Bi-layer cross chiral structure with strong optical activity and negative refractive index

**Jianfeng Dong,[1,2,*] Jiangfeng Zhou,[2,3] Thomas Koschny, [2,4]
and Costas Soukoulis[2,4]**

[1] *Institute of Optical Fiber Communication and Network Technology, Ningbo University, Ningbo, Zhejiang, 315211, China*
[2] *Ames Laboratory and Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA*
[3] *Center for Integrated Nanotechnologies, Materials Physics & Applications Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[4] *Institute of Electronic Structure and Laser - Foundation for Research and Technology Hellas (FORTH), and Department of Materials Science and Technology, University of Crete, Greece*
[*] *dongjianfeng@nbu.edu.cn*

Abstract: The properties of periodic pairs of mutually twisted metallic (silver) crosses separated by dielectric layer have been investigated by numerical simulation. The results show that the exceptionally strong polarization rotation and circular dichroism, negative permeability and negative refractive index are found at the infrared communication wavelength (1.55μm).

OCIS codes: (160.3918) Metamaterials; (350.3618) Left-handed materials; (260.5430) Polarization; (050.1930) Dichroism.

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1. Introduction

Metamaterials with negative refraction index [1] have gained a lot of attraction during the last decade. They have unique features and many potential applications such as "perfect lenses" [2] which can overcome the diffraction limit. The conventional design for negative refractive index material in the microwave frequency region is a combination of split ring resonators (SRR) which offer negative permeability [3] with thin metallic wires which offer negative permittivity [4]. However, SRR material is very sensitive to the polarization of the incident electromagnetic wave [5]. New cut-wire-pair metamaterials for waves propagating normal to the plane of the structures have been realized in the frequency region from microwave to infrared and optical wave [6-12], which have negative magnetic permeability or even negative refractive index. The cut-wire-pair arrangement has a distinct advantage over conventional SRRs because it can be built by conventional fabrication technique and can operate under normal incidence wave. The control of the magnetic-resonance frequency plays an important role in the cut-wire-pair metamaterials. It has been found that the magnetic-resonance frequency depends significantly on the length and width of cut-wire-pair [13,14] and almost unchanged for different distance between cut-wire-pair layers [13,15]. The periodic pairs of metallic crosses structure which can be looked upon as an extension of the cut-wire-pair has been theoretically analyzed in the microwave and terahertz region [16-18]. This structure also has negative refractive index and is independent of the polarization of the incident wave.

Recently, chiral media with strong optical activity have attracted a lot of attention as potential candidates for achieving negative refraction [19-23]. Because optical activity or chirality parameter in nature chiral material is very small, it is necessary to build artificial structures which possess strong optical activity or large chirality parameter. Very strong gyrotropy (chirality) was reported in the bi-layer chiral rosette structure and similar chiral magnetic metamaterials, which can be looked upon as a chiral version of the cut-wire-pair, at microwave and optical wave region [24-28]. It has been shown experimentally that negative refractive index occur in this type of structure at microwave frequency [29,30]. In the present paper, we study the properties of periodic pairs of mutually twisted metallic (silver) crosses separated by dielectric layer. Dependence of twist angle and dielectric layer thickness are examined to explore strong optical activity and negative refractive index at the infrared communication wavelength (1.55μm).

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2. Bi-layer cross chiral structure and simulation method

Our chiral metamaterial design is composed of square-periodic array pairs of mutually twisted metallic crosses separated by dielectric layer. We chose silver as metallic material since it has the smallest loss in optical and infrared region. This structure is simpler than rosette or gammadion structure reported in previous papers [26,27]. A schematic drawing of the unit cell of the mutually twisted cross chiral structure with all geometrical parameters is depicted in Fig. 1. Periodic constant a=500nm, length, width and thickness of cross bar are l=400nm, w=100nm and t=50nm, the thickness of spacer dielectric layer d=50nm, ϕ is a mutual anti-clockwise twist angle between crosses. Our numerical simulations were done with CST Microwave Studio (Computer Simulation Technology GmbH, Darmstadt, Germany), which use a frequency domain finite element method. In the simulations, the dielectric properties of the metal silver were handled with a frequency dependent Drude model ($\omega_p = 2\pi \times 2175\ THz$, $\omega_c = 2\pi \times 4.35\ THz$), and the dielectric constant of the dielectric layer is 2.1. A plane light wave incidents normally onto the front cross plane. Periodic boundary condition was used in the direction perpendicular to the propagation direction. The detailed calculations were used to determine reflection and transmission coefficients from a single unit cell. Circular dichroism and polarization azimuth rotation can be calculated by $\Delta = |T_{RCP\_RCP}| - |T_{LCP\_LCP}|$, and $\theta = -0.5[\arg(T_{RCP\_RCP}) - \arg(T_{LCP\_LCP})]$, where T is the transmission coefficient, the subscript represents the polarization of input and output wave [25]. Using the retrieval procedure for chiral metamaterial [29,30], the complex effective parameters n, ε and μ, and chirality parameter κ from the simulated transmission and reflection can be obtained.

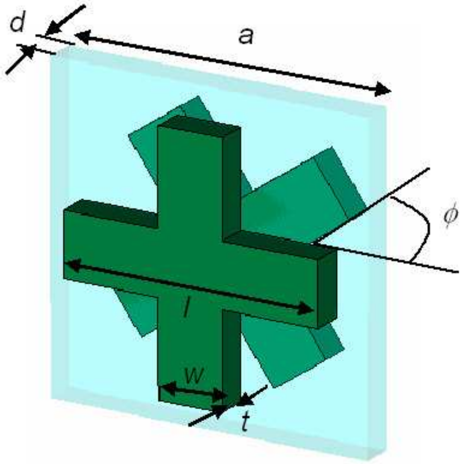

Fig. 1. Unit cell of bi-layer cross chiral structure.

3. Simulation results and discussion

3.1 Dependence of twist angle

Figure 2 shows dependence of twist angle ϕ for transmission spectra of left-handed (LCP) and right-handed (RCP) circular polarizations for LCP (RCP) incidence. The transmission between LCP and RCP polarization, T_{LCP_RCP} and $T_{RCP\_LCP,}$ are very small and can be ignored. Due to the fourfold symmetry of the cross, only 0 to 45 degree twist angle ϕ are presented. While the structure with ϕ in between 45 and 90 degrees, it is equivalent to its enantiomeric form with twist angle ϕ of 0 to 45 degree, therefore has an opposite sign of gyrotropy [25]. As well known, ϕ=0 correspond to the pair of cross with no twist between crosses. There are two

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band gaps in the transmission spectra. First band gap is due to the magnetic resonance and second band gap is due to the electric resonance [18] (It is confirmed from retrieval parameter below). It can be seen from Fig. 2 that the frequency of magnetic resonance increases as the twist angle increases. The magnetic-resonance frequency position shifts from about 180 THz to 200THz when the twist angle varies from 0 to 45 degree. The variety of the frequency of electric resonance is small. The transmission is nearly the same at the middle range between magnetic and electric resonances frequency for different twist angles. The resonance frequencies for RCP and LCP incidence are almost the same. Difference of magnetic and electric resonances frequency (f_m and f_e) $\Delta f=f_e-f_m$ linearly decreases as the twist angle increases (see Fig. 3). The behavior can be understood by the fact that the electric resonance is caused mainly by each metallic cross (electric dipole) and the magnetic resonance is caused mainly by coupling between two metallic crosses (magnetic dipole) [18]. As the twist angle increases, the coupling between two metallic crosses changes.

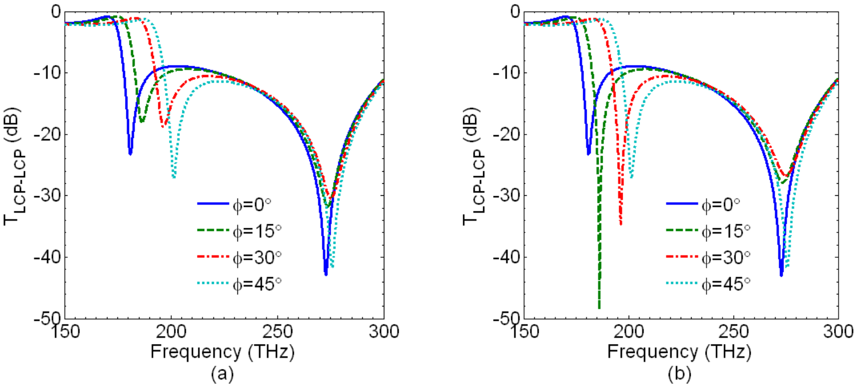


Fig. 2. Transmission spectra of the bi-layer cross chiral structure for different twist angles.

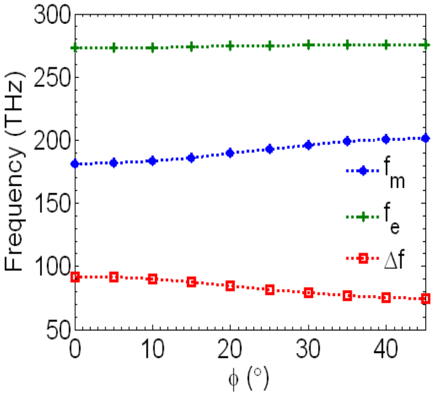
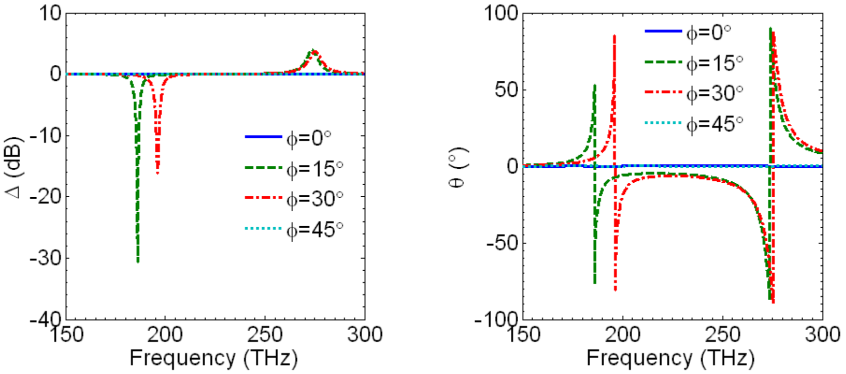


Fig. 3. Dependence of the resonance frequencies on twist angles.

For left-handed (LCP) and right-handed (RCP) circular polarizations the bi-layer cross chiral structure shows exceptionally strong circular dichroism and polarization azimuth rotation. Figure 4 shows dependence of the circular dichroism and polarization azimuth rotation on twist angles. No circular dichroism and polarization azimuth rotation for ϕ=0 and 45 degrees. The circular dichroism is negative in the magnetic resonance region and positive in the electric resonance region for ϕ>0. Up to 30dB is achieved for 15 degree twist angle. Polarization azimuth rotation has also two resonance regions. Of interest is in the band of infrared communication wavelength (1.55μm). Polarization azimuth rotation up to 70 degree at 193THz (1.55μm) is achieved for 25 degree twist angle. These values are substantial considering the material's thickness (150nm) of only 1/10 wavelength at 193THz (1.55μm). This corresponds to a giant specific rotary power of 47000°/mm. In the middle of two resonance frequencies, zero dichroism and pure rotation of polarization azimuth of about 7 degree was observed for 25 degree twist angle. This corresponds to a giant specific rotary power of 4700°/mm. These specific rotary power are much larger than those in Ref. 26 (2500°/mm and 600°/mm, respectively).



(a) (b)

Fig. 4. Dependence of circular dichroism (a) and polarization azimuth rotation (b) on twist angles.

Retrieval of the material's permittivity ε and permeability μ, refractive index n and chirality parameter κ show that bi-layer cross chiral structure has magnetic resonances at lower frequency and electric resonances at higher frequency. Retrieval parameters show that negative permeability occurs for any twist angle (including 0 degree) at magnetic resonances region (Fig. 5). But negative index for RCP can be obtained only for twist angle larger than 10 degree. Broad band of negative permeability and larger value negative refractive index for RCP at around 193 THz (1.55μm) can be obtained for 25 degree twist angle. It is noted that, the refractive indices n_{RCP} and n_{LCP} for RCP and LCP are given by $n+\kappa$ and $n-\kappa$, respectively [29,30], where n is the conventional definition of refractive index, $n=\sqrt{\varepsilon\mu}$, and κ is the chirality parameter.

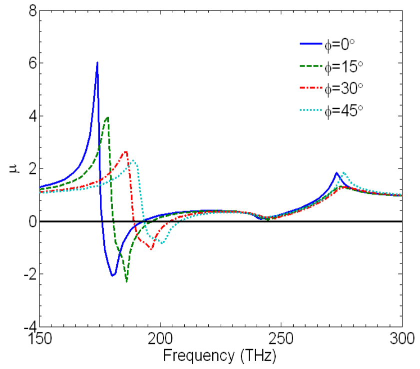


Fig. 5. Dependence of magnetic permeability on twist angles

Figure 6 presents the real parts of the permittivity ε and permeability μ, refractive index n and chirality parameter κ for 25 degree twist angle. It is clear from Fig. 6(a) that the resonance at lower frequency is magnetic resonance and the resonance at higher frequency is electric resonance. The negative refractive index for RCP is Re(n_{RCP})=-2.6 at about 193 THz

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(1.55μm). The negative refractive index for RCP and LCP originates from the chirality parameter if we notice that n (black dotted curve) is positive through the entire frequency range from 150 to 300 THz (Fig. 6(b)). n_{RCP}(red solid) is negative from 193 to 202 THz and n_{LCP} (blue dashed) has a negative region from 275 to 300 THz. The chirality parameter (green dash-dotted curve) shows two resonances at 193 and 275 THz, respectively. In the frequency range from 193 to 202 THz, the chirality parameter κ is negative and the value is bigger than refractive index n, leads to $n_{RCP}<0$. Similarly, in the frequency range from 275 to 300 THz, the chirality parameter κ is positive and the value is bigger than refractive index n, leads to $n_{LCP}<0$.

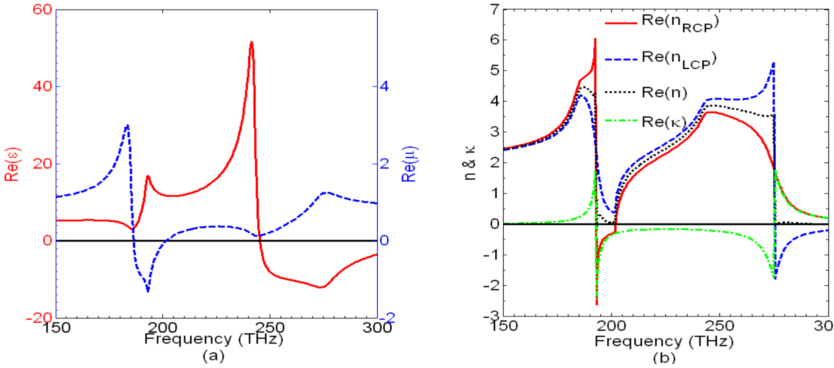

Fig. 6. (a). Permittivity and permeability; (b) Refractive index and chiral parameter; for 25 degree twist angle.

3.2 Dependence of dielectric layer thickness

Since large negative refractive index occur for 25 degree twist, we chose ϕ=25 degree to examine the dependence of dielectric layer thickness for bi-layer cross chiral structure. Keeping the other parameter unchanged, the dielectric layer thickness varies from 25nm to 200nm. Figure 7 shows the transmission spectra for different dielectric layer thickness. As the dielectric layer thickness increases, the frequency of magnetic resonance f_m increase and frequency of electric resonance f_e decrease, thus the difference of $\Delta f=f_e-f_m$ decreases (Fig. 8).

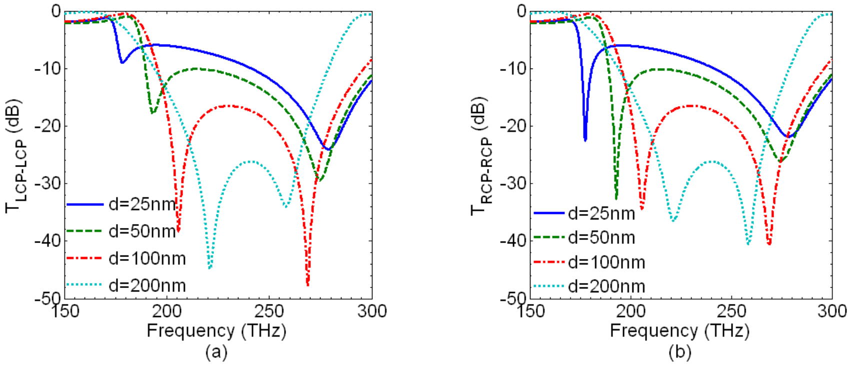

Fig. 7. Transmission spectra of the bi-layer cross chiral structure for different dielectric layer thickness.

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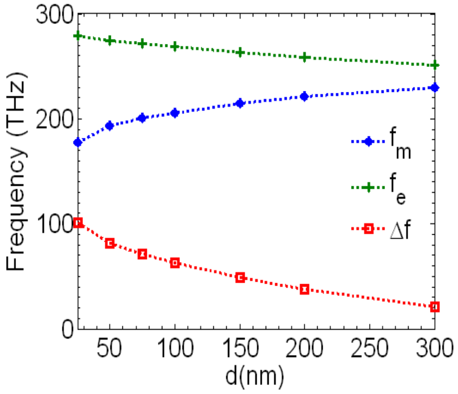
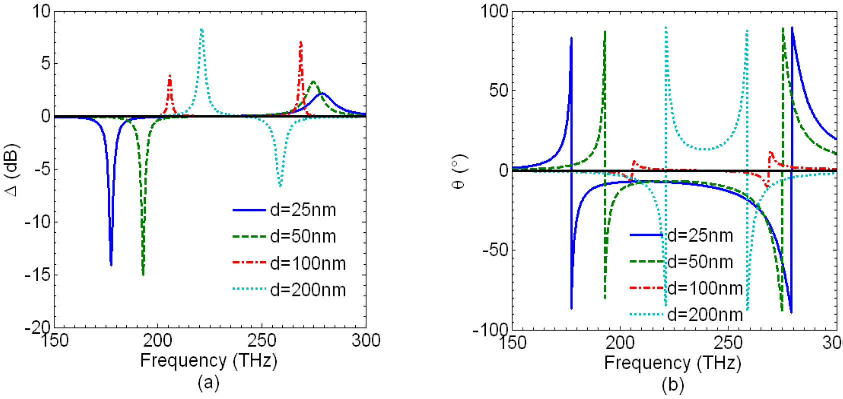


Fig. 8. Dependence of resonance frequencies on dielectric layer thickness.

As the dielectric layer thickness increases, circular dichroism and polarization azimuth rotation will reverse for *d*>100nm compare to *d*<100nm (Fig. 9). The resonant curves of circular dichroism and polarization azimuth rotation will reverse at the thickness *d*=95nm for magnetic resonance frequency, and at the thickness *d*=105nm for electric resonance frequency. Between two resonance frequencies, the polarization azimuth rotation is negative for smaller thickness and positive for larger thickness. The amplitude of polarization azimuth rotation increases from about 0 degree to 14 degree as the thickness increases from 100nm to 200nm. But the transmission also reduced rapidly. In the middle of two resonance frequencies, polarization azimuth rotation reaches about 7 degree for thickness *d*=25nm, nearly the same as that for *d*=50nm. It indicates that reduce dielectric layer thickness has advantage to obtain larger specific rotary power.



(a)

(b)

Fig. 9. Dependence of circular dichroism (a) and polarization azimuth rotation (b) on dielectric layer thickness.

The retrieval material's parameters also have larger negative value for *d*=25nm. But the magnetic resonance position shift to low frequency (about 175THz), permeability and refractive index can reach about -2 and -5 at the magnetic-resonance frequency.

3.3 Dependence of width of cross bar and dielectric constant of dielectric layer

We also simulated the bi-layer cross chiral structure for different width of cross bar *w*=50nm and *w*=150nm while keeping the other parameter unchanged. It is found that the width of cross bar affects remarkably the magnetic-resonance and electric-resonance frequencies. As the width of cross bar increases, both the frequencies of the magnetic resonance and electric resonance increase. Between two resonance frequencies the polarization azimuth rotation also

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reaches 7 degree for *w*=50nm while is much smaller for *w*=150nm. The polarization azimuth rotation is less than 10 degree in the magnetic-resonance region for *w*=150nm.

The range of band with negative permeability and negative refractive index becomes narrow for smaller width *w*=50nm of cross bar. For larger width *w*=150nm, no negative refractive index occurs in the magnetic-resonance region with broad range of negative permeability.

As for dependence of dielectric constant of dielectric layer, the frequencies of magnetic resonance and electric resonance are smaller for larger dielectric constant.

4. Conclusion

In summary, the properties of metamaterial based on bi-layered structure consisting of mutually twisted planar metallic crosses have been investigated by numerical simulation. The results show that the exceptionally strong polarization rotation and circular dichroism are observed in the cross chiral structure. The location and amplitude of magnetic-resonance frequency and negative permeability and negative refractive index band can be controlled by modifying the geometrical and material parameters of the cross chiral structure. Especially, the polarization azimuth rotation up to 70 degree at the infrared communication wavelength (1.55μm) is achieved for 25degree twist angle. The negative refractive index for RCP and LCP originates from the chirality parameter and the negative refractive index for RCP is $\mathrm{Re}(n_{\mathrm{RCP}})$=-2.6 at about 193 THz (1.55μm). The results presented here are helpful to build the metamaterial with negative refractive index at the infrared communication wavelength and have potential applications in the optical polarization devices and optical communication.

Acknowledgments

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