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Photonic Metamaterials by Direct Laser Writing

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Abstract: We present a planar magnetic metamaterial fabricated using 3D direct laser writing and silver chemical vapor deposition as well as a negative-index bi-anisotropic metamaterial metallized via silver shadow evaporation. Calculations and experiments show good agreement.

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Metamaterials are artificial composite structures composed of metallic sub-wavelength scale functional building blocks that allow for magnetism at optical frequencies [1,2]. In Ref. [3] we have presented an example for such a photonic material, i.e., the corrugated surface structure (see Fig. 1 (a)) that shows diamagnetism ($\chi_{\text{mag}} < 0$) at infrared frequencies and could be fabricated via 3D direct laser writing and silver chemical vapor deposition. Recently, we additionally processed this structure by using focused-ion beam milling in order to make a transition to electrically isolated split-ring resonators (SRR) as shown in Fig. 1(b)-(d) [4].

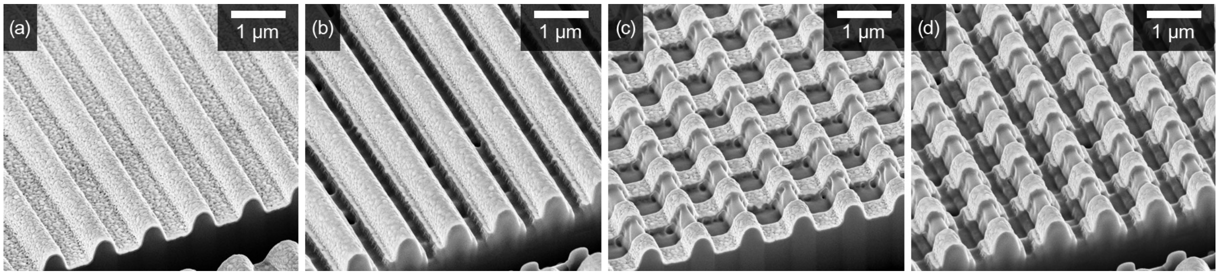

Fig. 1. Electron micrographs of fabricated structures. (a) is realized by direct laser writing and subsequent silver chemical vapor deposition. (b)-(d) have required additional post-processing by means of focused-ion beam (FIB) cutting. Taken from Ref. [4].

At first glance, switching from the corrugated surface structure in Fig. 1(a) to an array of SRR in Fig. 1(d) seems to be just a simple variation in that the SRR are merely electrically connected along both in-plane directions. But a closer look reveals fundamental differences between these cases. To optically characterize all structures, we have measured normal-incidence transmittance spectra using a Fourier-transform infrared-spectrometer and compared our results with corresponding FDTD and Fourier Modal Method computations (not shown). The qualitative behavior can be reproduced very well so that an investigation of simulated field distributions is justified. In Fig. 2, we depict characteristic snapshots of the computed local Ohmic current density vector whereas the size of the arrows is linearly proportional to its absolute value. By looking at these distributions, it is possible to identify the positions of SRR like illustrated as orange shaded areas.

For the structures shown in Fig. 1(b) and (d), the current distribution of the fundamental *LC* resonances is that of an upside down "U" (see Fig. 2(b)). Cutting perpendicular to the grooves results only in a minor shift of the resonance to longer wavelengths, but does not alter the underlying physics. The oscillating circulating currents and, hence, the magnetic dipoles are induced by both the magnetic field perpendicular to the plane of Fig. 2 and the voltage drop over the two ends of the plate capacitor part of the SRR. Therefore, a physical description in terms of bi-anisotropy is indispensable [3,5,6]. In Figs. 1(a) and (c) the right as well as the left plate of each SRR is electrically connected with the adjacent SRR. As all investigated structures are excited via a plane electromagnetic

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wave under normal incidence, the connected SRR arrays in Figs. 1(a) and (c) are forced to oscillate in phase. Thus, they have the same potential drop between their left and right capacitor plate. The configuration can also be regarded as short-circuited plate capacitors. Consequently, the capacitance *C* diverges and the fundamental *LC* eigenfrequency of the SRR arrays approaches zero frequency. The transmittance resonance observed in the experiment is rather a higher-order mode. In the quasi-static case (not shown) strong circulating currents lead to strong magnetic dipoles. Only if the structure is non-symmetric along the propagation direction of the incident light, the neighboring magnetic-dipole moments do not annihilate and a residual magnetization survives even in the static limit. For electrically separated SRR like those shown in Figs. 1(b) and (d), a continuous current flow is obviously not possible.

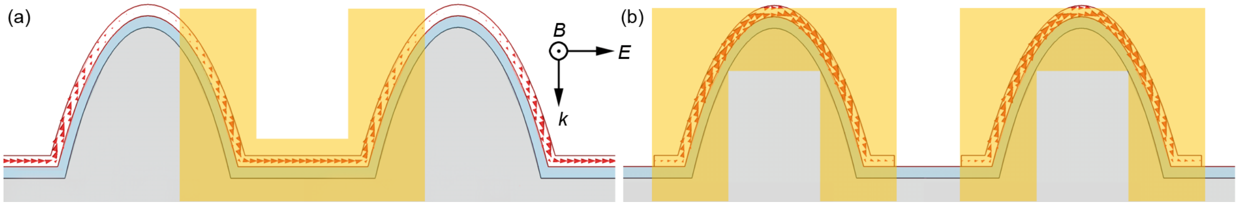

Fig. 2. Snapshots of the FDTD computed local Ohmic current density. (a) corresponds to the resonance frequency of 126 THz of the structure shown in Fig. 1(a), (b) to the resonance frequency of 80 THz of the structure shown in Fig. 1(b). The orange areas illustrate our intuitive interpretation. Taken from Ref. [4].

So far we have fabricated several types of photonic metamaterials that show a magnetic response. If additionally a "diluted metal" is provided, one could in principle expect a negative refractive index *n*. Since our fabricated structures are bi-anisotropic, we have to take the cross-term parameter ξ into consideration which also greatly influences *n*. Hence, we proposed the 2-layer structure shown in Fig. 3(a) whose dielectric backbone can also be realized by using direct laser writing. In this case, the metallization of the template was performed by silver shadow evaporation [7]. Again, the upside down "U" parts can be viewed as SRR. The elevated and elongated metal rods parallel to the incident electric-field vector cause a negative electric permittivity. The transmittance spectrum (not shown) reveals a resonance at around 3.85 µm wavelength.

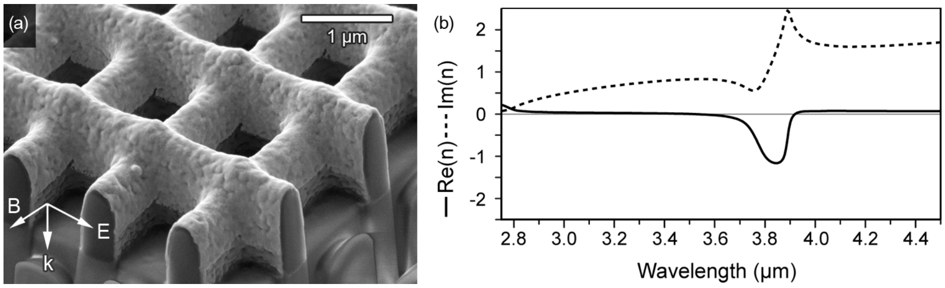

Fig. 3. (a) Electron micrograph of a bi-anisotropic metamaterial fabricated by direct laser writing and silver shadow evaporation that has been cut by a focused-ion beam in order to reveal its interior. (b) Retrieved real and imaginary part of the refractive index *n*. Taken from Ref. [7].

Results of the optical parameter retrieval show a negative real part of *n* from around 3.6 µm to 3.9 µm wavelength (see Fig. 3(b)). Using the imaginary part of *n*, a maximum figure of merit of FOM = Re(*n*)/Im(*n*) = 1.3 can be determined, which is comparable to previously investigated photonic metamaterials made via electron-beam lithography [1,2]. Since the lattice constant is smaller than half the wavelength of the incident light a description in terms of an effective medium is well justified. In conclusion, we have shown that bi-anisotropy does not generally prohibit negative refractive indices.

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