2.2446$ THz, one can see a narrow dip of an electric dipole moment accompanied with suppression of quadrupole moments and almost zero value of magnetic and toroidal dipoles. Accordingly, in this frequency range, radiation losses tend to zero, and this leads to full transparency at $f = 2.2446$ THz. This confirms our assumption that the transparency of metamaterial can be achieved due to the nullifying of all multipoles contemporaneously. This effect is accompanied by a very high Q-factor, corresponding to a narrow transparency window (Fig. 2).

We note that a high Q-factor value has been previously considered for all-dielectric metamaterial with broken symmetry in an optical range. In particular, the symmetry of a cubic dielectric metasurface was broken and placed on substrate to obtain resonance between two modes [27]. The authors of Ref. [28] presented high-Q metamaterial due to the overlapping of resonant modes of asymmetric metallic bars. As the result, very high-Q Fano resonances were obtained. Moreover, a high-Q response can be obtained due to toroidal mode excitation in planar toroidal metamaterials [29,30]. Our metamaterial is distinguished with the avoidance of such sophisticated manufacturing by placing cylinders in a defined sequence. This elegant approach is obviously technologically simple.

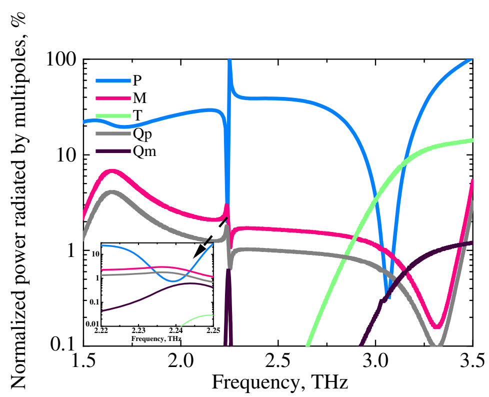

Fig. 4. Normalized power of the near-field distribution of a metamolecule up to second-order multipoles. The sharp dip of the electric dipole moment (light blue curve) corresponds to a transparency peak of 2.2446 THz. There are also the reduction of electric (gray curve) and magnetic (violet curve) quadrupole moments and magnetic (pink curve) and toroidal (green curve) dipolar moments. The inset shows excited multipoles close to $f = 2.2446$ THz.

Let us note that the first peak close to 1.5 THz corresponds to an electric dipole contribution with a strong influence of magnetic dipole and electric quadrupole modes. Moreover, the behavior of the third peak which is close to $f = 3$ THz gives the following outcomes. 3–3.14 THz range coincides to the third peak of the transmission spectra (Figs. 2 and 4), the peak becomes higher among other multipoles, leading to the establishment of toroidal mode. It is obvious that the presented effect is the result of collective Mie resonance within each meta-atom, specially chosen geometric parameters, and permittivity of cylinders. Based on the Mie electric mode of the single cylinder, we may call the magnetic mode induction in our observed metamaterial the collective Mie resonance, since these modes appear to be due to interparticle interaction. Owing to chosen unit cell geometry, these modes cancel each other, leading to a Fano-type transparency window.

In addition, we carried out simulations of various parameters of proposed terahertz metamaterial geometry exhibiting transparency. Figure 5 contains five graphs for different parameters of our proposed metamaterials in a wide range of values. Figure 5(a) illustrates transmission spectra for various radii r for cylinders, and one can see that reduction of the radius from initial 5 μm leads to the blueshift of resonant frequency and, for even smaller values, an $r = 2$ μm resonance is widening. Figure 5(b) corresponds to the changing of transmission spectra, depending on the center-to-center distance between clusters d of the metamaterial. The graph clearly shows that the varying of the center-to-center distance from initial value

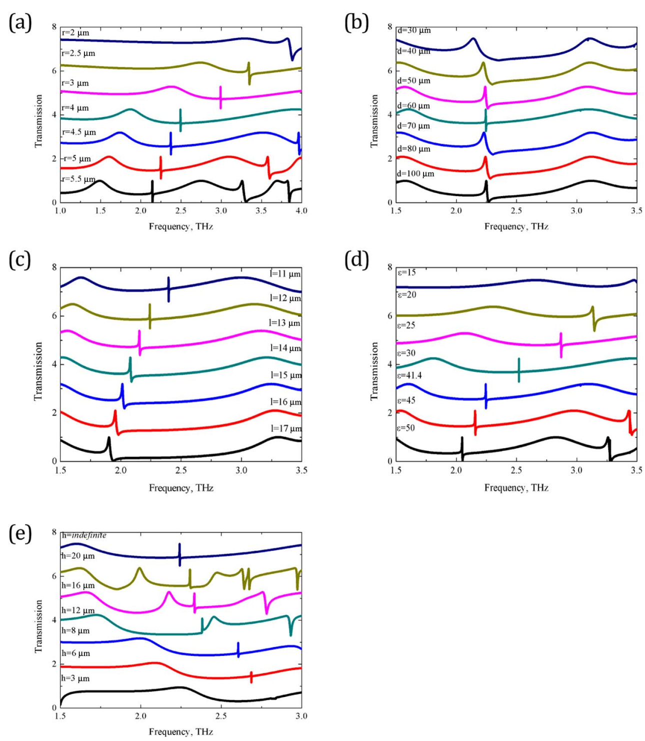

Fig. 5. Transmission versus frequency for various values of metamaterial parameters. (a) Transmission spectra for different radii r of cylinders of proposed terahertz metamaterial. (b) Transmission spectra for different center-to-center distances between clusters d. (c) Transmission spectra for different interparticle distances l. (d) Transmission spectra for different permittivities ε. (e) Transmission spectra for different heights h.

$d = 60$ μm leads to the widening of the resonant peak, i.e., a decrease of the Q-factor. In Fig. 5(c), the transmission spectrum for various values of interparticle distance l is depicted. The larger value (initial interparticle distance is $l = 12$ μm) results in a blueshift of resonant frequency with following widening of resonance. Figure 5(d) shows the transmission spectra behavior in dependence of different permittivities ε of cylinders. From the graph, the smaller values of permittivity ($\varepsilon = 15$) correspond to decrease of electric size of clusters terminating with the broadening of resonance. However, the increase of ε leads to the redshifting of resonance with squeezing of the peak. Moreover, Fig. 5(e) shows the transmission of metamaterial of realizable heights h of cylinders. For the purpose of experimental feasibility, we simulated proposed metamaterial height differing from 3 to 20 μm and for considered infinite $h = \infty$ height. Smaller heights of cylinders lead to a redshift of resonant frequency with eventual damping of resonance.

In this Letter, we present a new metamaterial-induced transparency effect arising from extinguishing all kinds of multipoles at the same time. To confirm our assumption, we propose a metamaterial structure and carry out multipolar decomposition. Simulation shows that at a transparency peak of $f = 2.2446$ THz of $Q = 1320$ there is suppression of all types of multipole moments up to zero assuming a non-radiative system. Although, the Q-factor of metamaterials is described as $1/Q = 1/Q_{\mathrm{rad}} + 1/Q_{\mathrm{non}}$, where Q_{rad} is the radiating loss and Q_{non} is the nonradiating or dissipative loss. While the radiating losses in our case are low due to the nullifying of multipoles, but not zero, the Q-factor is limited by the radiating losses of multipoles and Joule losses in $LiTaO_3$. For the ideal case of zero multipoles lossless materials, we can expect an extremely high Q-factor. These results are extremely important in designing invisible to external observer systems that could be used in many applicable fields such as nanophotonics and plasmonic and applied optics.

In summary, we discussed the difference between the proposed effect and well-known EIT and Fano-type resonances. Indeed, Fano resonance is determined by interference between dark and bright modes. However, EIT is a special case of Fano-resonance in which frequencies ω_1 and ω_2 of the modes are coincide. In this case, the Fano curve goes to the narrow peak of the Lorenz transparency form [31,32]. In our case, the power scattered by multipoles is very low for all multipoles on the resonance frequency 2.24 THz. Indeed, this behavior is defined by the contribution of electric, magnetic, and electric quadrupole dipole modes, which are very low, but uncoinciding frequencies. Figure 4 shows that the minimum deep of the electric dipole goes ahead of the maximum peak while, for magnetic and toroidal dipoles, vice versa for quadrupoles. Indeed, our resonance can be characterized as Fano-like form. Then, we present here, to the best of our knowledge, a novel type of transparency effect due to the mutual cancellation of multipoles of the same kind excited in each cylinder with coinciding resonant frequencies.

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