Bulk magnetic terahertz metamaterials based on dielectric microspheres

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Abstract—Rigid metamaterials were prepared by embedding TiO$_2$ microspheres into polyethylene. These structures exhibit a series of Mie resonances where the lowest one is associated with a strong dispersion in the effective permeability. Using THz spectroscopy, we confirmed the magnetic nature of the observed resonance.

I. INTRODUCTION AND BACKGROUND

We investigated THz metamaterials based on titanium dioxide (TiO$_2$) microsphere resonators. TiO$_2$ is a suitable dielectric material due to its high permittivity and low dielectric losses. In our previous work, the microspheres were dispersed in air, forming nearly a single-layer sample enclosed between two sapphire wafers [1]. Here we embedded the TiO$_2$ microspheres into a polyethylene (PE) matrix which enabled us to prepare a rigid bulk metamaterial with a controllable concentration of microresonators. We performed measurements using time-domain THz spectroscopy to characterize the response of such structures and to confirm its magnetic character. The retrieved spectra of effective dielectric permittivity and magnetic permeability are discussed within Mie theory and Maxwell-Garnett effective medium model.

II. SAMPLES

TiO$_2$ microspheres with a diameter of a few tens of micrometers were prepared by the bottom up approach described in [1]. They were mixed with PE powder and a pressure of 14 MPa was used to prepare rigid pellets with random spatial distribution of the TiO$_2$ microspheres. Pellets with thicknesses of 1 and 3 mm were prepared.

III. SIMULATIONS

Dispersed dielectric microspheres with high permittivity represent a Mie resonance-based metamaterial, where the effective response relies on the resonance of individual elements while the coupling between isolated microparticles has only minor influence on the resonance properties. This allows us to simplify the theoretical investigations: we consider a periodic array of the microspheres and neglect the influence of the disorder. Note that this metamaterial behavior fundamentally differs from that of photonic crystals where the optical response is controlled mainly by the coupling between the constituents [2]. We employed a finite-difference time-domain (FDTD) simulation software package MEEP [3] to calculate the transmission and reflection spectra of TiO$_2$ microspheres with diameter $d = 35 \mu m$ arranged in a square lattice with unit cell $a \times a$ embedded in a medium with permittivity $\varepsilon_H$ and thickness $a$. (a) Variable filling fraction $s$ (and lattice constant $a$), host permittivity $\varepsilon_H = 2$; (b) Variable host permittivity, $a = 50 \mu m$ (filling factor of 18%).
from the transmittances $T_0$ and $T_1$ corresponding to the direct pass and to the first echo in the sample, respectively. A magnetic resonance around 0.9 THz is clearly resolved (see Fig. 2). This confirms the effective magnetic behavior of the metamaterial associated with the first Mie mode.

For higher filling fractions, since $T_1$ dramatically decreases, we carried out our investigations based exclusively on the transmittance amplitude obtained from long time-domain scans which involved the sum of all measurable Fabry-Perot reflections. In order to gain a further insight into the properties of the metamaterial, we employed a dynamic Maxwell-Garnett theory [8], in which we accounted for the distribution of the particle sizes of the microspheres. We found a good match between theory and experiment (see Fig. 3). These parameters are supported by an optical microscope analysis, which revealed a comparable ellipticity of the microparticles. Furthermore, the filling fractions obtained from the fit by the Maxwell-Garnett theory are in good agreement with those determined from the weights of the components (nominal values).

V. CONCLUSION

Using a bottom up approach, we fabricated rigid metamaterials made of TiO$_2$ microresonators embedded in polyethylene. We experimentally confirmed the magnetic effective response in the vicinity of the first Mie resonance near 0.9 THz. Using FDTD calculations of the effective response we found out that a range of negative effective magnetic permeability can be achieved for sufficiently high filling fractions and contrasts between the permittivities of the resonators and the embedding medium [9]. The developed structures are prototypes of cheap mechanically stable terahertz metamaterials.

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REFERENCES

[1] H. Němec, C. Kadlec, F. Kadlec, P. Kuzel, R. Yahiaoui, U-C. Chung, C. Elissalde, M. Maglione and P. Mounaix, “Resonant magnetic response of TiO$_2$ microspheres at terahertz frequencies”, Appl. Phys. Lett. 100, 061117, 2012.

[2] F. Dominic, C. Kadlec, H. Němec, P. Kuzel, and F. Kadlec, “Transition between metamaterial and photonic-crystal behavior in arrays of dielectric rods,” Opt. Express 22, 30492, 2014.

[3] A. F. Oskooi, D. Roundy, M. Ibanescu, P. Bermel, J. D. Joannopoulos, and S. G. Johnson, “MEEP: A flexible free-software package for electromagnetic simulations by the FDTD method,” Comput. Phys. Commun. 181, 687, 2010.

[4] A. M. Nicolaou and G. F. Ross, “Measurement of the intrinsic properties of materials by time-domain techniques,” IEEE Trans. Instrum. Meas. 19, 377, 1970.

[5] W. Weir, “Automatic measurement of complex dielectric constant and permeability at microwave frequencies,” Proc. IEEE 62, 33, 1974.

[6] D. R. Smith, S. Schultz, P. Markos, and C. M. Soukoulis, “Determination of effective permittivity and permeability of metamaterials from reflection and transmission coefficients,” Phys. Rev. B 65, 195104, 2002.

[7] P. Kuzel, H. Neme, C. Kadlec and C. Kadlec, “Gouy shift correction for highly accurate refractive index retrieval in time-domain terahertz spectroscopy”, Opt. Express 18, 15338, 2010.

[8] V. Vannopapas and A. Moroz, “Negative refractive index metamaterials from inherently non-magnetic materials for deep infrared to terahertz frequency ranges”, J. Phys.-Condens. Matter 17, 3717, 2005.

[9] M. Sindler, C. Kadlec, F. Dominc, P. Kuzel, C. Elissalde, A. Kassas, J. Leseur, D. Bernard, P. Mounaix, and H. Neme, “Bulk magnetic terahertz metamaterials based on dielectric microspheres”, accepted to publication in Opt. Express 24, 2016.