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Identifying and Separating Magnetic and Electric Microwave Responses of Chiral Elements

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Abstract—We propose a technique for identifying the type of resonance excitation by ac magnetic or electric fields in conducting chiral elements by reflection of electromagnetic waves in the standing- and traveling-wave modes. The technique was tested experimentally in the microwave range and confirmed numerically. We demonstrate the possibility of broadband matching of composite radar absorbing materials with the use of a lattice of resonance elements excited by magnetic field of the wave rather instead of the traditional quarter-wavelength effects.

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Intense investigations of chiral media have been stimulated by the transition from the optical to microwave range due to the creation of artificial chiral composites containing inclusions much smaller than the wavelength and spatially similar optically active molecules in the form of spirals and spiral chains. Recently, an inverse process has been observed, in which the results of microwave investigations initiate the creation of optical metastructures with the use of nanotechnologies and the optical and microwave techniques interpenetrate. The interest in chiral media is mainly related to the unique effects caused by resonant ring (closed) currents, which can be induced in chiral elements (depending on their orientations) under the action of alternating magnetic field h or electric field E. The current induced by magnetic field h creates the alternating magnetic and electric dipole moments; the magnetic moment contributes to permeability μ, while the electric moment contributes to the chirality parameter affecting the magnetic induction. When the ring current is induced by electric field E, the magnetic and electric dipole moments are also formed, but, in this case, the electric moment contributes to permittivity ε and the magnetic moment, to the chirality parameter affecting the electric induction. In addition, in chiral elements the electric field can induce resonant currents, which cause the resonance effects analogously to ordinary dipoles. In the literature, the resonance effect caused by the induced resonant ring currents is sometimes called the "magnetic resonance" or "magnetic response" when it is induced by a magnetic or electric field of the wave, while the resonance effects caused by excitation of dipole currents are called the "electric resonance" [1]. By "magnetic response" we shall basically mean the response to the magnetic excitation; the resonance effects caused by the ring currents will be called the "ring resonance" (RR). The resonance effects excited by the dipole currents will be called the "dipole resonance" (DR).

Taking into account the vast variety of elements, multiple resonances, and difficulties in direct measurements of the magnetic and electrical parameters [2], it is important to develop techniques for identifying the type of excitation. The exact resonator method makes it possible to perform direct measurements, but requires preparing special samples [3, 4]. The authors of [3] obtained the relations between the parameters of a resonator and chiral media; in [4], we prepared special chiral samples and measured complex ε and μ.

The available identification methods are based on studying transmittance (T) spectra. In [1], it was proposed to identify the magnetic response by comparing resonance responses of transmittance T for double split rings (spit ring resonator, SRR [5]) and continuous rings. The resonance response, which vanishes in the closed rings, is identified as magnetic. In this case, the resonance effects of the ring and linear currents (RR and DR) are separated, but the effects of magnetic and electric excitation of the RR are not. In [6], the magnetic and electric responses are identified by the positions of transparency bands in evanescent waveguide structures.

This Letter proposes to identify magnetic and electric excitation by reflectance in free space or a waveguide in the standing- or traveling-wave modes by the features observed in the dispersion characteristics.

We demonstrate the main results by the example of the double split rings (SRR). The resonance excitation

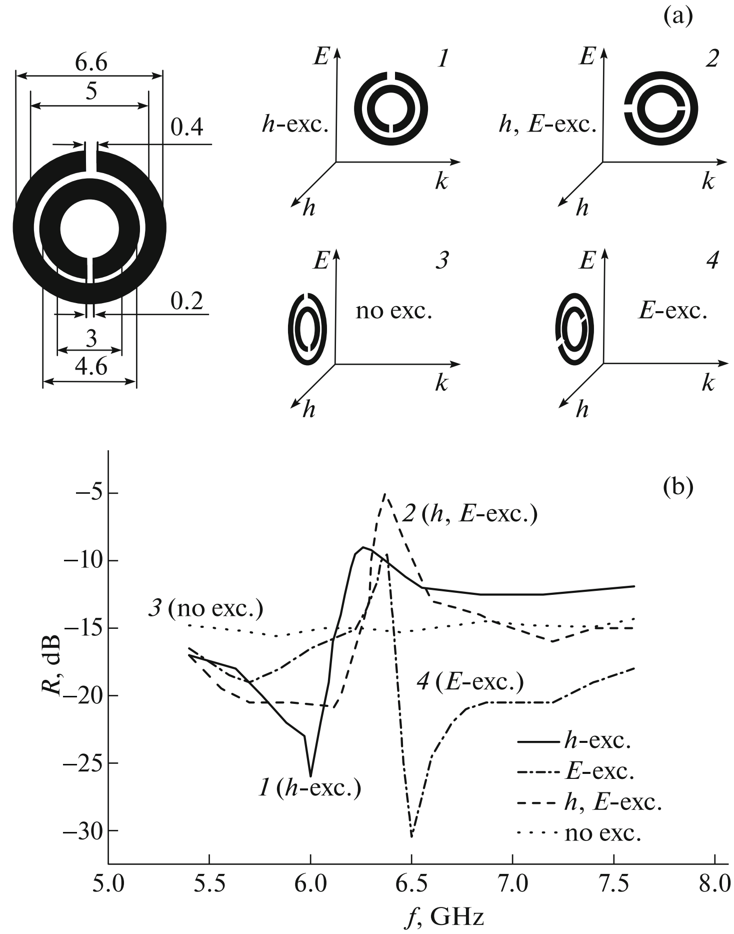

Fig. 1. (a) Geometry of the double SRR and investigated SRR orientations relative to wave vector *k* and fields *h* and *E* of the incident electromagnetic wave. (b) Measured frequency dependences of reflectance *R* in a rectangular waveguide in the traveling-wave mode in the RR region at different orientations (different resonance excitations).

in the SRRs was thoroughly investigated analytically and numerically in [7, 8]. We used P2-58 (3–5.5 GHz) and P2-59 (5.3–7.6 GHz) voltage standing wave ratio meters and a one-channel method for measuring reflectance *R* in a rectangular waveguide: the standing-wave mode with a metal plug and the traveling-wave mode with a tuned load. The SRR is placed at the center of a rectangular waveguide with a cross section of 48 × 24 and 35 × 15 mm in different orientations relative to the components of the incident electromagnetic wave field (Fig. 1a). In Fig. 1a, the RR excitation type is indicated for each investigated SRR orientation (*1*–*4*). In the standing-wave mode, for the SRR located on the metal plug, i.e., in the antinode of magnetic field *h*, in orientation *1* (*h*-exc.), the resonance minimum of the reflectance is observed, which vanishes in the minimum of field *h* when the SRR is located at a distance of $s = \lambda/4$ from the plug. At $s = \lambda/4$, resonance is observed in orientation *4* (*E*-exc.) in the maximum of field *E* and vanishes at $s = 0$ in the minimum of *E*. This simple method for separating the magnetic and electric excitations requires samples that are small relative to the wavelength, so that the sample will not be affected by an electric (magnetic) field in its antinode.

In the traveling-wave mode, resonance effects manifest themselves in the form of a resonance dip in the frequency transmittance curves, which corresponds to the resonance maximum in the reflectance curve. Such curves are typical of composites consisting of randomly located resonance elements. However, in the case of oriented chiral elements, including single ones, the resonance reflectance curves are more complex: along with the resonance maximum, one can observe the related resonance minimum whose position depends on the type of excitation. At the electric excitation, the resonance minimum is observed at higher frequencies than the resonance maximum. Under magnetic excitation, the resonance minimum is observed at lower frequencies; in this case, from the

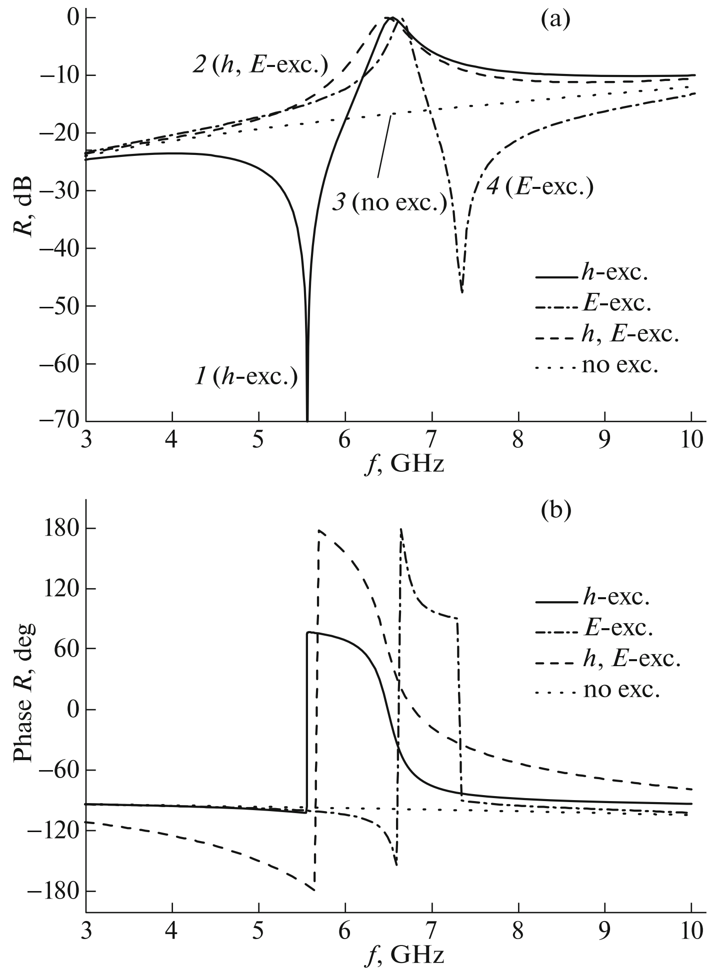

Fig. 2. Calculated frequency dependences of reflectance R for the periodic SRR lattice in free space in the RR region at different orientations of the rings (different types of the resonance excitation). The lattice period is $P = 13$ mm. (a) R value and (b) R phase.

side of higher frequencies relative to the maximum, the reflectance slowly decreases, remaining fairly large in a certain frequency range. In addition, during magnetic excitation, the reflectance phase changes smoothly and passes through zero at the resonance frequency, in contrast to its stepwise change under electric excitation.

The measured frequency dependences of reflectance R in the RR region in the traveling-wave mode are shown in Fig. 1b. We can see that the frequency dependences of R are drastically different at different orientations. Along with the resonance maxima at frequency $f_{max} = 6.3$ GHz, there are resonance minima at frequencies that are lower at the magnetic excitation (h-exc) and higher at the electric excitation (E-exc): $f_{min,\, h\text{-exc}} = 6$ GHz and $f_{min,\, E\text{-exc}} = 6.5$ GHz. In orientation *2*, both h-exc and E-exc can take place; then, the R curve contains spread minima. Orientation *3* does not allow RR excitation, and the R curve does not demonstrate the resonance effect.

The curves obtained numerically for the absolute value and phase of R also have distinguishing features (Figs. 2a and 2b). The shape of the resonance R curve significantly depends on the excitation, in contrast to the resonance dip of transmittance T. These features were experimentally confirmed for inclusions in the form of a planar spiral, single split ring, and cylindrical sample consisting of oriented spirals. The difference between the frequency characteristics makes it possible to identify the type of excitation and separate the magnetic and electric resonance responses for inclusions of different shapes.

Magnetic excitation that causes artificial magnetism used in creation and application of the so-called left media is of special interest [9]. The disclosed features in the frequency characteristics of R (smooth phase variation at the large value kept above the reso-

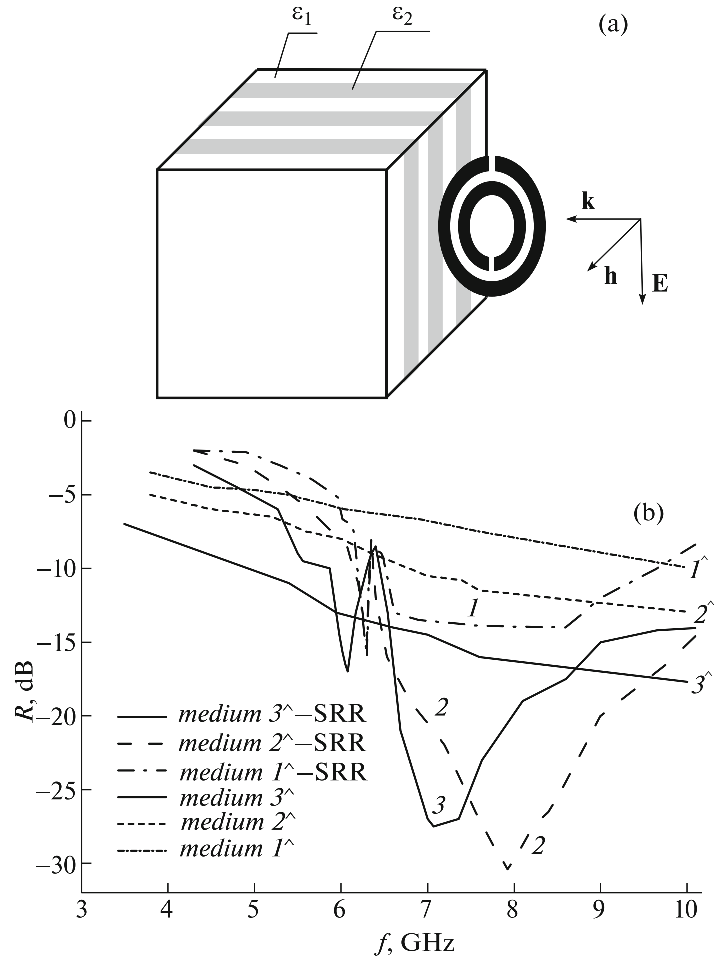

Fig. 3. (a) Geometry of the experiment with the medium–SRR structure. (b) Measured frequency dependences of reflectance *R* in a rectangular waveguide with different absorbing composites (media *1*^, *2*^, and *3*^) with different reflectances *R* (thin curves *1*^, *2*^, and *3*^) in comparison to the medium–SRR structures (thick curves *1*, *2*, and *3*).

nance frequency) opens a new aspect of the absorption problem, specifically, the possibility of broadband compensation of frequency-dependent reflections from traditional absorbing composites based on resistive threads or films with ensured equal values of antiphase reflections from the composite and the adjacent lattice of resonance elements excited by the magnetic field of the wave above their resonance frequency. In [10], the compensation of reflections with the use of interference coatings and coatings from metamaterials with ε and $\mu \approx 1$ or -1 was studied.

Reference samples were fabricated from absorbing composites (media) containing layers of carbon paper with a thickness of 0.07 mm and $\varepsilon_1' = 15$ and foamed polystyrene with thicknesses of $d_2 = 1$, 3, and 4 mm. The *R* values were measured in a waveguide in comparison with the medium–SRR structures (Figs. 3a and 3b).

Thus, the disclosed features in the frequency reflectance characteristics of the magnetic and electric microwave responses make it possible to reveal the magnetic response for inclusions of different shapes, which is not only useful for the development and application of metamaterials with artificial magnetism and left media, but also opens a new aspect of application of the magnetic response for broadband compensation of reflections from absorbing composite materials.

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