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Fiber metamaterials with negative magnetic permeability in the terahertz

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Abstract: We present a novel method for producing metamaterials with a terahertz magnetic response via fiber drawing, which can be inexpensively scaled up to mass production. We draw a centimeter preform to fiber, spool it, and partially sputter it with metal to produce extended slotted resonators. We characterize metamaterial fiber arrays with different orientations via terahertz time domain spectroscopy, observing distinct magnetic resonances between 0.3 and 0.4 THz, in excellent agreement with simulations. Numerical parameters retrieval techniques confirm that such metamaterials possess negative magnetic permeability. Combined with fiber-based negative permittivity materials, this will enable the development of the first woven negative index materials, as well as the fabrication of magnetic surface plasmon waveguides and subwavelength waveguides.

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1. Introduction

Metamaterials are artificial materials, composed of sub-wavelength "atoms" that can collectively exhibit effective electromagnetic responses not found in nature. A large number of extraordinary metamaterial devices have been recently reported, e.g. superlenses [1], electromagnetic cloaks [2] and negative refractive index materials [3]. Producing terahertz (THz) and optical metamaterials usually requires expensive and labor-intensive micro- and nano- fabrication processes, such as electron-beam lithography, focused-ion beam milling, nanoimprint lithography and direct laser writing, which limit metamaterial sample sizes to a few centimeters [4]. Here we present a method for the production of a fiber metamaterial possessing negative magnetic permeability, μ , in the THz. Fiber drawing has emerged as means of realizing inexpensive metamaterials, where a macroscopic (centimeter-sized) preform is heated until softened, and drawn into a fiber that is reduced in area by several orders of magnitude and greatly increased in length. Although continuous metal wires down to the micrometer [5–9] and nanometer [10] scale have been reported using such techniques, giving the ability to tailor the effective electric permittivity, ϵ , this approach has previously never been used for creating magnetically responsive metamaterials.

2. Fabrication and sample preparation

A common approach to produce a negative μ material is to use sub-wavelength metallic split ring resonators (SRRs) composed of a planar open conductive split loop with an inductance L and a capacitance C that opposes incident magnetic fields at frequencies near the LC resonance. The geometry considered here however is the slotted resonator. This has a geometry similar to that of SRRs, but instead of being inscribed in a plane, has a finite depth and is invariant along the longitudinal axis. Slotted resonators can also exhibit a negative magnetic response [11], however their depth demands new fabrication strategies. Recently, slotted resonators in the near- and mid-infrared were produced via a combination of polymer direct-laser writing and chemical vapor deposition [12]. Our approach is to fabricate slotted

Fig. 1. Schematic of the fabrication procedure. i) A dielectric square preform is drawn, ii) sputtered with silver on three sides and iii) spooled into an array. (b) Optical microscope image of the metamaterial array. (c) SEM micrograph of i) the cross section of the metamaterial fiber and ii) of its 250nm silver coating.

resonators in the fiber form, utilizing the longitudinal uniformity of the fiber drawing process to create kilometers of the required structure.

Figure 1(a) shows a schematic of our fabrication procedure. A preform with a square cross section with 2 cm side was milled from a rod of extruded cyclo-olefin Zeonex [13], a drawable polymer with low loss in the THz region. A square cross-section was chosen to facilitate the spooling of the resulting fiber with a controlled orientation. The preform was drawn to $125 \pm 5 \mu\text{m}$ side, and spooled onto a cylinder which was subsequently loaded in a DC magnetron sputtering deposition system to coat a 200-250 nm silver thin film on three sides.

To ensure the strongest magnetic resonance possible with this geometry [14], the silver coating thickness was selected to be larger than the skin depth δ at 0.1-1 THz. A good approximation of the skin depth for this range of frequencies can be obtained using the d.c. conductivity of silver [15], $\sigma_{dc} = 6 \times 10^7 \Omega^{-1}\text{m}^{-1}$, through $\delta = 1/(f\pi\mu_0\sigma_{dc})^{1/2}$ with μ_0 the permeability of free space and f the frequency at which the skin depth is defined. This yields a skin depth between 50 and 200 nm over the frequency range of interest. To improve adhesion, a chromium interlayer ($\sim 10\text{-}20 \text{ nm}$) was applied prior to the silver layer deposition. Good silver coating coverage of the three exposed sides was ensured by translating and rotating the spool inside the sputtering chamber [Fig. 1(a)]. The resulting fiber formed a single slotted square prism resonator that is invariant along the axis of the fiber. The coated fiber was then spooled again to produce a single flat array, which was supported in a frame [Fig. 1(b)]. Figure 1(c) shows a scanning electron microscope (SEM) image of the cross section of our final fiber with $125 \mu\text{m}$ square edge, and a 250 nm thick silver coating.

By controlling the orientation of the coated fiber at the start of the second spooling process it was possible to produce arrays with different resonator orientations, each with different electromagnetic properties, depending on whether the resonators are symmetric or asymmetric with respect to the forwards- and backwards-propagating wave [16]. Figure 2(c) illustrates the resonator array geometries studied here. In both cases, we consider fields under normal incidence (i.e. propagating in the x-direction), with either the magnetic field (TM polarization) or the electric field (TE polarization) directed along the fiber in the z-direction. In the symmetric case, the resonator will respond isotropically along the x-axis (i.e. the transmission and reflection will be identical whether illumination is from the left or the right), whereas in the asymmetric case it will respond bianisotropically - transmission and reflection will depend on whether the light comes from the left or right. This is due to the lack of inversion symmetry and leads to a magnetoelectric coupling: the magnetic field in z induces an electric

Fig. 2. (a) Experimental and simulated transmittance and phase (inset) under TM polarization. The transmission dip indicates a magnetic resonance. (b) Experimental and simulated transmittance under TE polarization. (c) Schematic of the fiber array orientations. (d) Relative phase of the simulated magnetic field at the center of the resonator with respect to the incident field. (e) Color plot of the simulated magnetic field incident under TM polarization for the symmetric resonator at (i) 0.15 THz, (ii) 0.34 THz and (iii) 0.37 THz.

dipole in y , and the electric field in y also induces a magnetic dipole in z , in particular leading to two different characteristic impedances for two waves propagating in opposite directions [16]. This issue will be considered in the next section, in the context of effective parameter extraction.

Note that in this geometry and for TM incidence, the magnetic field is parallel to the fiber and thus has a nonzero magnetic flux through the resonator loop. By contrast, arrays of thin SRRs are usually printed onto a substrate so that the resonator loops are in the same plane as the array; experimental characterization of one to a few layers of arrays in these cases can only use light normally incident to the substrate as such samples are too thin and would be strongly diffracting in side incidence. The magnetic field is then parallel to the plane of the resonator loops, has zero magnetic flux and is unable to excite a magnetic response. Instead, the electric field is used to generate currents which couple to the magnetic resonance [17] while transmission features due to a magnetic response can be seen in these experiments they do not correspond to a negative permeability [18].

3. Characterization

The transmittance of our samples between 0.1 and 1 THz was measured experimentally via THz time domain spectroscopy [19,20]. The transmittance results for the TM and TE waves are shown in Figs. 2(a)-2(b) for the two fiber orientations. Under TM illumination, our arrays exhibit distinct magnetic resonances between 0.3 and 0.4 THz, depending on fiber orientation. Under TE illumination, they possess high-pass filtering behavior (without magnetic resonances), analogous to the response of metallic wire-grid structures [21].

We modeled our geometries with the finite element solver COMSOL, using a periodic 2-dimensional array of 125 μm Zeonex squares, coated with a 250 nm silver layer on three sides (using a Drude model [15] for ϵ) and unit cell size 350 μm . A polynomial fit to experimental data for the refractive index of Zeonex was used in our numerical simulations. There was excellent agreement with experiment in both fiber orientations and polarizations [Figs. 2(a)-2(b)]. To demonstrate the observed resonances are indeed magnetic, we consider in more

Fig. 3. Real and imaginary parts of the retrieved (a) μ , (b) ϵ , and (c) magnetoelectric coupling coefficient ξ for the symmetric and asymmetric fiber orientations, under TM polarization. Note that for symmetric resonator orientations ξ is zero.

detail the fields inside the resonator: Fig. 2(d) shows the relative phase of the simulated magnetic field at the center of the resonator with respect to the incident field at that point, indicating a near- π phase shift centered around resonance at 0.36 THz. Figure 2(e) shows a color plot of the simulated magnetic field incident under TM polarization for the symmetric resonator (i) far below resonance at 0.15 THz (no magnetic response), (ii) just below resonance at 0.34 THz (in-phase magnetic response) and (iii) just above resonance at 0.37 THz (out-of-phase magnetic response).

We extracted μ and ϵ of the metamaterial arrays from simulations under TM polarization using the retrieval procedure presented in Ref. [16], taking into account the bianisotropic behavior of our asymmetric fiber array. The complex scattering matrix elements which describe the reflection (S_{11} and S_{22}) and transmission (S_{12} and S_{21}) of the field incident along the x-axis from either side of the array were obtained from the finite element calculations. In the symmetric case there is no magnetoelectric coupling, $S_{11} = S_{22}$ and $S_{12} = S_{21}$; in the asymmetric case however magnetoelectric coupling leads to $S_{11} \neq S_{22}$ and $S_{12} \neq S_{21}$. Knowledge of the scattering matrix coefficients and metamaterial thickness enable the extraction of the refractive index n , from which ϵ and μ and the magnetoelectric coupling coefficient ξ can be obtained. The results are presented in Figs. 3(a)-3(c). The symmetric resonator possesses a minimum $\mu = -2 + 2.2i$ with no magnetoelectric coupling, whereas the asymmetric resonator displays a shallower, red-shifted magnetic response due to magnetoelectric coupling, with a minimum $\mu = -0.9 + 1.2i$. Correspondingly, ϵ exhibits antiresonant behavior in the former case, and resonant behavior in the latter [16,22].

Note that in this work we have measured the transmittance and extracted the effective parameters of a *single* metamaterial layer composed of periodic sub-wavelength resonators. Simulations of single slabs of homogenized material with the extracted ϵ , μ and ξ indeed reproduce the same transmission and reflection curves as simulations of the full system (not shown). It is known [23] that when considering stacks of *multiple* layers, these parameters differ from the single layer case due to coupling effects between adjacent layers. It follows that the effective ϵ and μ depend on whether the layer lies inside or on the edge of an arbitrary stack, and effective parameters of stacked layers will also depend on the way layers are stacked (e.g. distance between layers). In such a multiple-layer case, ϵ and μ can be obtained by analyzing scattering matrices of two- and three- layer systems [23]. Such an analysis becomes relevant in the case of a multi-layer system, and is beyond the scope of this paper. Furthermore, it is important to note that parameters extracted using the above method come from matching of boundary conditions, but do not necessarily reproduce the intrinsic electromagnetic response within the metamaterial [24].

4. Conclusion

In conclusion, we have presented a procedure for making THz metamaterials with a negative effective μ near resonance. The excellent agreement between experiment and simulations demonstrates the very high quality of the fabricated structures. The resonant frequency can be tuned simply by scaling the structure, and can be extended to higher frequencies. Drawing from a preform allows the fabrication of fibers of $\sim 100\ \mu\text{m}$ diameter, however smaller diameters ($\sim 10\ \mu\text{m}$) can be obtained with standard fibers spinning techniques [25], which would move the resonant frequency up to $\sim 10\ \text{THz}$. Further optimization may allow a reduction in size down to $1\ \mu\text{m}$, allowing the fabrication of resonators into the mid-IR. Whereas for THz resonators the metal thickness is far smaller than the wavelength and surface roughness is not an issue, more care would need to be taken at shorter wavelengths. While in our fabrication setup we use a batch process with a closed sputtering chamber, in-line coating with a continuous operation from preform to metamaterial fiber is possible, with the unique advantage of being able to fabricate metamaterials with a continuous process in very large quantities, literally by the kilometer. Combined with the previously presented fabrication of fiber-based negative ϵ materials [8] this will enable the development of woven negative index materials, as well as the fabrication of magnetic surface plasmon waveguides and subwavelength waveguides [26]. Advanced weaving techniques will allow the production of materials with gradients of both positive and negative ϵ and μ , providing the opportunity to demonstrate three dimensional cloaks, as well as hyperlensing from the THz to the mid-IR.

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