Photonic Metamaterials by Direct Laser Writing and Silver Chemical Vapor Deposition

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Abstract: We fabricate planar magnetic photonic metamaterials via direct laser writing and silver chemical vapor deposition, an approach, which is also suitable for three-dimensional structures. Retrieval of the effective metamaterial parameters reveals the importance of bi-anisotropy.

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Metamaterials are man-made composite structures composed of metallic sub-wavelength scale functional building blocks that are densely packed into an effective material. This approach especially allows for artificial magnetism at elevated frequencies. Using planar lithography approaches such as electron-beam lithography, single functional layers [1,2] and N=1,2,3 functional layers [3] have been realized. However, this route does not appear to be promising for realizing truly three-dimensional (3D) metamaterials with reasonable effort/cost.

Three-dimensional polymer nanostructures with lateral feature sizes down to 100 nm can routinely be fabricated by means of direct laser writing (DLW) [4]. Here, we report on our first steps (unpublished) towards metamaterials made by DLW and subsequent silver coating via chemical vapor deposition (CVD). The main experimental challenge lies in realizing thin silver films of sufficient optical quality in 3D at optical frequencies. The present paper will address this point. In addition, the process of combined DLW and CVD inherently leads to *connected* metal structures. Thus, another challenge lies in developing theoretical blueprints – appreciating this conceptual boundary condition – for meaningful 3D structures (e.g., magnetic response, negative index). Unfortunately, such blueprints are presently not available. Hence, here we give a proof-of-principle via a (more or less) planar structure.

The fabrication starts with the 3D polymeric template (SU-8) made by DLW. This SU-8 template is coated with a thin layer of SiO_2 (typically few 10 nm) via atomic layer deposition, serving for stabilization in the subsequent silver CVD process in which the template needs to be heated at 125 degrees Celsius. Here, the metal-organic precursor (COD)(hfac)Ag(I) is sublimed at temperatures of 40-90 degrees Celsius, the wall temperature of the CVD chamber is 60 degrees. In each quasi-static cycle, we deposit about 3 nm of silver. The samples discussed below have resulted from 15 CVD cycles, equivalent to a nominal silver thickness of about 47 nm. Fig.1 shows an electron micrograph of a resulting structure.

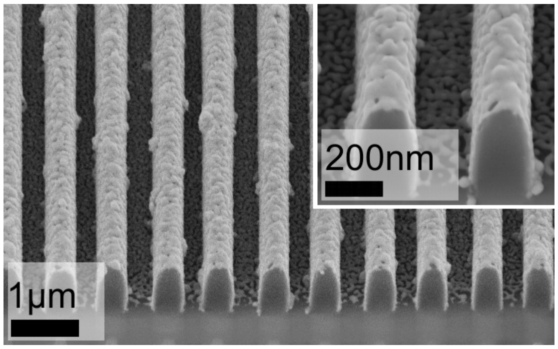

Fig.1. Metamaterial composed of connected elongated magnetic split-ring resonators made by DLW and silver CVD. By the same approach, truly 3D structures can be fabricated.

To assess the optical quality of the silver films, we have measured their optical transmittance (not shown). The behavior can nicely be fitted by a usual Drude free-electron model. For unconnected films or films with excessive roughness, one rather expects (and finds) an undesired Mie resonance behavior. We conclude that the films can be viewed as closed films – possibly with an effective thickness smaller than the nominal one.

The structure shown in Fig.1 can be viewed as a lattice of connected elongated (upside-down) split-ring resonators – one of the basic building blocks of magnetic metamaterials. The measured and calculated transmittance spectra, respectively, are depicted in Fig.2 and agree qualitatively. This serves as another indicator of reasonable quality of the deposited CVD silver films.

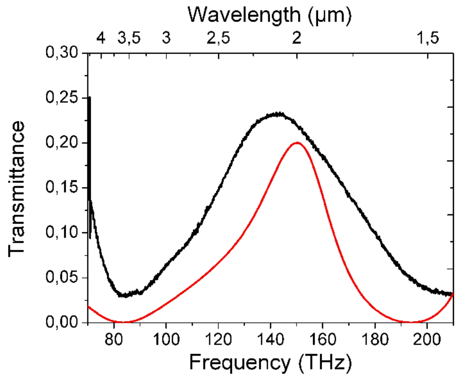

Fig.2. Comparison of CST Microwave Studio calculation (red) and measured (black) transmittance spectra of the metamaterial structure shown in Fig.1.

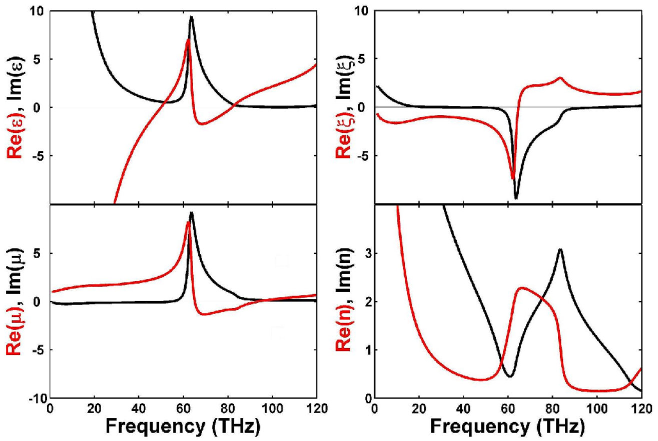

Fig.3. Retrieved permittivity ε, permeability μ, bi-anisotropy parameter ξ and index of refraction n corresponding to Fig.2 based on the ansatz of Ref. [5].

When retrieving effective metamaterial parameters for normal incidence of light, one has to be cautious because the structure in Fig.1 is non-centrosymmetric. Thus, a description in terms of just electric permittivity ε and magnetic permeability μ is fundamentally *not* possible. Here, we follow the bi-anisotropic ansatz described in Ref. [5]. Results are depicted in Fig.3 for the same parameters as in Fig.2. Clearly, a negative magnetic permeability is observed. However, note that the ξ parameter – which describes magnetic dipole moments induced by the electric-field component of the incident light – has a very strong influence as well. As a result of this, the refractive index does not become negative (lower RHS of Fig.3) despite the fact that the real parts of permittivity and permeability are simultaneously negative. The underlying physics will be discussed.

We will also report on other metamaterial structures that we are presently fabricating along the same lines.

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