Towards 3D Photonic Metamaterials by Direct Laser Writing

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We have fabricated planar magnetic and negative-index metamaterials via direct laser writing and subsequent metallization, an approach, which is also suitable for three-dimensional structures. Retrieval of the effective material parameters reveals the importance of bi-anisotropy.

Novel optical applications, such as perfect lenses [1], optical cloaking [2] and quantum levitation [3], have encouraged researchers to look for artificial materials that exhibit magnetism at optical frequencies. However, fabricating these required nanostructures in three dimensions is still a significant challenge. Although all reported three-dimensional (3D) photonic metamaterials have been made from stacks of separated, two-dimensional functional layers [4-6], a genuinely 3D fabrication process is preferable.

Toward this end, we have combined direct laser writing (DLW) – a commercially available method to realize connected polymer nanostructures with lateral feature sizes down to 100 nm – and silver chemical vapor deposition to fabricate a planar test structure composed of elongated split-ring resonators (**Fig. 1(a)**) [7]. Additionally, we showed a structure composed of bars which was metallized uniformly around the structure even in 3D (see **Fig. 1(b)**). The optical characterization of the elongated split-ring resonators is in good agreement with theory, showing decent material quality and a magnetic dipole resonance at around 3-μm wavelength. The theoretical analysis has also demonstrated the importance of bi-anisotropy due to the non-centrosymmetric design of the investigated structure, i.e., the real part of the refractive index remains positive even though the real part of the permittivity and the real part of the permeability are both negative and the damping is reasonably small.

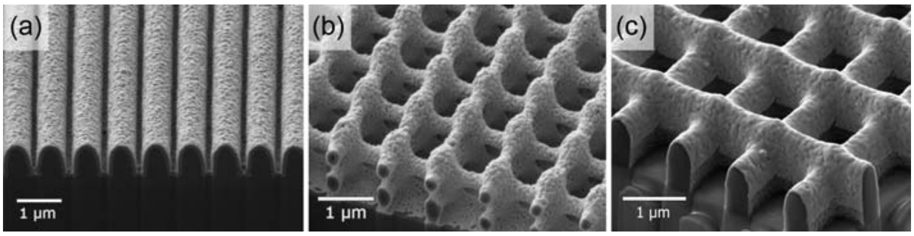

Fig. 1: Electron micrographs of investigated structures. **(a)** Elongated split-ring resonators and **(b)** 3D structure fabricated by DLW and silver chemical vapor deposition. **(c)** Negative-index metamaterial fabricated by DLW and silver shadow evaporation.

Next, we will present a novel design for a metamaterial that can be made via DLW and silver shadow evaporation. Corresponding structures have been fabricated and characterized by us (see **Fig.1(c)**) [8]. Their measured optical spectra agree qualitatively with simulations. A negative real part of the refractive index n at around 3.8-μm wavelength was retrieved, despite the fact that the metamaterial structure is bi-anisotropic. The corresponding imaginary part of n could be translated into a maximum figure of merit of FOM = Re(n) / Im(n) = 1.3, which is comparable to double-fishnet-type negative-index metamaterials made by electron-beam lithography (see, e.g., [9]).

Finally, we will discuss new ideas for 3D metamaterial designs which are compatible with our fabrication method and could lead to first isotropic and chiral 3D metamaterials at optical frequencies.

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