Strong and Broadband Circular Dichroism based on Helix-like Chiral Metamaterials

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***Abstract*—In this paper, a helix-like chiral metamaterials, which can be realized with multiple electron beam lithography, has been proposed to achieve strong and broadband circular dichroism. A preferential transmission of right-handed polarized waves spanning over a wavelength range of above 5 μm is realized owning to the combined effects of internal and Bragg resonance.**

Keywords—chiral metamaterial; circular dichroism; helix-like

I. INTRODUCTION

Chiral metamaterials have attracted increasing attention for varies unique properties. In particular, circular dichroism (CD), the optical response difference between left- and right-handed circularly polarized light, in chiral metamaterials can exceed the corresponding effects in natural chiral materials by many orders of magnitude. Hence, chiral electromagnetic meta-materials are interesting candidates for future circular polarization control applications.

A straightforward idea of the asymmetry chiral structure is a helix, in 2009, J. K. Ganselbut ect. proposed to prepare three-dimensional gold helices via direct laser writing followed by electrochemical deposition. CD in the wavelength range from 3.5 to 7.5 μm is obtained[1]. However, after them, rarely other works reported of experiments on helix as this 3-D structure is quite difficult to be fabricated. Thus, quasi-planar structures are proposed to realize a similar function. Many researchers are focused on the bi-layer or multi-layer planar structures, such as the conjugated gammadion [2], the rotating rosette [3], the twisted cross [4], the U-shaped split-ring resonators (SRR) [5], etc., however, the CD effect of all these structures have been restricted to narrow frequency ranges, which is a major drawback for many potential applications.

In this paper, an alternative venue is proposed to achieve strong and broadband circular dichroism effects in metamaterials based on a helix-like chiral structure, which can be realized with multiple electron beam lithography. Our goal is to show that, by introducing vertical metallic connections between a stacked layer twisted split-ring structure, one can achieve exotic effects analogous to helical metamaterials.

II. STRUCTURE AND DESIGN

The unit cell of the helix-like chiral metamaterial (HLCMM) structure is shown in Fig. 1. Here, a four-layer helix-like chiral metamaterial is taken for an example. It consists of cascading four identical golden one-third-rings with a separation distance d and a specific rotation angle θ of the second surface compared with the first one. The rings are separated with silicon monoxide spacer and three golden cylinders are employed to connect the neighboring rings. Every golden rings and cylinders are adherent to the spacer with a 5-nm titanium adhesion layer. The geometry dimension parameters of the spilt-rings are as follow: thickness t=200 nm, inside radius r_i=364 nm, outside radius r_o=604 nm, separation distance d=235 nm, rotation angle θ=120°. The radii of the connection cylinders are r_c=120 nm. The whole structure is fabricated on silicon substrate with a period of p_x=p_y=1200 nm. The simulation is performed by commercial software (Lumerical FDTD Solutions), which is based on the Finite Difference Time Domain (FDTD) method. The dielectric properties of gold and titanium as given by Palik are used.

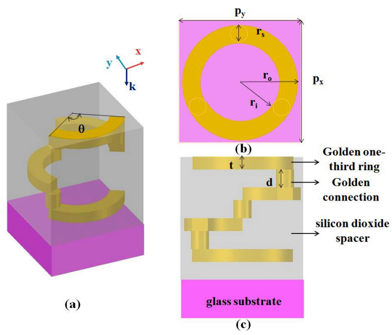

Fig. 1. (a) Schematic of the unit cell for helix-like chiral metamaterial structure. (b) Top view; (c) X-Y side view.

The structure is excited by a source with a wavelength range from 2 μm to 10 μm, propagating along the negative z direction with the electric field polarized in the x(y) direction. Perfectly match layer (PML) absorbing boundaries are applied in the z direction and periodic boundaries are used for a unit cell in the x-y plane. The transmission matrix for circularly polarized waves is calculated with the equation (1).

$$T_c=\begin{pmatrix} T_{++} & T_{+-} \\ T_{-+} & T_{--} \end{pmatrix}=\frac{1}{2}\begin{pmatrix} \left(T_{xx}+T_{yy}\right)+i\left(T_{xy}-T_{yx}\right) & \left(T_{xx}-T_{yy}\right)-i\left(T_{xy}+T_{yx}\right) \\ \left(T_{xx}-T_{yy}\right)+i\left(T_{xy}+T_{yx}\right) & \left(T_{xx}+T_{yy}\right)-i\left(T_{xy}-T_{yx}\right) \end{pmatrix} \quad (1)$$

where the subscripts + and − represent the right-handed polarized (RCP) and left-handed polarized (LCP) waves, respectively.

III. RESULTS AND DISCUSSIONS

Fig. 2 shows the transmission spectra of the four-layer HLCMM structure in normal incidence. Results show that take air (n=1) as substrate and spacers, a preferential transmission of RCP waves spanning over a wavelength range above 7.5 μm is realized. And with silicon monoxide spacers and silicon substrate, the broad CD range still can be obtained but with a red-shift and transmittance decrease due to the influence of higher reflection and other effects caused by the change of refractive index.

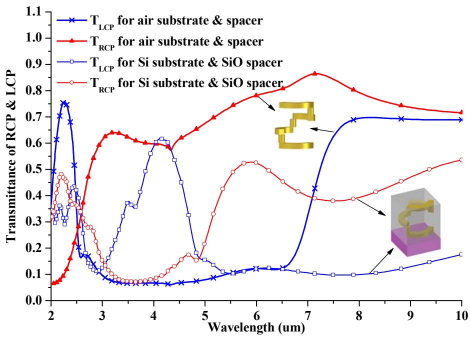

Fig. 2. 3D-FDTD simulation of transmission of HLCMM structure for both RCP and LCP in normal incidence.

As Fig. 2 shows, the broadband CD originates from broad stop band of LCP in the asymmetry structure. To clarify the nature of this broad stop band, firstly, the transmission spectra of different layer combinations without substrate and spacers is shown in Fig. 3. For a single layer, a split-ring can be treat as a tiny resonant electromagnet induced by the incident optical field [1]. For more layers, in the case without periodical building blocks, narrow resonance is observed due to electric-magnetic dipole coupling. While in the case with periodically arranged unit, Bragg resonances will appear. Thus, to the combination of layer 1,2,3&4, a broad stop band results from the superposition of the above resonances, a broad stop band is achieved. Thus, one can indicate that by adding more layers, more internal and Bragg resonances may appear to achieve a wider stop band.

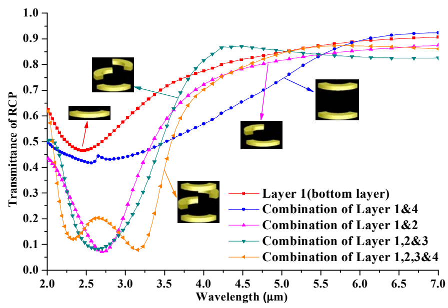

Fig. 3. Normal-incident LCP transmittance of different layer combinations.

In order to further elucidate the underlying mechanism of the wider stop band after adding connections, transmittance of the structures with different numbers of connections are simulated as Fig. 4 shows. After adding the connections to the neighboring rings, the capacitive coupling between the two layers will disappear, leading to the change of the inductance and capacity in the equivalent LC circuit, and finally changes the resonant wavelength and contributes to a much more wider stop band.

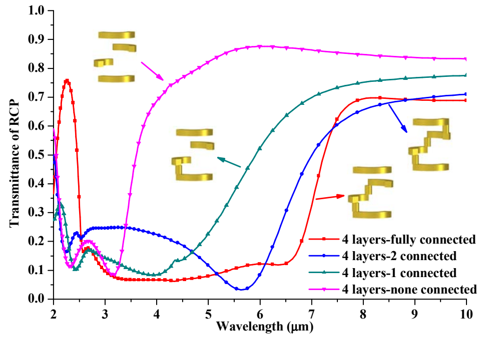

Fig. 4. Transmittance of the structures with different number of connections

IV. SUMMARY AND CONCLUSIONS

In this paper, a HLCMM structure is proposed to achieve strong and broadband CD effect owning to the combined effects of Bragg resonance and internal resonance. This structure is promising for a variety of exciting applications for polarization control such as achromatic quarter-wave plates or broadband circular polarizers which are currently unavailable.

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REFERENCES

[1] Justyna K. Gansel, Michael Thiel, Michael S. Rill, Manuel Decker, Klaus Bade, Volker Saile, Georg von Freymann, Stefan Linden, Martin Wegener, "Gold helix photonic metamaterial as broadband circular polarizer," Science, vol 325, pp 1513–1515, 2009.

[2] Tun Cao, Lei Zhang, Robert E. Simpson, Chenwei Wei, and Martin J. Cryan, " Strongly tunable circular dichroism in gammadion chiral phase-change metamaterials," Optics Express, vol. 21, pp 27841, November 2013.

[3] E. Plum, V. A. Fedotov, A. S. Schwanecke, N. I. Zheludev, and Y. Chen, " Giant optical gyrotropy due to electromagnetic coupling," Applied Physics Letters, vol 90, pp 223113, May 2007.

[4] Weiren Zhu, Ivan D Rukhlenko , Yongjun Huang , GuangjunWen and Malin Premaratne," Wideband giant optical activity and negligible circular dichroism of near-infrared chiral metamaterial based on a complementary twisted configuration," J. Opt. vol 15, pp 125101, October 2013.

[5] Mehmet Mutlu, Ahmet E. Akosman, Andriy E. Serebryannikov, and Ekmel Ozbay," Asymmetric chiral metamaterial circular polarizer based on four U-shaped split ring resonators," Optics Letters, vol. 36, pp 1653-1655, May 2011.

[6] R. Abdeddaïm, G. Guida, A. Priou, B. Gallas and J. Rivory, " Negative permittivity and permeability of gold square nanospirals, "Appl. Phys. Lett. vol. 94, pp 081907 , February 2009.