Extremely high Q-factor metamaterials due to anapole excitation

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We have designed and fabricated a metamaterial consisting of planar metamolecules which exhibit unusual, almost perfect anapole behavior in the sense that the electric dipole radiation is almost canceled by the toroidal dipole one, producing thus an extremely high Q-factor at the resonance frequency. Thus we have demonstrated theoretically and experimentally that metamaterials approaching ideal anapole behavior have very high Q-factor. The size of the system, at the millimeter range, and the parasitic magnetic quadrupole radiation are the factors limiting the size of the Q-factor. In spite of the very low radiation losses the estimated local fields at the metamolecules are extremely high, of the order of 10^4 higher than the external incoming field.

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I. INTRODUCTION

The static toroidal dipole moment, also known as the anapole, was firstly introduced by Zel'dovich in 1958 [1]. Its importance is widely recognized in nuclear, molecular, and atomic physics [2]. The static toroidal moment can be represented as poloidal currents flowing on the surface of the torus perpendicularly to its axis and producing a static magnetic field entirely concentrated within a torus. Zel'dovich [1] was able to explain parity violation of weak interactions in atomic nuclei due to the anapole concept. This current configuration allowed him to predict the nuclear anapole moment in cesium 14 as an atomic parity violating effect.

It should be noted that the concept of static currents on a surface of the torus is very close to an idea examined by Tamm in 1956. [3]. We can imagine a system of two currents, one of them $\mathbf{j_1}$, flowing along the circumference of a circle and the second current $\mathbf{j_2}$ flowing along a straight line perpendicular to the plane of the circle and passing through its center. The first current $\mathbf{j_1}$ excites the poloidal magnetic fields $\mathbf{H_1}$ along the meridians of a gedanken torus, while the $\mathbf{j_2}$ generates the fields $\mathbf{H_2}$ representing the concentric circles tangential to the surface of a torus. This implies that the lines of total field $\mathbf{H}$ form a helix on the surface of a torus. It is obvious that this helix for a given cross section of the torus will be closed at certain ratios between the currents. Thus the presented configuration of currents is analogous to the static toroidal dipole and is most similar to the geometry of the supertoroidal moment considered by Afanasiev and Dubovik [4].

The dynamic toroidal moment is less known. Although it radiates electromagnetic fields with angular momentum equal to conventional dynamic multipole momenta, toroidal moments are often excluded from the standard multipole expansion of current excitation [5,6]. Interestingly, omitting the toroidal moment in the multipole expansions leads to nonphysical results in media with toroidal topology [7,8], although the toroidal moment in multipole expansion does not usually contribute significantly to radiation stemming from sources with dominating electric and magnetic moments. The concept of dynamic toroidal moment must also be taken into account for the whole family of radiating modes of the sources; as pointed out in Ref. [9], classical multipoles are related to transverse currents, while the dynamic toroidal multipoles are the result of oscillations of radial currents. These radial components give rise to an additional family of multipoles, radiating on top of conventional electric and magnetic multipoles.

The dynamic toroidal moment was studied quite recently [6–8] by exploiting the idea of metamaterials. Metamaterials in general are composite systems employing geometrical features in their structure so as to produce new resonances leading to electromagnetic properties which do not occur in natural materials. In particular, they present a unique opportunity for manipulating features on the subwavelength scale, allowing thus to achieve effects such as negative refraction, cloaking, strong field localization, etc. [10–16].

Recently, the first experimental demonstration of toroidal metamaterials was performed. Kaelberer *et al.* [17] were able to induce currents in split ring resonator (SRR) arrangements, resembling poloidal currents flowing along the meridians of the torus due to the configuration of conductive currents in the SRR. This configuration allowed for strengthening of the toroidal moment to a detectable level, while simultaneously weakening the electric and magnetic moments. Observation of the toroidal response in specially designed three-dimensional clusters caused a significant impact on the metamaterial community [2,17–23] and gave rise to a series of exciting discoveries in the field of toroidal electrodynamics (see Ref. [2] and references therein).

A distinct feature of toroidal metamaterials, the anapole excitation, is of nontrivial, nonradiating nature. In particular, the term "nontrivial" refers here to the ability of radiating the vector potential in the absence of electromagnetic fields. Moreover, at the same time, several publications emphasize the properties of destructive interference between the toroidal and the electric dipole moments. The result of this interference is the reduction of the radiation losses in materials or metamaterials which produces an effect analogous to electromagnetically induced transparency (EIT) [19–21]. Several works discussed the possibility of radiating vector potentials in the absence of electromagnetic fields leading to the dynamic Aharonov-Bohm effect [4,19,7,22]. These works claimed a high Q-factor associated with toroidal metamaterials to be due to the anapole excitations. This is significant for cloaking behavior and many

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other applications in photonics and plasmonics demanding strong localized fields, such as nonlinear excitations, and high Q-factor cavities of spacers, lasers, and qubits [2,20,22–24]. As mentioned above, anapole sources might also offer important applications for the dynamic Aharonov-Bohm effect. This problem is of interest for many reasons; one of them is the prospect for secure data communication [5,7,19,22,23].

We note that the toroidal geometry of metamolecules (the elementary blocks of this kind of metamaterial) is complicated because of the necessity to design elements resembling the toroid geometry [2]. This requirement limits the application of toroidal metamaterials in the visible and THz frequency range, where the toroidal metamolecules could be fabricated as three-dimensional (3D) inclusions at the micro- and nanoscales. The planar metamolecules can be fabricatedmore easily, e.g., by photolithography [25].

Traditional planar metamaterials based on SRRs and their hybrid modifications have been extensively studied in recent years for demonstrating negative refraction, magnetoinductive waves, THz modulators, and biological and chemical sensors [26–33].

Exotic properties of hybrid SRRs are observed in connection with the resonant nature of their response. Both the electric and magnetic responses are accompanied by strongly localized electromagnetic fields within the metamolecules. However, the Q-factor of such metamaterials is limited by nonradiative and radiative losses in metamolecules. Nonradiative losses are especially crucial for metallic elements at high frequencies and can be reduced by employing as elements in metamolecules, materials of low loss, such as superconductors or even dielectrics. On the other hand, the radiation losses are defined by the electromagnetic fields' localization inside the metamolecule and are controlled by the geometry of resonators.

There are several approaches to minimize the radiation losses in metamolecules. The first method is to use an asymmetric SRR with the possibility of exciting two destructively interfering bright modes. In particular, Fedotov *et al.* proposed two asymmetric SRRs with slightly different shapes. The radiation losses are rather low here due to the dark mode caused by destructive interference between currents in each SRR [34]. This interference leads to an asymmetric peak in transmission characteristics and a high Q-factor. At the same time, such SRR elements need to be almost overlapping, which implies strict requirements for fabrication.

The second method, as well as the first one, is known as the EIT (electromagnetically induced transparency) in metamaterials and involves the excitation of two modes, bright and dark. This approach allows coupling of a radiative bright mode with a subradiative and noninteracting with plane wave dark mode. In this case the hybrid metamolecule consists of two elements, each one of them supporting these modes. Hybridization of the resulting resonances produces a narrow peak of the Fano-type resonance which was considered previously in atomic systems [35,36]. The concept of metamaterials allows for observing EIT in many artificial structures [37–39].

The third approach, based on the anapole excitation, is known as a new mechanism of electromagnetic transparency in toroidal metamaterials [2,7,19]. In contrast to the Fano-type resonance, the anapole excitation does not require two scattering channels in metamolecules. It is generally accepted that anapole is a mode that occurs as a result of destructive interference between the toroidal and electric dipole moments, which are both radiating [5,8,19,22]. For the ideal anapole, radiation losses are absent due to the above-mentioned interference in the far-field zone. Thus one can expect a very high Q-factor in almost ideal anapole metamaterials.

In this paper, we theoretically and experimentally study planar anapole metamaterials. We show that the anapole metamolecule is an almost ideal resonator with an extremely high Q-factor accompanied by strong localization of the electromagnetic fields within the metamolecule.

II. POINT ANAPOLE RESONATOR

Let us consider first the toroidal dipole $\mathbf{T}$ source given by the following formula in terms of the current density $\mathbf{j}$ (we shall consider the limit as the source approaches the pointlike limit [3], and a harmonic excitation of the form $\exp(i\omega t)$)**:**

$$\boldsymbol{T} = \frac{1}{10c}\int d^3r[\boldsymbol{r}(\boldsymbol{r}\cdot\boldsymbol{j}) - 2\boldsymbol{j}r^2]. \tag{1}$$

At the same time the electric dipole is given by the well known formula

$$\boldsymbol{P} = \frac{1}{i\omega}\int d^3r\,\boldsymbol{j}. \tag{2}$$

A distinctive feature of the toroidal dipole is its ability to radiate with the same angular momentum as the electric dipole [3]. Indeed, consider the toroidal and electric dipoles placed at the origin, $r = 0$. One can see that the electric and magnetic fields radiated by superposition of the two dipoles are

$$\boldsymbol{E}_{\text{tot}} = \boldsymbol{E}_P + \boldsymbol{E}_T = \left[\frac{\boldsymbol{r}\cdot(\boldsymbol{P} - ik\boldsymbol{T})F(\omega,r)}{c^2r^2}\boldsymbol{r} - \frac{G(\omega,r)}{c^2}(\boldsymbol{P} - ik\boldsymbol{T})\right]\frac{\exp(-ikr + i\omega t)}{r}, \tag{3a}$$

$$\boldsymbol{H}_{\text{tot}} = \boldsymbol{H}_P + \boldsymbol{H}_T = -\frac{ikD(\omega,r)}{cr}[\boldsymbol{r}\times(\boldsymbol{P} - ik\boldsymbol{T})]\frac{\exp(-ikr + i\omega t)}{r}, \tag{3b}$$

where D, F, G can be found in [5,19].

Note that the fields of the anapole disappear in the case of $\mathbf{P} = ik\mathbf{T}$; i.e., destructive interference of toroidal and electric dipole moments takes place everywhere except $r = 0$ [3,17]. This configuration forms a nonradiating point anapole, with the fields existing only at the point $r = 0$, and described by the δ function [5,22]:

$$\boldsymbol{E}_{\mathbf{tot}}(r=0) = ik\boldsymbol{T}\delta(\boldsymbol{r})\exp(i\omega t), \tag{4a}$$

$$\boldsymbol{H}_{\mathbf{tot}}(r=0) = ik\,\mathrm{curl}[\boldsymbol{T}\delta(\boldsymbol{r})]\,\exp(i\omega t). \tag{4b}$$

It is worthwhile to describe the field topology of the point anapole [22]. Equations (4a) and (4b) determine a localized electric field at the point of origin ($r = 0$) while the magnetic field is represented by a loop in the plane, orthogonal to the **E** vector. Without dissipation losses, this allows us to design a resonator which is free of radiation losses; the entire power is confined at only one point, which corresponds to the pointlike distribution of currents, proportional to $\delta(r)$. It also means that the anapole is an ideal resonator with an extremely high, actually infinite, Q-factor. A high Q-factor resonator has a minimum loss power P_d, i.e., $Q = \omega_0 W/P_d$, where W is the energy stored in the resonator. Obviously, our intention will be to apply the resulting property for the realistic case of a practical configuration. Finite size current density can be expanded in powers of a/r, where a is the characteristic size of the source and r is the distance from the source. In practice, other parasitic multipoles besides toroidal and electric dipole moments will be excited and will contribute to a significant reduction of the Q-factor as a result of their radiation. To reduce the role of the parasitic multipoles and boost the anapole contribution, the resonator design needs to maintain a spatially confined magnetization, circulating around a concentrated electric field. It is important that the volume occupied by electric and magnetic fields tends to zero within the metamolecule. The field distributions, different from the δ function, will be accompanied by the contribution of additional dipole moments, thus further reducing the Q-factor.

Metamaterials that support a strong toroidal response are well known. Usually they consist of rather complicated 3D metamolecules, although some of them are based on SRR modified inclusions [2]. Fabrication of 3D metamolecules is challenging, especially in the visible and THz spectrum. In this regard, the need for a design of a planar toroidal metamaterial is evident, especially for the anapole metamaterials.

III. STRUCTURE OF THE SYSTEM

Here we report metamaterials consisting of planar conductive metamolecules. Each metamolecule is formed by the two symmetrical split rings (inset of Fig. 1). The incident plane wave with electric field **E** paralled to the central wire excites circular currents **j** along the loops. Each current induces the circulating magnetic moments **m** wreathing around the central part of the metamolecule. As a result, this leads to a toroidal moment **T** oscillating back and forth along the axis of the metamolecule. Two side gaps also support a magnetic quadrupole moment **Qm**. Moreover, due to the central gap, electric moment **P** can be excited in the metamolecule (Fig. 1); the central gap is a necessary part of the anapole. We aim to miniaturize metamolecules in order to bring their field close to the geometry of a point anapole. However, in the present work the dimensions of the metamolecule shown in Fig. 1 are rather large and are given in the caption of Fig. 1. Calculations for other sizes were also performed and are presented in the Appendix.

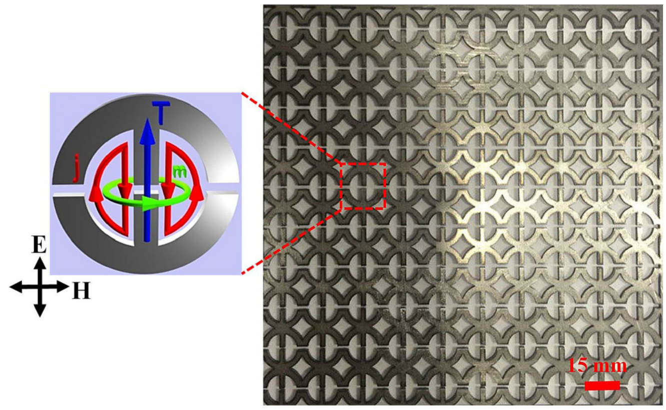

FIG. 1. A fragment of a metamaterial supporting toroidal dipolar excitation. Red arrows show displacement currents $\boldsymbol{j}$ induced by the vertically polarized plane wave, blue arrow shows toroidal dipole moments **T** of the metamolecule, green arrow shows circulated magnetic moment **m**; the picture shows a metamaterial sample. The dimensions of the fragment are 15 mm × 15 mm with the central gap equal to 0.75 mm and the lateral gaps at 1 mm. The period of the metamaterial is 15 mm in both directions.

The anapole character of our design, besides this extremely narrow resonance shown in Fig. 2, is confirmed by calculating the distribution of the local fields and the density of the displacement currents induced in the metamolecule, which are depicted in Fig. 3. The magnetic field at the resonance frequency corresponds to the closed vortex circulating around the central axis of the metamolecule. At the same time, the electric field is localized in the central gap in a region of about $(1/50)\lambda$ and is related to the field E_0 of the incoming plane wave as $E/E_0 = 19160$, whereas magnetic field is related to H_0 as $H/H_0 = 688$. We note that this configuration of fields is close to the topology of point anapole proportional to a δ function.

To assess the role of the anapole contribution in forming the observed response, we calculate the relative strength of the standard multipoles in terms of the electromagnetic power they scatter in the far-field zone. These contributions of the multipole moments induced in the metamolecules are calculated [Fig. 4(a)] based on the density of the conducting currents in metamolecules (Fig. 3). This approach allows us to clearly reveal the near-field signature of the multipolar current excitations to their electromagnetic response in the far field. One can see that at the resonance, the contribution of the magnetic dipole and electric quadrupole are strongly suppressed and there is a narrow range of frequencies close to 9.55 GHz, where the far-field scattering due to the resonant toroidal and electric excitations dominates all other standard multipoles. It is important that in the vicinity of the frequency $f = 9.54143$GHz the power radiated by the toroidal dipole **T** prevails in the system and is equal to the power of the electric dipole moment **P**. This corresponds to the anapole excitation in metamolecules and confirms the field configuration shown in Fig. 3. We also compared the phases of toroidal and electric dipoles [Fig. 4(b)] produced by the metamaterial slab. Indeed, the phase calculation of the complex functions is a problem with multiple solutions. Solution choosing must be performed

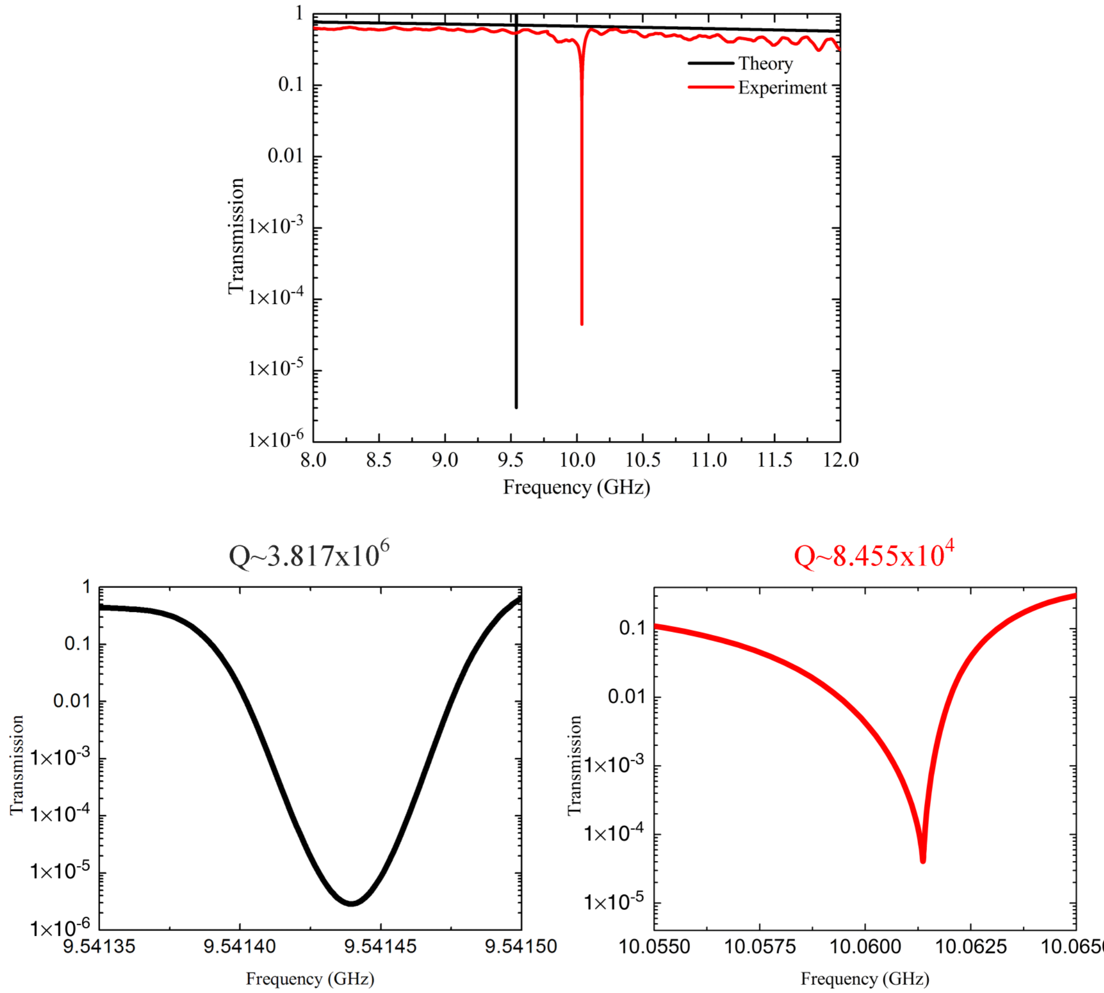

FIG. 2. Theoretical results of transmission calculated by CST MICROWAVE STUDIO (black lines) and experimental (red lines) spectra obtained for the sample shown in Fig. 1. These results and data as well as those in Figs. 3 and 4 were obtained for the dimensions shown in the caption of Fig. 1.

accurately by using conditions such as Kramers-Kronig, etc. The excited dipoles at the resonance frequency 9.54143 GHz are characterized by contributions of equal strength, while the phases have a 90° difference [see Fig. 4(b)]. Such values of amplitudes and phases of the toroidal and electric dipole moments satisfy the relation $\mathbf{P} = \mathbf{T}$ which leads to their cancellation and forms an anapole according to Eq. (3). At the same time, $\mathbf{T}$ and $\mathbf{P}$ are more than 10^2 times greater than the other multipoles in the system with the exception of the magnetic quadrupole **Qm** which is quite high. Interestingly, it was concluded in [25] that an isolated toroidal dipole moment is in principle unachievable in planar geometry and a strong magnetic quadrupole moment **Qm**, as well as an electric octopule moment **Oe** always accompanied this metamaterial response. The contribution of the magnetic quadrupole **Qm** is fully distinguished from the anapole contribution in the metamolecule. Its manifestation is obvious and completely corresponds to the Savinov's consideration [25]. The presence of quadrupole **Qm** is a parasitic factor and prevents us from achieving the even higher Q-factor predicted by the point anapole concept. Nevertheless, to our knowledge, the numerically computed $Q = 3.817 \times 10^6$ is the highest value ever achieved by modeling of a metamaterial at which $a/\lambda \ll 1$.

Let us mention now other types of resonators that achieve high values of Q-factor and are classified as ultrahigh Q resonators according to the standards in optical resonators. These resonators possess complicated bulk geometry and have dimensions higher than those corresponding to the resonance wavelength. They are based on principles such as the Fabry-Perot resonances ($Q \sim 2000$), the photonic crystals ($\sim$15 000), and the whispering gallery ideas ($Q \sim 10^9$, although with the cavity volume $\sim 3000\,\mu\text{m}^3$) ([40] and references therein). The highest Q-factor planar resonator ($Q \sim 10^6$), known as the superconductor spiral resonator, has an effective dimension of more than a wavelength [41]. Moreover, the laser cavities exhibit a higher Q-factor but their size and, most importantly, the field localization spot exceed the subwavelength limit, while the metamolecules proposed here make it possible to localize the fields at a much smaller scale.

We note that planar metamaterials have important limitations due to dissipation losses of metamolecules and substrate (in particular, due to Fabry-Perot resonances at certain frequencies such that the wavelength in the dielectric fits in the substrate thickness; as a result, multiple reflection of electromagnetic waves occurs between the walls of the substrate [25]).

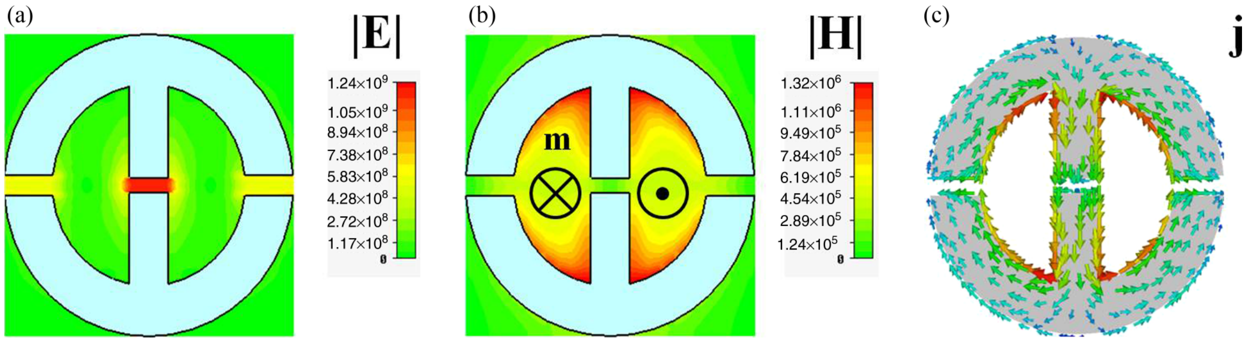

FIG. 3. Calculated distributions of the corresponding electric field $|E|$ (a), magnetic field [absolute value |H| (b)], and amplitude of the conductive current **j** (c) induced in the metamolecule at 9.54 143 GHz.

To demonstrate the possibilities of the proposed metamaterial, we have fabricated the sample from a slab of steel using the laser cutting method. We have skipped the dielectric substrate to avoid the loss factors associated with it. We included in the sample 10×10 metamolecules of 2 mm thickness; each metamolecule is cut in the form depicted in Fig. 1. The size of each metamolecule is $15\,\text{mm} \times 15\,\text{mm}$ and the period of the metamaterial is 15 mm.

IV. EXPERIMENTAL CHARACTERIZATION OF A METAMATERIAL SAMPLE

For experimental characterization of metamaterials we carried out measurements of $S21$ parameters (transmission) in an anechoic chamber by the two-horns method. Two broadband horn antennas P6-23M for electromagnetic radiation emission and detection were located at a distance 1 m from the metamaterials samples. The transmission coefficient $S21$ of the electromagnetic waves through the metamaterial slab was measured by a vector network analyzer Rohde & Schwarz SVB20 at frequencies 8–12 GHz.

We would like to stress here relevant experiment details. A narrow resonance peak or dip is expected to be sensitive to a variety of external factors: vibrations, multiple reflections, and, especially, the position of the metamaterial sample relative to the distribution of the external field. For this reason we have applied micrometer screws for accurate adjustment of the sample position. Thus we found a high Q-factor resonance dip close to the frequency of 10.06 GHz (Fig. 2, red line). To identify this narrow dip, we used the 40 000 points in a selected frequency range. A sharp resonance dip (at half power above the minimum transmission its width was 119 KHz) was found at the central frequency of 10.061 GHz. This value is rather close to that of 9.54143 GHz expected from simulations. The inset in Fig. 2 shows an expanded graph of the dip in the frequency range 10.0550–10.0650 GHz. Thus we can estimate the Q-factor of the resonance as 8.455×10^4. The origin of the dip is defined as the anapole mode ($\mathbf{T} + \mathbf{P}$) accompanied by a parasitic magnetic quadrupole **Qm**.

Next we discuss possible applications of anapole metamaterials. The anapole high Q-factor metamaterial proposed in this paper offers interesting opportunities in connection with the light-matter interaction. Tunable metamaterials and modulators at the THz range are accompanied by interaction of strong fields localized at metamolecules and the surfaces of semiconductor inclusions; the latter are located near

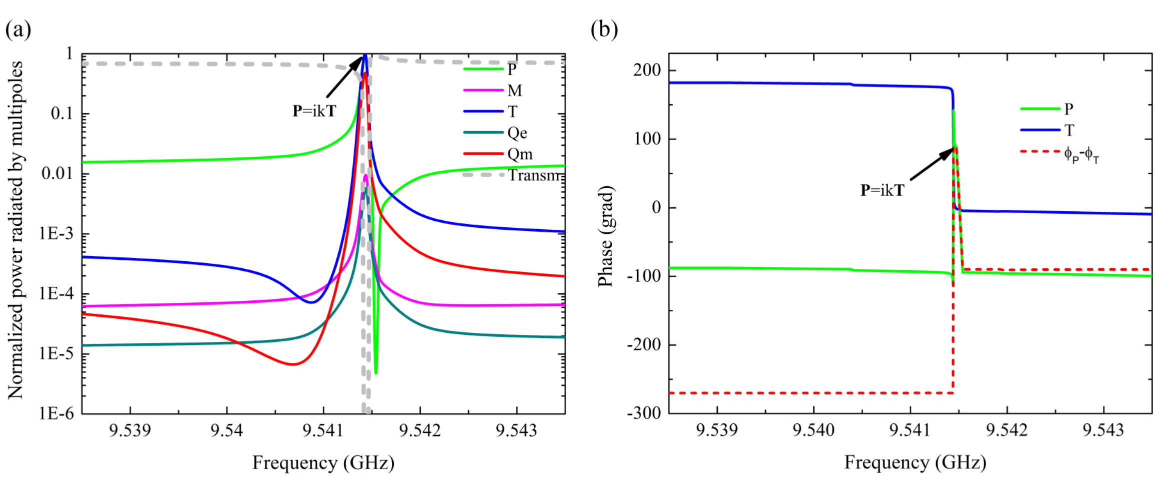

FIG. 4. Contributions of the five strongest multipolar excitations (see text) to the reflection of the metamaterial array. The reflection amplitude is obtained by coherent (amplitude and phase) summation of all multipole contributions. The log scale in the y axis is chosen so as to reveal more clearly the contribution of the quadrupole terms as well. (b) The phases as well as their difference $\phi_P - \phi_T$ (dashed line) of the electric and the toroidal dipole moments vs frequency.

metamolecules and can act as tunable elements [42]. The tunability appears here because the conductivity of semiconductors can be varied by an external femtosecond pump laser or by electrical gating. The semiconductor inclusion can be metamaterial substrate or an additional inclusion in the gap of the SRR where the ac electric field has its maximum amplitude. However, THz modulators and sensors achieving strong tunability and sensitivity are limited usually by the low Q-factor of metamaterials, mainly due to radiation losses associated with the electric and magnetic dipolar responses of metamolecules. Thus metamaterials with dominating anapole response should be capable of supporting extremely high Q-factors and are promising candidates for modulators achieving strong tunability with smaller pump power. Since the region of localized electric field is of subwavelength extent, one can reduce device dimensions for the so-called THz spectral regime, for which less pump power is required for tuning the properties of semiconductors.

Another possibility for anapole response application is in reducing radiation loss of superconducting quantum bits [43–45] and, in particular, in qubits playing the role of meta-atoms in quantum metamaterials [24]. When cooled to ultralow temperatures, superconducting loops containing Josephson junctions work as macroscopic two-level quantum systems, commonly called qubits. Reducing radiation loss of qubits makes their coherence times higher, which brings an advantage for qubit functionality.

We note that quantum nonlinear resonators, in order to act as qubits, need to have as low as possible radiation losses. Therefore, in order to increase the lifetime of the qubit, resonators should have a high Q-factor and should be miniaturized. Increasing the size of meta-atoms to the dimensions comparable to the wavelength leads to radiation losses. Anapole meta-atoms are promising candidates for being used as qubits, providing significant benefits in this area due to their high Q-factor and reduced radiation losses.

Moreover, the prior metamaterials based on hybrid metamolecules, in which asymmetrical currents can be excited, are characterized by the strong presence of the electric and magnetic moments. These are the so-called electric-field-coupled resonators and their modifications [46]. In these metamaterials, generally one has the ability to act with either one gap in the center of the metamolecule or with the lateral gaps; this situation does not allow achieving high Q-factors. However, due to similar configuration of currents inside such metamolecules, we expect that the contribution of the toroidal moment can be significant in them. More likely, the toroidal concept can contribute to the explanation of many effects in such metamaterials, such as negative values of permittivity, permeability, and negative refractive index. Thus it seems worthwhile for certain phenomena in planar metamaterials and other types of metamaterials to be reconsidered by the inclusion of the toroidal moment, because at the time of publication of relevant works (before 2010), much attention had not been given yet to the toroidal moment.

However, a strong coupling between electric and toroidal multipoles within metamolecules is more typical in anapole metamaterials with both central and lateral gaps, as in our case. We think that the design of high Q-factor metamaterials needs to focus on such a ratio between currents in metamolecules that can lead to destructive interference between the toroidal and electric moments [due to Eq. (3)] and other significantly reduced multipoles.

In summary, we have designed and fabricated an anapole metamaterial consisting of planar metamolecules. The anapole behavior stems from the fact that the contributions of the dipole moments of toroidal and electric nature interfere destructively. As a result, a very high Q-factor is obtained at the resonance which is limited mainly by higher-order effects. Such an anapole behavior and the corresponding high Q-factor can find their use in modulators and sensors as well as in superconducting qubits, substantially increasing their quantum coherence times.

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APPENDIX

We also studied our metamaterial for various values of period, gap sizes, thickness of dielectric substrate, and for other polarization. Figure 5(a) shows the results of our simulations as the lateral gaps vary in the range 0.25–3 mm. The size of the central gap is fixed at 0.75 mm. For the smallest gap of $d = 0.25$ mm a narrow resonance dip appears characterized by a relatively strong toroidal contributions **T**, which, however, is 100 times less than electric dipolar response **P** [Fig. 5(b)]. As the side gaps are increasing the size difference between the contributions of **P** and **T** diminishes and disappears at $d = 1$mm. Thus, at this size of the lateral gaps, the equality in size of the contributions of the toroidal and the electric dipoles and their phase difference leads to their almost perfect destructive interference and generates the anapole excitation. As a result, we can observe very high Q-factor resonance for gaps close to 1 mm [Fig. 5(a)]. The further increase of the size of the lateral gaps is nonmonotonic and produces a broadening of resonance and moving to the high frequencies due to decoupling between electric and toroidal dipolar modes and the dominance of the contribution of the electric dipole **P**. Presumably, we observe decreasing of Q-factor out of anapole parameters [Fig. 5(a)].

Although the proposed metamaterial is a monolith with touching adjacent inclusions (period equal to 15 mm), it is important to estimate how its response will be modified as the inclusions increase their size (while still touching each other) so that the period D becomes larger. We calculated the transmission of the metamaterials slab for the period D in the range 15–55 mm [Fig. 6(a)]. Evidently, the calculated spectra attain a redshift of resonances due to the increased

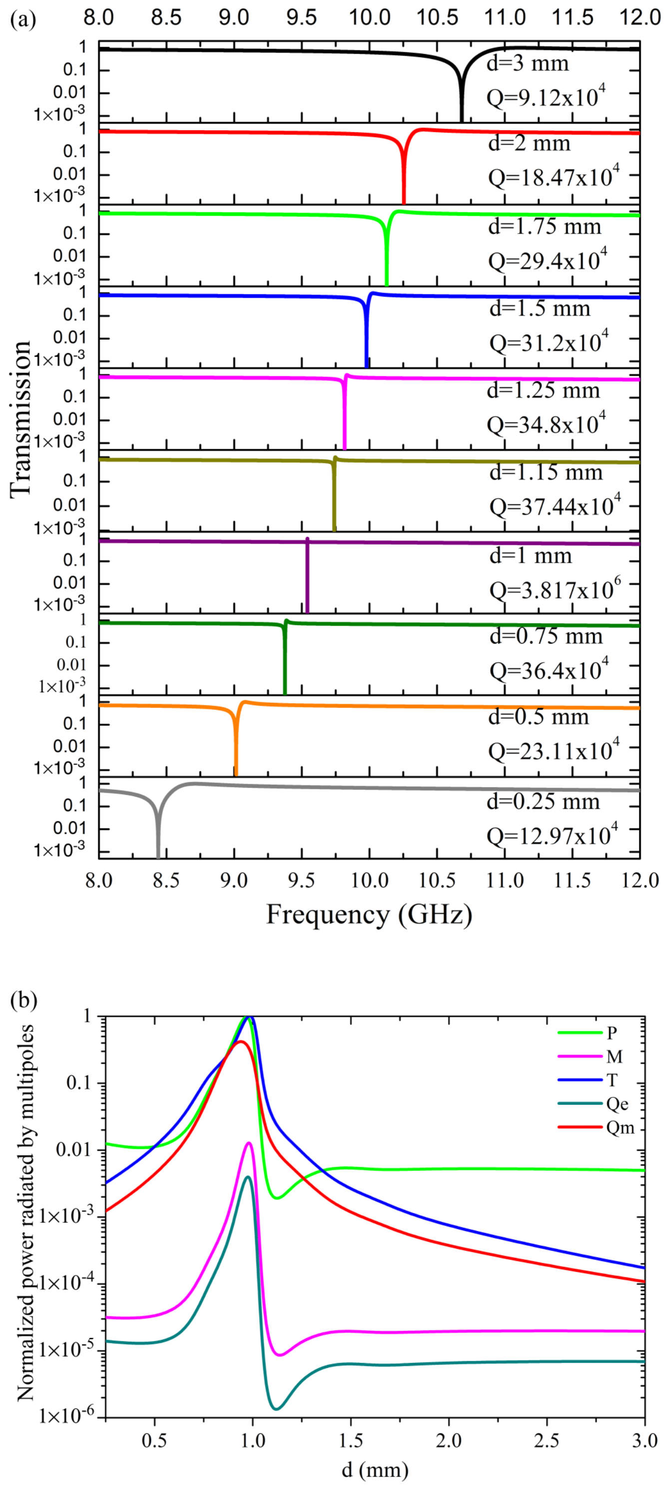

FIG. 5. (a) Theoretical results of transmission calculated by CST MICROWAVE STUDIO obtained for the sample shown in Fig. 1 for different sizes of the thickness d of the lateral gaps (0.25, 0.5, 0.75, 1, 1.15, 1.25, 1.5, 1.75, 2, and 3 mm; the correspondence of sizes and curves is shown at the points of their maxima). (b) Contributions of the five strongest multipolar excitations (see text) to the radiation of the metamaterial array for different d. The radiation is obtained by coherent (amplitude and phase) summation of all multipole contributions. The log scale in the y axis is chosen so as to reveal more clearly the contribution of the quadrupole terms as well.

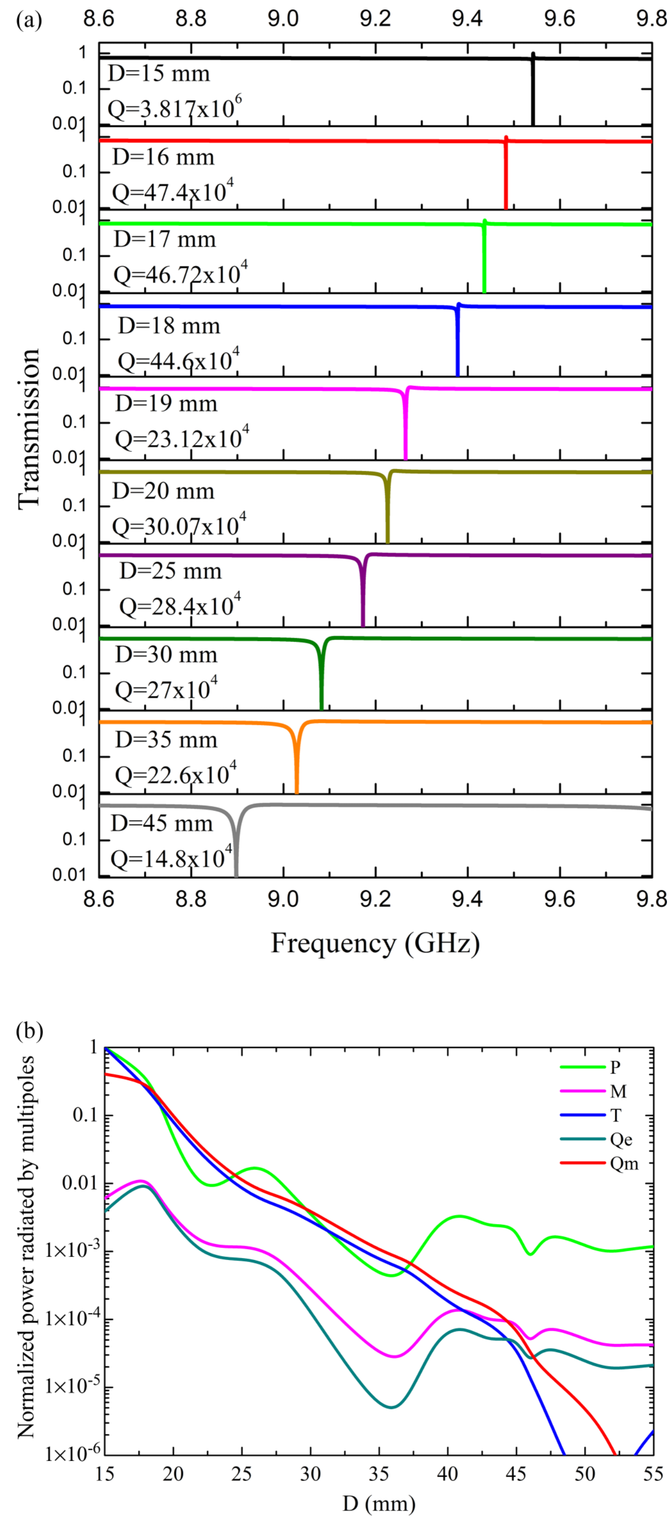

FIG. 6. (a) Theoretical results of transmission calculated by CST MICROWAVE STUDIO obtained for the sample shown in Fig. 1 for different periods of metamolecules D (15, 16, 17, 18, 19, 20, 25, 30, 35, 45 mm). (b) Contributions of the five strongest multipolar excitations (see text) of the metamaterial array for different D. The transmission amplitude is obtained by coherent (amplitude and phase) summation of all multipole contributions. The log scale in the y axis is chosen so as to reveal more clearly the contribution of the quadrupole terms as well.

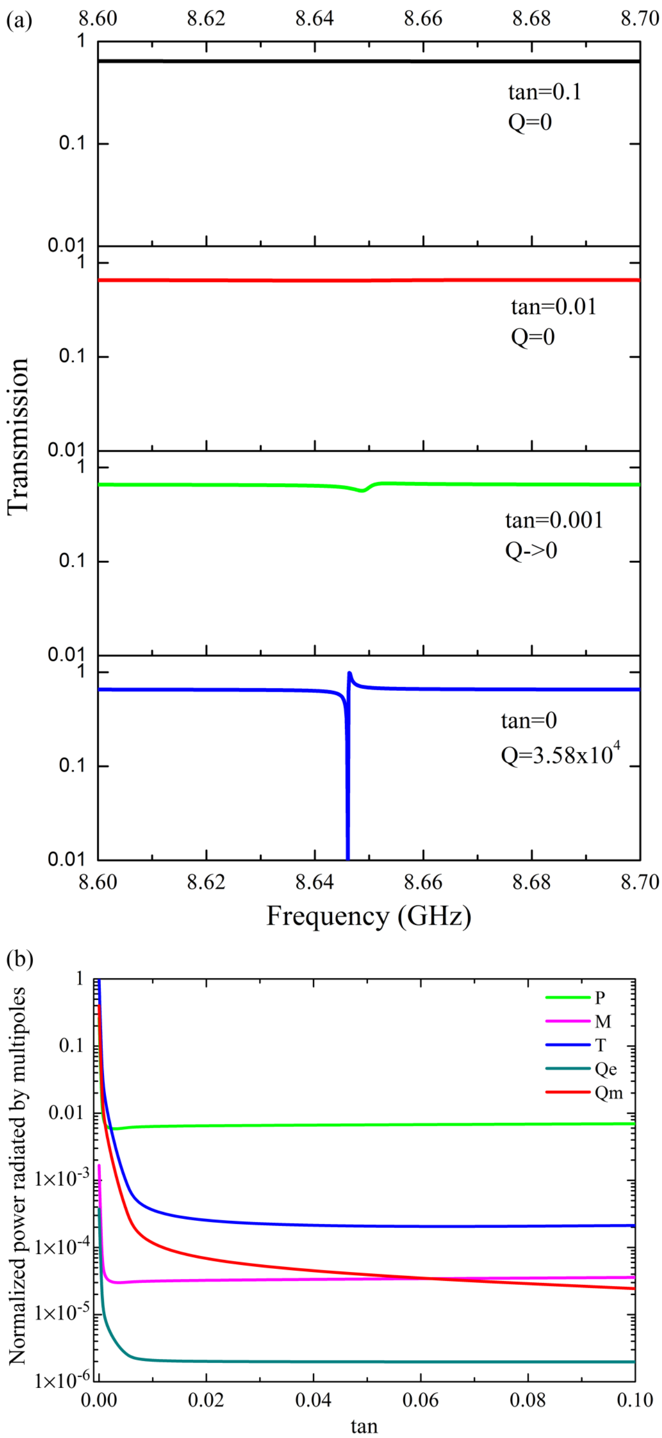

FIG. 7. (a) Theoretical results of transmission calculated by CST MICROWAVE STUDIO obtained for the sample shown in Fig. 1 placed on substrate, characterized by permittivity of $\varepsilon = 2$ and loss tangent 0, 0.001, 0.01, and 0.1, respectively. (b) Contributions of the five strongest multipolar excitations (see text) of the metamaterial array for different loss tangent. The transmission amplitude is obtained by coherent (amplitude and phase) summation of all multipole contributions. The log scale in the y axis is chosen so as to reveal more clearly the contribution of the quadrupole terms as well.

dimensions of the metamolecules, although the multipole contributions of radiated power retain anapolelike excitation

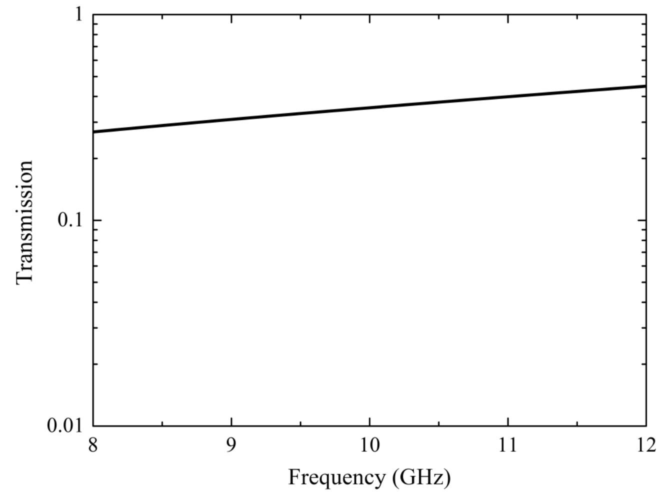

FIG. 8. Theoretical results of transmission calculated by CST MICROWAVE STUDIO obtained for the sample shown in Fig. 1, in the case of orthogonal polarization, i.e., when the electric field of the incident field is perpendicular to the center wire of the metamolecule shown in Fig. 1.

only for the smallest periods [Fig. 6(b)], which gives high $Q \sim 3.817 \times 10^6$ periods [Fig. 6(c)]; the electric dipole contribution dominates at large periods, which is the reason of resonance broadening and Q-factor damping less than 100 times [Fig. 6(a)].

Generally, in the metamaterial fabrications the planar inclusions are usually deposited on a dielectric substrate of certain thickness. The dielectric losses of the substrate can strongly reduce the resonance Q-factor and other characteristics of the metamaterial. Here we estimate the influence of the loss factor related to the dielectric substrate of 2 mm thickness; permittivity $\varepsilon = 2$; and loss tangent 0, 0.001, 0.01, and 0.1, respectively. For zero loss tangent we observe $Q = 3.58 \times 10^4$. We note that the resonant dip is strongly reduced already for tangent 0.001 and is moved to lower frequencies of 8.645 GHz; it is completely eliminated for losses equal to tangent 0.01 or higher. At the same time, one can estimate that the Q-factor for these cases tends to zero. Therefore, absence of a dielectric substrate seems to be required for a successful experimental realization of the high Q resonance. The contribution of the electric dipole, although broadened, dominates the radiated power and is, therefore, decoupled from the toroidal dipole, while the other multipoles are strongly reduced by the dielectric losses [Figs. 7(a) and 7(b)].

We also studied the other polarization case where the $\mathbf{E}$ vector is perpendicular to the center wire of the metamolecule (Fig. 8). Indeed, it is not possible to observe the anapole response for this polarization. A significant component for anapole observation is toroidal response which is a result of a magnetic closed field vortex. The corresponding vortex can be excited due to asymmetrical currents and magnetic moments circulated in each part of the hybrid metamolecule consisting of SRRs as depicted in Fig. 1, but for orthogonal polarization these currents are impossible.

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