Tailoring Radiation Patterns in Planar RF Metamaterials

Alena Shchelokova[1], Polina Kapitanova[1]*, Dmitry Filonov[1], Alexander Poddubny[1,2]
Pavel Ginzburg[3], Anatoly Zayats[3], Pavel Belov[1], and Yuri Kivshar[1,4]

[1] National Research University of Information Technologies, Mechanics and Optics (ITMO), Saint Petersburg 197101, Russia
[2] Ioffe Physical-Technical Institute of the Russian Academy of Science, St. Petersburg 194021, Russia
[3] Department of Physics, King's College London, Strand, London WC2R 2LS, United Kingdom
[4] Nonlinear Physics Centre, Australian National University, Canberra ACT 0200, Australia
*corresponding author, E-mail: `kapitanova.poli@phoi.ifmo.ru`

Abstract

We realize an indefinite media with hyperbolic isofrequency surfaces in wavevector space by employing two-dimensional metamaterial transmission lines in radio-frequency range. We classify different types of such media, and visualize the peculiar character of wave propagation by study of the cross-like emission pattern of a linearly polarized emitter placed in the lattice center. We also demonstrate an excitation of extraordinary waves propagating in a prescribed direction controlled by the polarization handedness of localized circularly polarized emitter. Our results are supported by a solution of the Kirchhoff equations, an analytical theory, and experimental data.

1. Introduction

Hyperbolic metamaterials, being a particular class of indefinite media [1], are described by the electric or/and magnetic tensors with the components of the opposite sign. Due to the hyperbolic isofrequency contours in the wave-vector space, such structures exhibit a number of unusual properties. First, waves at their boundaries may exhibit negative refraction, similarly to the case of double-negative metamaterials. Second, they have a diverging density of photonic states that allows enhancing the strength of light-matter coupling [2]-[4]. This makes a concept of hyperbolic media very promising for tailoring broad-band light-matter interaction, nanophotonics applications, including single-photon generation, sensing, and photovoltaics [5]-[7].

Here, we consider an uniaxial anisotropic hyperbolic medium characterized by the scalar permittivity ε and longitudinal and transverse permeabilities μ_{xx} and μ_{yy}. In the radio-frequency (RF) regime we mimic such a medium by artificial two-dimensional transmission lines based on lumped elements [8]. We demonstrate that a circularly polarised emitter near an anisotropic hyperbolic metamaterial unidirectionally emits in extraordinary modes of the metamaterial with the directionality of energy propagation controlled by the circular dipole handedness. The effect is numerically demonstrated and confirmed by the experimental investigation of the hyperbolic metamaterial prototype operating at 36 MHz frequency.

2. Hyperbolic Metamaterial at RF

We mimic an uniaxial anisotropic hyperbolic medium characterized by permeabilities ±0.33 at the operational frequency f_0= 36 MHz by artificial two-dimensional transmission lines (Fig. 1 (a)) whit the values of lumped elements C_y=3.2 nF, L_x=3.2 nH and Lz=9.5 nH. [8]. For the grid consisting of 21×21 unit cells, we analytically solve the Kirchhoff equations and obtain the voltage distribution along the grid. A radiating dipole is mimicked by small current filaments, while nearly harmonic regime of weak coupling between the dipole and the metamaterial is assumed. To mimic the linearly polarized dipole, two voltage sources with the same amplitude and opposite phases in two diagonal nodes of the structure (marked in Fig. 1 (a) as +1 and -1, respectively) are used. A circular dipole is implemented using four voltage sources connected to neighboring four nodes at the centre of the array. The sources share the same amplitude but are 90^o phase-shifted with respect to each other (marked in Figs.1 (b) and (c)).

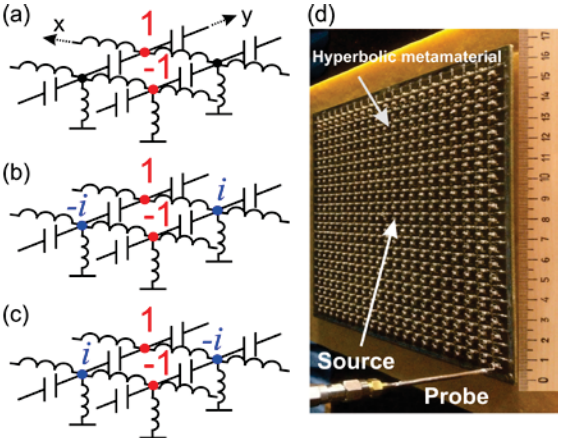

Figure 1: The unit cell of the two dimensional transmission line metamaterial composed of lumped elements excited by (a) a linearly polarized and (b,c) circularly polarized dipoles. (d) Photograph of the two-dimensional hyperbolic metamaterial prototype composed of 21 × 21 unit cells.

The modeled magnetic field distribution in the RF hyperbolic metamaterial excited by the linearly polarized dipole (Fig. 2(a)) placed at the centre of metamaterials shows a symmetric radiation pattern, where the energy propagates equally along the direction of the extraordinary axes. Strongly directional, not symmetric magnetic field intensity distributions are excited by either left-hand or right-hand polarised dipoles (Fig. 2 (b,c)). The contrast ratio of the intensity in orthogonal directions corresponds to about 10 dB, with the width of the excited mode being λ/300 (full width at half maximum). Fig. 2 (d-f) represents the modeled magnetic field distribution with Ohmic loss in all components and 10% tolerance of component nominal values taken in to account.

3. Experimentall Investigation

The photograph of the two-dimensional hyperbolic metamaterial prototype composed of commercially available RF components and operating at the frequency f_0=36 MHz is depicted in Fig. 3(d) [8]. We have experimentally studied the emission of a dipole of different polarisations placed inside of this two-dimensional hyperbolic metamaterials using a two-port VNA Agilent E8362C PNA. To achieve the dipoles with different polarizations, we have used the commercially available splitters (SBTCJ-1W+, JSPQ-65W+) from Mini-Circuits®. We measured the magnetic field distribution with the help of a magnetic probe at a distance of 1 mm above the top surface of the prototype using the automatic, mechanical, near-field scanner. The field has been measured along the metamaterial surface with a 4 mm step (λ/2500). The measured field distribution has a pronounced cross-like shape for the linearly polarised dipole (Fig. 2 (g)) in agreement with the simulations. For the circularly polarised dipoles, the measured field exhibits unidirectional energy propagation depending on the dipole polarization handedness (Fig. 2 (h and i)).

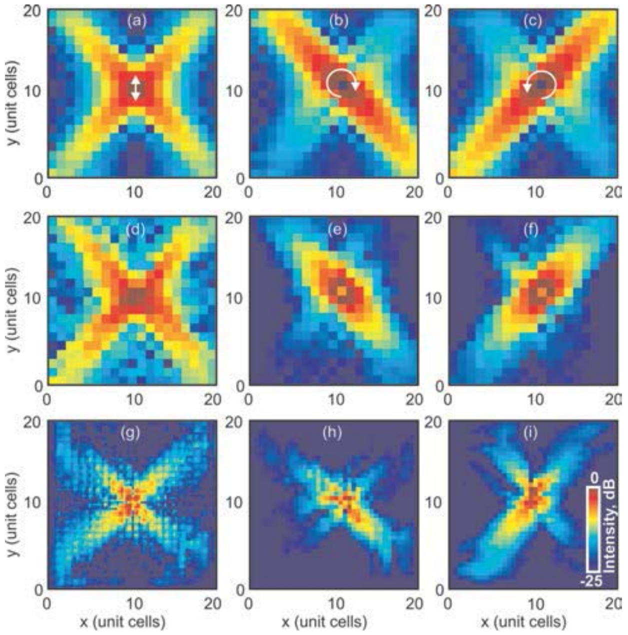

Figure 2: The intensity distributions of the waveguided modes in the metamaterial excited by linear polarised (left column) and circular polarised dipole of different handedness (middle and right columns). (a-c) Simulated intensity maps in the case of ideal lossless metamaterial, (d-f) simulated intensity maps in the case of metamaterial with random imperfections, and (g-l) experimentally measured intensity maps. The excitation dipole polarization is indicated in the figures.

4. Conclusions

We have numerically and experimentally demonstrated that the circularly polarised emitter near the RF anisotropic hyperbolic metamaterial unidirectionally emits in extraordinary modes of the metamaterial with the directionality of energy propagation controlled by the circular dipole handedness.

Acknowledgements

This work has been supported, in part, by EPSRC (UK), the Ministry of Education and Science of Russian Fed. (Projects 11.G34.31.0020, 14.B37.21.1941), Scholarship of the President of Russian Federation, and by the Australian Research Council (CUDOS Centre of Excellence CE110001018).

References

[1] D. R. Smith and D. Schurig, Electromagnetic wave propagation in media with indefinite permittivity and permeability tensors, *Phys. Rev. Lett.* 9: 077405, 2003.

[2] I. Iorsh, A. Poddubny, A. Orlov, P. Belov, and Yu. S. Kivshar, Spontaneous emission enhancement in metal-dielectric metamaterials, *Phys. Lett. A* 376: 18587, 2012.

[3] H. N. S. Krishnamoorthy, Z. Jacob, E. Narimanov, I. Kretzschmar, and V.M. Menon, Topological Transitions in Metamaterials, *Science* 336: 205-209, 2012.

[4] O. Kidwai, S. V. Zhukovsky, and J. E. Sipe, Physical nature of volume plasmon polaritons in hyperbolic metamaterials, *Opt. Lett.* 36: 2530, 2011.

[5] A. V. Kabashin, P. Evans, S. Pastkovsky, W. Hendren, G. A. Wurtz, R. Atkinson, R. Pollard, V. A. Podolskiy, and A. V. Zayats, Plasmonic nanorod metamaterials for biosensing, *Nature Materials* 8: 867 – 871,2009.

[6] Z. Jacob, L.V. Alekseyev, and E. Narimanov, Optical Hyperlens: Far-field imaging beyond the diffraction limit, *Opt. Express* 14: 8247-8256, 2006.

[7] F.J. Rodríguez-Fortuño, G. Marino, P. Ginzburg, D. O'Connor, A. Martínez, G. A. Wurtz, and A. V. Zayats, Near-Field Interference for the Unidirectional Excitation of Electromagnetic Guided Modes, *Science* 340: 328-330, 2013.

[8] A. V. Chshelokova, P. V. Kapitanova, A. N. Poddubny, D. S. Filonov, A. P. Slobozhanyuk, Y. S. Kivshar, and P. A. Belov, Hyperbolic transmission-line metamaterials, *J. Appl. Phys.* 112: 073116, 2012..