3D-Chiral Metamaterial Showing Artificial Magnetic Response
and Negative Refraction∗

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Abstract

Artificial magnetism, negative permeability and negative refractive index are demonstrated in 3D-chiral metamaterial that shows giant polarization rotation and circular dichroism.

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A simultaneous presence of electric and magnetic responses at optical frequencies is a necessary condition for any medium to show optical activity, i.e. differential circular dichroism and birefringence. However, in natural media such as optically active crystals and organic liquids the magnetic response is much weaker than the electric response. Here we demonstrate that artificially created new optically active 3D metamaterial shows strong resonant magnetic permeability. The structure exhibits bands of negative permeability for one and both circular polarizations and a negative refractive index for one circular polarization. The metamaterial also shows exceptionally strong circular dichroism and polarization rotation in relatively wide frequency bands with low transmission losses, which makes it a very efficient material for circular polarizers and polarization rotators.

The metamaterial is based on a double-periodic array of layered 3D-chiral meta-molecules (unit cells) formed by pairs of mutually twisted rosette-like metallic particles, with no contact between individual layers. Here chiral interaction between the layers is provided by electromagnetic coupling [1, 2]. Recently we showed experimentally that this type of structures manifests a “left-handed” behavior: the phase and group velocities for one of the circularly polarized eigenstates have opposite signs indicating the appearance of a backward wave. The latter was noted as a signature of negative refraction in resonant chiral media, as predicted by J. Pendry [3].

Here we provide evidence that indeed negative refraction takes place in these structures. We also extend this study to multi-layered chiral structures. We study three structures with different unit cells containing correspondingly 2, 4 and 6 coaxial planar copper rosettes of 4-fold symmetry. The rosettes are located in parallel planes and separated by very thin (1.6 mm) dielectric layers, which results in the metamaterial’s overall thickness of only 1.6, 4.8 and 8.0 mm correspondingly. A mutual anti-clockwise twist of 15° is introduced between adjacent rosettes (see Fig. 1a inset, Fig. 2a), whose lateral dimension of 15×15 mm² ensures no diffraction by the metamaterial at frequencies below 20 GHz.

Fig. 1a shows transmission properties of the bi-layered form of the metamaterial. For left-handed (LCP) and right-handed (RCP) circular polarizations the material shows exceptionally strong circular dichroism of up to 20 dB. For linear polarization azimuth rotation of up to 30° is achieved. These values are substantial considering the material’s thickness of only 1/30 wavelength (λ) at 6 GHz where the strongest effects occur. Apart from a minor frequency shift, numerical results (dots, Fig. 1a) are in excellent agreement with the experi-
FIG. 1: Properties of the bi-layered form of the metamaterial, which is shown in the left inset. (a) Transmission levels for right-handed (RCP) and left-handed (LCP) circular polarizations and azimuth rotation for linear polarization. Measurements (solid lines) and simulations (points) are shown. (b) Effective parameters derived from the material’s simulated transmission and reflection properties. The insets show the horizontal component of the current modes corresponding to the negative permeability resonance (RCP, middle) and the negative permittivity resonance (LCP, bottom).

The current modes determined by these simulations show that the low frequency resonances correspond to $\lambda/2$ current modes while the high frequency resonances have $3\lambda/2$ current modes. Retrieval of the material’s effective refractive index $n$, permittivity $\varepsilon$ and permeability $\mu$ (see Fig. 1b) shows that the structure has magnetic resonances at 4.5 and 13.5 GHz and electric resonances at 6 and 16 GHz. The 6 GHz electric resonance, which corresponds to excitation of a symmetric current mode in pairs of rosettes (see Fig. 1b inset), is much stronger for LCP ($\text{Re}(\varepsilon) \approx -143$) than for RCP ($\text{Re}(\varepsilon) \approx -53$). Importantly the 4.5 GHz magnetic resonance leads to a negative permeability for RCP of $\text{Re}(\mu) \approx -1.9$, while the permeability for LCP shows only weakly resonant behavior and remains positive. The negative magnetic response for RCP arises from the excitation of anti-symmetric currents in pairs of rosettes (see Fig. 1b, inset). The RCP magnetic resonance is so strong that it leads to a negative refractive index of $\text{Re}(n) \approx -0.9$ at about 4.5 GHz. Simultaneously the strong LCP electric resonance near 6 GHz causes the refractive index to become negative.

Fig. 2b shows experimental results for the 4-layered form of the metamaterial. The most
striking difference compared to the bi-layered case is a splitting of all resonances into LCP and RCP resonances which leads to exceptionally high circular dichroism of up to 20 dB with simultaneously low losses for one circular polarization. This makes the metamaterial, which is only 1/5 of the wavelength in thickness (around 13 GHz), well-suited as circular polarizer. Furthermore the 4-layered material shows giant azimuth rotation. True optical activity with a rotation angle of at least 65° is achieved at moderate losses and without making the polarization state elliptical. The 6-layered version of the metamaterial shows similarly strong polarization rotation and circular dichroism.

All measurements were performed in an anechoic chamber using broadband horn antennas (Schwarzbeck BBHA 9120D) and a vector network analyzer (Agilent E8364B). Our numerical simulations were done with CST Microwave Studio (Computer Simulation Technology GmbH, Darmstadt, Germany) and Comsol Multiphysics, which both use a frequency domain finite element method. Using the retrieval procedure [4], we calculated the complex effective parameters $n$, $\varepsilon$ and $\mu$ from the simulated transmission and reflection.

In summary we demonstrate exceptionally strong gyrotropy in metamaterial based on multi-layered meta-molecules consisting of mutually twisted planar metal structures. Especially in forms of the material composed of four or more layers we observe giant circular dichroism and optical activity at moderate losses, which makes such structures promising as sub-wavelength polarization rotators and circular polarizers. Numerical simulations of the bi-layered structure are in excellent agreement with the experimental results and effective
parameters derived from them show bands of negative permeability for one and both circular polarizations and bands of negative refractive index for each circular polarization.

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