Metallic helix array as a broadband wave plate

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Abstract

This study demonstrates theoretically and experimentally that a metallic helix array can operate as a highly transparent broadband wave plate in propagation directions perpendicular to the axis of helices. The functionality arises from a special property of the helix array, namely, that two branches of elliptically right-handed and left-handed polarized states are nearly rigidly shifted in frequency and their dispersions are controlled by different mechanisms that can be independently tuned by structural parameters.

1. Introduction

Manipulating the polarization of electromagnetic (EM) waves is instrumental in both fundamental optical physics and photonics applications. A wave plate, in the form a birefringent crystal with specific orientation and thickness, has long been used for the purpose of polarization control. It transforms the polarization of EM waves by the superposition of two linearly polarized states that are orthogonal to each other propagating inside the crystal with different phase velocity [1]. The two orthogonal states can also be, alternatively, left-handed and right-handed elliptically polarized (LEP and REP) eigenstates of uniaxial bi-anisotropic medium [2]. It is worth noting that, such a wave plate with a certain thickness can only operate in a narrow frequency range [1, 2] as the difference of phase velocity of two polarized eigenstates is frequency dependent. To build a broadband wave plate with a homogeneous medium, it requires not only that the difference of phase velocity but also the axis ratios of the two polarized states must not change throughout the whole operational band. To the best of our knowledge, no natural or artificial medium exhibits such properties.

In this paper, we demonstrate that a metallic helix array, as one classical representative in chiral metamaterials [3, 4], is also very unique in that the EM properties of such kind of structure are the collective effect between the local resonance that governs metamaterials and Bragg scattering that governs photonic crystals [5]. Specifically, we show how the helical symmetry of helices provides additional degrees of freedom for tuning the dispersion branches in different handedness, namely the REP and LEP eigenstates on the transverse plane of metallic helix array are controlled respectively by Bragg scattering and the EM coupling derived from the continuous helical symmetry. The ellipticity and difference between wavevectors of the two states can be fixed in a wide frequency range by choosing appropriate geometric parameters, leading to a helix solution for highly transparent broadband wave plate. The proof-of-principle microwave experiments, in good agreement with theoretical calculations, verify the thickness-dependent polarization character of transmitted waves through three helix samples. This is a first realization of a broadband wave plate which utilizes the LEP and REP states of metallic helix array.

ISBN 978-952-67611-2-1

2. Dispersion tuning and wave plate functionality of metallic helix array

Figure 1 presents the schematic configuration of a wave plate made with right-handed (RH) metallic helix array [Fig. 1 (a)], a photo of the 7-layered slab sample, the corresponding dispersion diagram $\omega(k_x, k_y = k_z = 0)$ [Fig. 1 (b)], and the comparative results by varying critical geometric parameters associated with helical symmetry and Bragg scattering [Fig. 1 (c) and (d)].

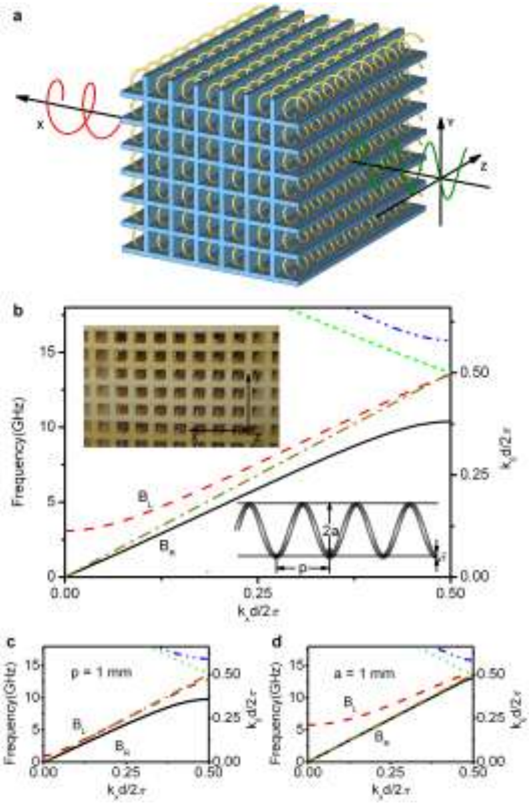

Fig. 1: A Slab of Helices as Wave Plate for Transversely Propagating Waves. The geometric parameters are the pitch p = 4mm, helix radius a = 3 mm, wire diameter δ = 0.6 mm, the lattice constant d = 11 mm; and the comparative results by (c) varying pitch only to p = 1 mm, and (d) varying helix radius only to a = 1 mm, all other parameters are fixed to their respective values in Fig. 1(b).

It is interesting to note that the dispersions of the B_L and B_R branches can be modulated to be in parallel to each other in a wide frequency range. This is because they are controlled by the EM coupling along the helix (z) axis and the Bragg scattering (in the xy plane) among the helices, respectively, and the two different mechanisms can be independently modulated by different sets of structural parameters. Such property is not likely to be found in other systems. More calculations show that the lowest branch B_R [black solid line in Fig. 1 (b)] is dictated by the degenerate $\pm 1^{st}$ orders of helical Bloch states with the electric fields along the y direction, while the second lowest branch B_L [red dashed line in Fig. 1 (b)] is dictated by the 0^{th} order of helical Bloch state with the electric fields along the helix axis (Wu et al. 2010). Consequently, a B_R/B_L state shall pick up an REP/LEP character with long axis along the y /z direction. A salient feature of the band structure shown in Fig. 1(b) is that the B_L and B_R branches are essentially linear and parallel to each other in a wide frequency range of 3.9 GHz ~9.6 GHz. Within this band, two orthogonal eigenstates $|\phi_{LEP}\rangle$ and $|\phi_{REP}\rangle$ of the B_L and B_R branches pick up the same difference $\Delta k = k_{REP} - k_{LEP}$ between their wavevectors. The analysis of equi-frequency surfaces (EFS) indicates that this property generally holds for all directions in the transverse plane as if the helix array behaves as an isotropic medium for the transversely propagating waves. We also note that, within the same frequency range, the axial ratio of the in-plane field components for the LEP/REP branch [Fig. 1 (b)] is roughly fixed as well. These properties are adequate for producing a broadband wave plate which surpasses the narrow bandwidth limitation of a birefringent crystal as wave plate.

We perform transmission measurements inside an anechoic chamber through a slab of the helix array with the aforementioned geometric parameters. Helix samples are fabricated by periodically embedding the clockwise metallic helices in a polyurethane foam slab which is nearly lossless with a dielectric constant of $\varepsilon \approx 1.01$. According to the calculated band structure in Fig. 1 (b), the thinnest wave plate for linear-to-circular polarization transformation (or vice versa) only requires 7 periods along the x direction. The sample slab contains 7×60 metallic helices (i.e. 7 periods along the x-direction and 60 periods along the y-direction), each helix has 200 periods along the helix axis. The calculated/measured transmittance is above /85% at the most of the frequencies in the range of 3.9 ~ 9.6 GHz. Measured results show that the signal-to-noise ratios are larger than 20dB in the frequency range of 4.1-8.8GHz. Note that this entity only relies on intrinsic response of metallic helix array as an artificially made chiral material. And the performance can be much improved by tuning the structural parameters of helix array. It is also noted that the thickness-dependent results for the 14- and 21-period sample slabs verify the wave plate functionality of metallic helix array.

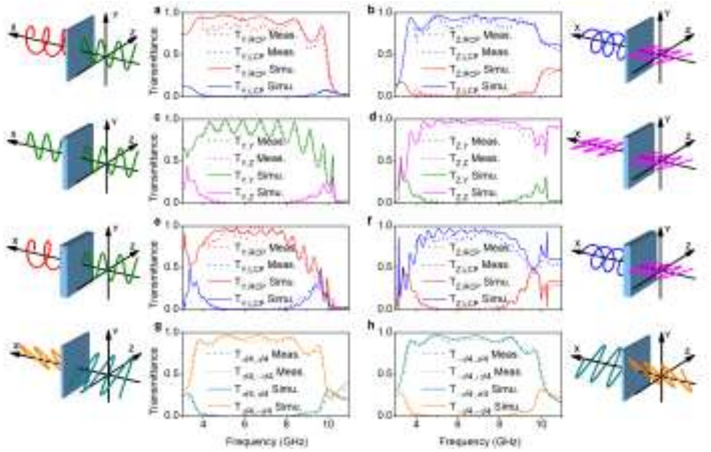

Fig. 2: Measured/Calculated Transmission Spectra of Helix Samples with 7, 14 and 21 periods along the propagating direction (x-direction). (a) and (b), (g) and (h) for 7-period sample, (c) and (d), (e) and (f) for 14-, 21-period samples, respectively. The first and the second subscripts, i, and j, of the transmission spectra $T_{i,j}$ refers to the polarized state of the incident and the transmitted waves, respectively. The letter Y or Z denotes a linear polarization along y- or z- direction.

3. Summary

Most of conventional wave plates, such as those utilizing birefringence effect of liquid crystals, typically rely on the staking of different wave plates and system optimizing to extend the operation bandwidth at the cost of transmission attenuation. Here, we provide an entirely new and different strategy for broadband wave plate basing on the unique properties of chiral material. Our findings can be generalized to other frequency regimes such as THz and even the infrared regimes.

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