Optik 125 (2014) 1723–1726

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Electromagnetic behaviors in a bilayered metal helical structure

Peng Zhang, Ming Zhao*, Lin Wu, ZeQin Lu, YongZhi Cheng, RongZhou Gong, ZhenYu Yang

School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan, Hubei, 430074, China

ARTICLE INFO

Article history:
Received 26 April 2013
Accepted 14 September 2013

Keywords:
Resonance
Bilayered metal helical structure
Circularly polarized wave
Transmission performance

ABSTRACT

We studied both numerically and experimentally electromagnetic behaviors of a bilayered metal helical structure in the microwave-frequency. Two resonances are found in the transmission spectrum of the circularly polarized wave which has the same handedness with the helices. The resonance frequencies are almost independent on the distance between the two layers. In addition, the center frequency of full width at half-maximum (FWHM) in the transmission spectrum is approximately inversely proportional to the distance between the two layers.

1. Introduction

Metamaterials have been widely and intensively investigated because of their fascinating properties and potential applications, for example, negative refractive index [1–3], "perfect lenses" [4], and cloaking [5]. These properties have close relation with electromagnetic responses in the metamaterials, such as split ring resonators (SRRs) [6,7] and cross-wire structures [8]. In addition, electromagnetic responses also play a crucial role in some bilayered or multi-layered structures [9–12]. In the last few years, as a typical structure with chirality in three-dimension, metal helical structure has been studied widely due to the application for a compact and broadband circular polarizer proposed by Gansel et al. [13,14]. The dependence of optical properties on structural parameters, i.e., the diameter of wire, the number of helix-period, the spacing grid, the length of helix-period, the diameter of helix, and the angle of incidence, has been studied [14–16]. The metal helical structure has also been studied in the terahertz and gigahertz region, showing circular dichroism [17–19] and negative refraction [19,20]. Although the metal helical structure has been investigated intensively as discussed above, the electromagnetic behaviors in a bilayered metal helical structure are unknown.

In our work, we simulated the bilayered metal helical structure consisting of left-handed helices using the finite-difference time-domain (FDTD) method in the microwave frequency of 8–18 GHz. Considering the difficulties to fabricate multiple-helical structure and the convenience to analyze, we only studied the bilayered metal helical structure consisting of single helices with NH = 1. It is found that the bilayered metal helical structure transmits the right circularly polarized (RCP) wave which has the opposite handedness with the helices, whereas two distinct and sharp resonances are found in the transmission spectrum of the left circularly polarized (LCP) wave. The resonance frequencies are almost independent on the distance between the two layers. Furthermore, the resonances occurring in the single helical structure of each layer will also emerge in the bilayered helical structure with almost same frequencies. In addition, the center frequency of full width at half-maximum (FWHM) in the spectrum of the LCP wave is approximately inversely proportional to the distance between the two layers. In addition, we also measured the transmission performances of the bilayered helical structure composed of iron (Fe) wires. Apart from the spectra positions of the resonances, all of the features observed in the experimental transmission spectra have a good agreement with the simulations.

2. Numerical models and experimental techniques

Fig. 1 shows the schematic diagram of a bilayered metal helical structure consisting of left-handed helices. The LCP and RCP waves are used as excitation sources to incident along the *Z* direction, respectively. The parameters of DW, NH, SG, LH, DH, and DL in Fig. 1 stand for the diameter of wire, the number of helix-period, the spacing grid, the length of helix-period, the diameter of helix, and the distance between the two layers, respectively. The bilayered metal helical structure was simulated using the FDTD method. The perfectly matched layers (PML) were applied to the *Z* direction [21]. The boundaries along *X* and *Y* directions were confined

* Corresponding author.
E-mail address: zhaoming@mail.hust.edu.cn (M. Zhao).

0030-4026/$ – see front matter © 2013 Elsevier GmbH. All rights reserved.
http://dx.doi.org/10.1016/j.ijleo.2013.09.059

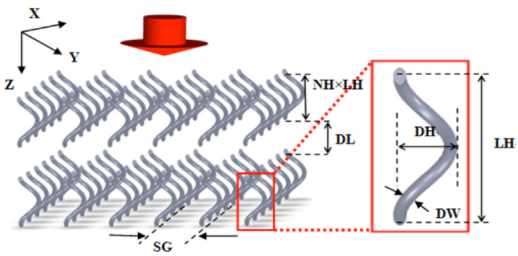

Fig. 1. The schematic diagram of the bilayered helical structure.

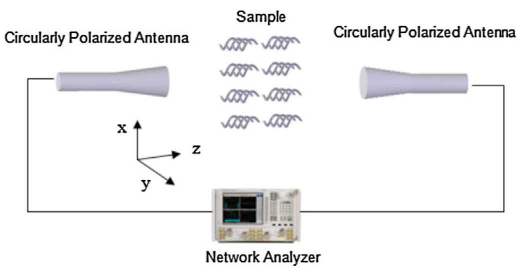

Fig. 2. The schematic diagram of the experimental setup.

with the periodic boundary conditions due to the periodicity of the structure [22]. As the structure operated in the microwave frequency of 8–18 GHz, perfect electric conductor (PEC) was used as material of the Fe wires during the simulations.

We performed the transmission coefficient measurements inside a microwave anechoic chamber. Fig. 2 shows the schematic diagram of the experimental setup. The LCP and RCP waves were obtained and measured by using an Agilent N5244A network analyzer, which was connected with two circularly polarized antennas of the 8–18 GHz frequency range. The sample of the bilayered metal helical structure was composed of two polystyrene foam slabs with a distance DL between them. Oriented along the *Z* axis, the left-handed helices were periodically embedded into the polystyrene foam slab to form a single metallic helix array in the XY plane. The polystyrene foam is lossless with a very low permittivity in the microwave frequencies. Every foam slab has a dimension of 25 × 25 unit cells.

3. Results and discussions

We firstly studied the dependence of electromagnetic behaviors in the bilayered metal helical structure on the value of DL. Fig. 3 shows the simulated transmission spectra of the bilayered metal helical structures with different DL from 6 to 12 mm, while other parameters of the two layers are same and remain unchanged as follows: DW = 1 mm, NH = 1, LH = 8 mm, DH = 4 mm, and SG = 10 mm. It is obviously found that, though DL is varied, these structures

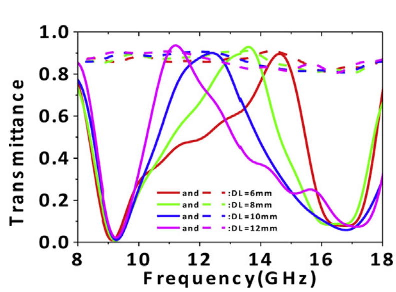

Fig. 3. The simulated transmission spectra of the bilayered metal helical structures with different DL. The solid lines are the results for the LCP wave and the dashed lines are the results for the RCP wave. The distance DL is varied from 6 to 12 mm.

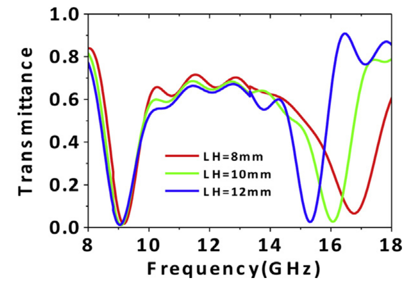

Fig. 4. The simulated transmission spectra of the single metal helical structures for the LCP wave with different LH.

have similar phenomena. The bilayered metal helical structures transmit almost all the RCP wave, which has the opposite handedness as the helices, whereas two distinct and sharp resonances occur for the LCP wave. It can be explained by the knowledge of antenna. According to the theory of antenna [23,24], when waves propagate along the helix axis, circularly polarized antenna will receive the circular polarization with the same handedness, whereas it cannot receive the other. Considering the left-handed helices are used in the simulations, it is easily understood that the structures transmit the RCP wave, whereas block the LCP wave. These phenomena are also found in single metal helical structure [13]. What makes us curious is that the spectral positions of the two resonances remain essentially unchanged, even though DL changes. Two frequencies f = 9.14 GHz and 16.78 GHz correspond to the two resonances, respectively. From the phenomena above, we made an assumption that the two resonances were closely related to the structure of each layer, whereas independent on the distance DL.

In order to verify our assumption, considering the bilayered metal helical structure has a significant relation with each single metal helical layer, we studied briefly the electromagnetic behaviors of the single metal helical structure. As the bilayered metal helical structure consisting of the left-handed helices transmits the RCP wave, we only discuss the transmission spectra for the LCP wave. Fig. 4 shows the simulated transmission spectra of the single metal helical structures for the LCP wave with LH = 8, 10 and 12 mm, respectively. The other parameters are as follows: DW = 1 mm, NH = 1, DH = 4 mm, and SG = 10 mm. For each value of LH, two distinct resonances still emerge for the LCP wave. Their lower resonance frequencies are almost the same with f_{low} = 9.14 GHz, while their higher resonance frequencies are different as follows: f_{high} = 16.78, 15.97 and 15.25 GHz correspond to LH = 8, 10 and 12 mm, respectively. As argued in [13,14], the number of nodes of the current on the helix wire changes with different frequencies. For the low-frequency resonance, the current has nodes only at the ends of the metal wire. The current in the helix wire is flowing in one direction at any point within an optical cycle. It is similar to a ring current which can generate a magnetic dipole. Although LH is different, the intensity of magnetic dipoles produced by the current remains unchanged due to the same DH. It has been tested by simulations that the spectral position of the low-frequency resonance will change if DH is varied and other parameters stay unchanged (the results of simulations are not shown here). For the high-frequency resonance, the current has one additional node in the middle of the metal wire. The current distribution on the wire resembles closely a standing wave that the positions of current nodes only change slightly with time. Thus LH is approximately proportional to the resonance wavelength λ. So the spectra position of the high-frequency resonance red-shifts with the increase of LH.

Considering different from the single metal helical structure, the spectra positions of resonances may change in the bilayered metal