Planar Superconducting Toroidal Metamaterial: A Source for Oscillating Vector-Potential?

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Abstract: We demonstrate the first superconducting metamaterial that can exhibit a profound toroidal dipolar resonance. Quantum behaviour of the superconductor and toroidal excitation of the metamaterial are both necessary prerequisites for observing the time-dependent Aharonov-Bohm effect.

OCIS codes: (160.3918) Metamaterials; (160.1245) Artificially engineered materials

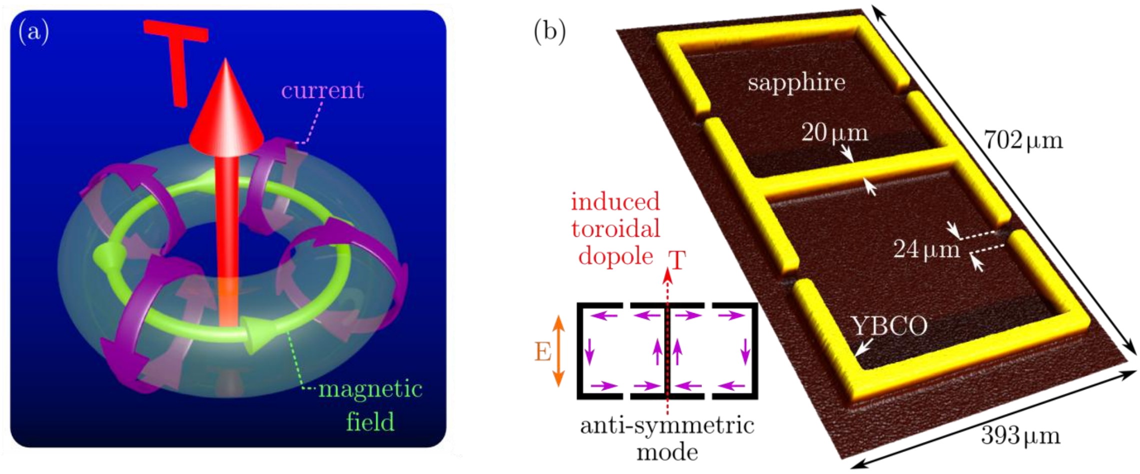

Fig. 1. (a) Artistic impression of the toroidal dipole. Currents flowing along the meridians of a torus create a closed contour of magnetic field which constintutes a toroidal dipole. (b) Three-dimensional profile scan of the unit cell of the manufactured metamaterial (colour represents height). Inset shows the polarization of the incident radiation relative to the unit cell (orange arrow, labeled 'E'), the configuration of currents in the anti-symmetric mode (purple arrows), and the orientation of the induced toroidal dipole (red arrow, labeled 'T').

Toroidal dipole is an exotic fundamental electromagnetic excitation that can be visualized as current oscillating along the meridians of a torus (see Fig. 1a) [1, 2]. Such configuration of currents cannot be represented in terms of the existing standard multipole expansion; toroidal dipole is in fact the lowest member of the whole family of toroidal multipoles. Although the contribution of toroidal excitations is weak in most natural phenomena, they can be resonantly enhanced using the metamaterial approach [2]. Following the first demonstration of a metamaterial with toroidal dipolar resonance, several alternative metamaterial designs have been studied, all of them relying on the fabrication of complex three-dimensional structures. Here we will demonstrate a truly planar metamaterial with a strong toroidal dipole response, which can be etched photolithographically in a thin superconducting film. Its high-quality resonance arises as a result of destructive interference between the toroidal dipole and several other multipolar modes. We note that similar configurations of interfering electric and toroidal dipoles are expected to enable testing the time-dependent Ahronov-Bohm effect, i.e. detecting the presence of time-varying electromagnetic vector-potential (**A**) in the region with no time-dependent electromagnetic fields (**E,H**) [3]. In case of our metamaterial, exploiting superconductivity not only helps to tackle losses, and thus enhance the toroidal response, but it is also necessary, due to macroscopic quantum behaviour, for observing the time-dependent Ahronov-Bohm effect.

The metamaterial, shown in Fig. 1b, has been created by patterning 300nm thick yttrium-barium-copper-oxide (YBCO) film on a sapphire substrate (1mm thick). The unit-cell of the metamaterial consisted of two asymmetrically split squares merged into a single elongated meta-molecule. The metamaterial was driven with radiation polarized along the short dimension of the unit cell (inset to Fig. 1b). The asymmetry in the splits of the squares allowed to excite an anti-symmetric current mode within the meta-molecule (inset to Fig. 1b) which lead to suppression of scattering via the electric dipole and strengthened the induced toroidal dipole response. Due to supressed scattering, the anti-symmetric mode was extremely sensitive to Joule losses. The material used for the conductive thin film, YBCO, is a high-temperature superconductor with the transition temperature in the range 80-90K. Therefore the Joule losses of the metamaterial could be significantly lowered by characterizing it at cryogenic temperatures.

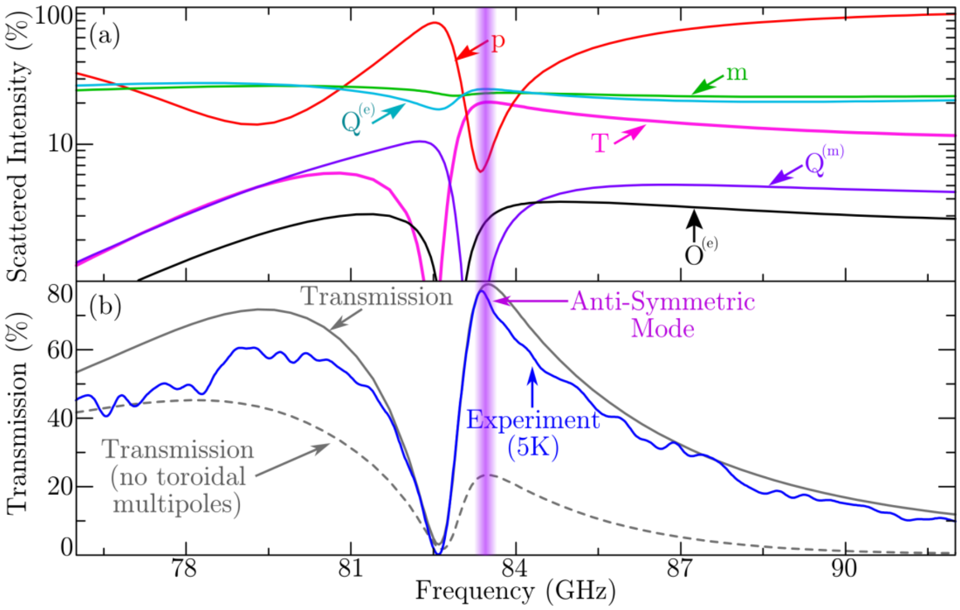

Fig. 2. Multipole decomposition of the response of planar toroidal metamaterial. (a) Intensity of the radiation scattered by the arrays of the six leading multipole excitations (**p**-electric dipole, **m**-magnetic dipole, **T**-toroidal dipole, $\mathbf{Q^{(e)}}$-electric quadrupole, $\mathbf{Q^{(m)}}$- magnetic quadrupole, $\mathbf{O^{(e)}}$-electric octupole). The scattered intensity is normalized with respect to incident radiation intensity. (b) Transmission of the metamaterial measured experimentally at temperature 5K (solid blue curve), calculated from multipole scattering with (solid grey curve) and without (dotted grey curve) the input of the scattering by the toroidal multipoles.

Figure 2a shows the decomposition of the radiation scattered by the metamaterial into the multipole contributions. All multipoles have been computed from the distribution of current density within the metamaterial, which, in turn, has been found by modelling the electromagnetic response of the metamaterial driven by normally incident plane-wave radiation. Each curve (in Fig. 2a) corresponds to the intensity of radiation that would be emitted by an array of multipoles (same pitch as the metamaterial) of just one type. For example, the radiation intensity scattered by the electric dipoles (**p**, red curve) corresponds to the intensity of radiation that would be emitted by an array of just the electric dipoles with the same amplitude as excited in each meta-molecule of the metamaterial by the incident radiation. The other multipoles considered in the decomposition are the magnetic dipole (**m**), toroidal dipole (**T**), electric quadrupole ($\mathbf{Q^{(e)}}$), magnetic quadrupole ($\mathbf{Q^{(m)}}$), toroidal quadrupole (too small to show in Fig. 2a), electric octupole ($\mathbf{O^{(e)}}$) and magnetic octupole (too small to show in Fig. 2a). The solid grey curve in Fig. 2b shows the net metamaterial transmission resulting from the combination of all considered multipoles, the experimentally measured metamaterial transmission at temperature 5K is also shown in Fig. 2b, with a solid blue curve.

From Fig. 2a one can clearly see that the contribution of the toroidal dipole is maximized at the anti-symmetric mode whilst the overall scattering of the metamaterial falls (leading to transparency window). The analysis of relative multipole contributions is complicated by the need to account for interference of radiation scattered by different multipoles. Figure 2b get around this difficulty by showing the metamaterial transmission that is computed by taking all multipole scattering into account (solid grey curve) and by including all multipole scattering *except* for the toroidal multipole scattering (dashed grey curve). Removal of toroidal multipole scattering results in a drastic reduction in metamaterial transmission. One therefore concludes that the anti-symmetric mode of the metamaterial is created through destructive interference of the toroidal dipole with other multipoles, including the electric dipole.

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