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Influence of the geometry of terahertz chiral metamaterial on transmission group delays

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Abstract Recently, group delay has been proven as a very convenient tool for control of terahertz electromagnetic signals used for filters, waveguides and polarization components. Here, we investigate the propagation of circularly polarised terahertz pulse via analysis of group delays in Ω particle chiral metamaterial. When varying the geometry of the Ω particle chiral metamaterial, significant modification of chiroptical effects—optical activity and circular dichroism can be observed. Through the analysis of group delays in the frequency region between 1 and 3 THz we conclude that the right circularly polarised wave is more sensitive to changes in the geometry than the left circularly polarised wave. This result implies that the right circularly polarised wave is responsible for variation of chiroptical effects in these structures and opens up a possibility for potential applications.

Keywords Chiral metamaterial · Terahertz · Group delay · Circular polarisation

1 Introduction

Nowadays, terahertz (THz) technology is receiving more and more attention due to huge range of important applications, such as information and communication technology, biomedical sensing, analytical chemistry, spectroscopy, materials characterization and imaging. Due to

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weak responses produced by conventional materials during interaction with THz radiation, they are not appropriate for application in THz range. However, artificially made materials, metamaterials, can provide unprecedented manipulation of THz radiation (Ferguson and Zhang 2002; Yen et al. 2004; Solymar and Shamonina 2009; Smith et al. 2004).

Chiral metamaterials (CMMs) are attracting a huge attention due to optical activity which in chiral media can result in negative refraction (Pendry 2004) and negative reflection (Zhang and Cui 2007) without necessity for having negative permeability and permittivity. In interaction with light, CMM exibits magnetoelectric coupling which means that magnetic dipoles are excited by the electric field and vice versa (Wang et al. 2009; Li et al. 2013; Luan et al. 2011). The consequence of extraordinary interaction of electromagnetic waves with these structures is circular dichroism (Gorkunov et al. 2014; Decker et al. 2010), which presents a difference in transmissions of right circularly (RCP) and left circularly polarised waves (LCP) (Barron 2004). In this study, we investigate how the chiroptical effects are affected by the geometry of the Ω particle chiral metamaterial.

Given that the THz technology is considered as very important for wireless and sensing applications, the development of high speed optical components becomes essential. In view of that, it was recently demonstrated that the group delay presents a suitable tool for control of the THz electromagnetic signals (Miyamaru et al. 2014). In measurements, the group delay in transmission was considered as the time at which the intensity at the exit reaches a peak, relative to the time at which the intensity at the entrance would have reached the peak in the case when the slab is not existing (Winful 2006). Here, we consider a propagation of THz pulse through Ω particles chiral metamaterial which could be controlled by the group delay. As the geometry of the structure influences the chiroptical effects, it also influences the group delays. It has been concluded that the group delay of RCP wave is much more affected by the geometry of the structure.

2 Chiral metamaterial geometry

For this investigation, we have considered a CMM unit cell made of four folded rotated Ω particles as in Ref. Zhao et al. (2010). The Ω particle is a helix element which introduces the magnetisation and electric polarisation. Currents in this structure are introduced by the short wires generating electric dipole moment while the currents in the loop generate magnetic dipole moment (Jaggard et al. 1979). The Coulomb interactions in CMM affect transmissions of RCP and LCP waves and thus the circular dichroism and the optical activity become strongly dependent on the geometry of the structure (Gansel et al. 2009; Fan and Govorov 2010).

Simulations of transmission of circularly polarised waves through the Ω particle CMM slab were carried out by solving the Maxwell equations in the frequency domain by finite element method in the Comsol Multiphysics software. The impedance boundary conditions were used as it is assumed that the field penetrates just a little inside the metallic particles. The wave is considered to propagate through the slab with the zero angle of incidence while the frequency range which was examined extends from 1 to 3 THz.

Our model consists of a slab whose thickness is $d = 12$ μm surrounded by air (Fig. 1a). Each Ω particle entails a wire loop and two short wires attached to the ends of the loop (Fig. 1b). The wire is made of gold which is characterized by the Drude model with the plasma frequency $\omega_p = 137.15 \times 10^{14}$ rad/s and the collision frequency $\omega_c = 40.5 \times 10^{12}$ rad/s (Ordal et al. 1985). The thickness of individual wire is $D = 0.5$ μm and the gap

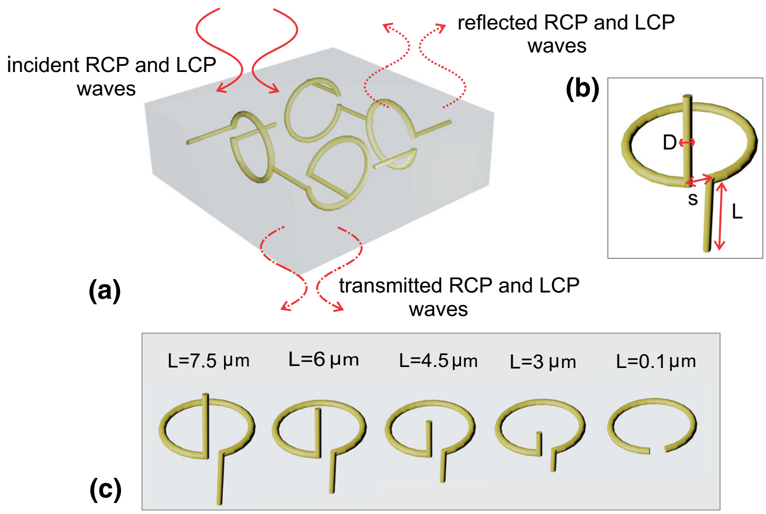

Fig. 1 **a** The Ω particle CMM unit cell. **b** Single Ω particle. **c** Different values of L parameter of single Ω particle

between them is $s = 0.5$ μm. The background material is polyimide with $\varepsilon = 2.5 \times (1 + 0.03i)$. One of the parameters which is responsible for the chiroptical effects of the material is the length of the short wires—L. In this study, we have examined the changes of the group delays of RCP and LCP waves with different values of L ($7.5 - 0.1$ μm—Fig. 1c).

3 Numerical results and discussion

For the description of linear chiroptical effects we have used azimuth rotation angle θ which presents the angle between the direction of the incident polarization and the direction of the major axis of the polarization ellipse of transmitted light, and the ellipticity η defined as the arctangent of the ratio of the minor and major axes of the ellipse polarization (Barron 2004). Mathematically, they are presented by the following formulas:

$$\eta = arctan\left(\frac{|t_+| - |t_-|}{|t_+| + |t_-|}\right) \quad (1)$$

$$\theta = \frac{1}{2}(arg(t_+) - arg(t_-)) \quad (2)$$

where t_+ is the transmission coefficient of RCP wave and t_- is the transmission coefficient of LCP wave. Figure 2a illustrates η and θ as a functions of frequency where the regimes of nearly pure optical activity ($\eta \approx 0$), for frequencies higher than 2.5 THz and lower than 1.14 THz can be noticed. Strong circular dichroism can be seen at resonant frequency. In Fig. 2b, c, θ and η are presented for different values of parameter L (from the Fig. 1c). We consider the rotation angle θ from the frequency range above 2.5 THz as only in this range the wave exhibits pure optical activity which means that the incident linearly polarized light stays linearly polarized after the transmission. For frequencies lower than 2.5 THz,

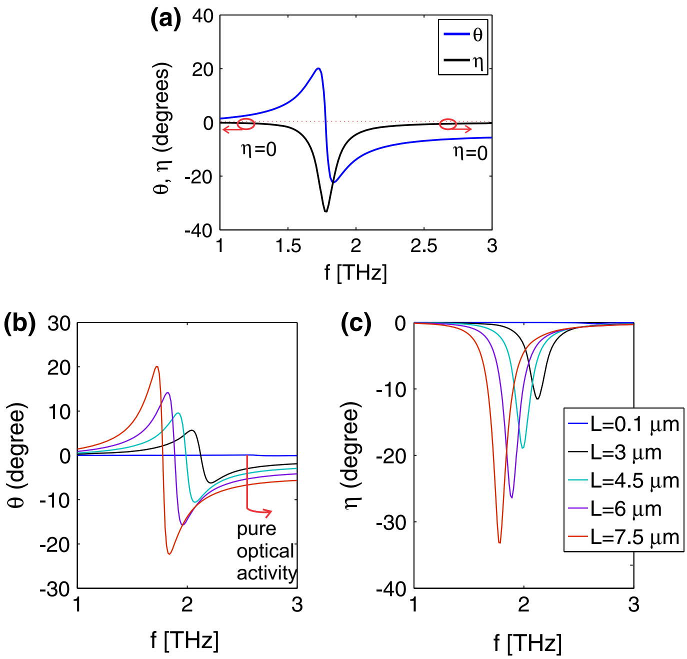

Fig. 2 **a** The η and θ dependencies on frequency for the L = 7.5 µm. **b** The angle of rotation θ dependency on frequency for different values of parameter L. **c** The ellipticity angle η dependency on frequency for different values of parameter L

the incident linearly polarized wave becomes elliptically polarized. It is evident that these angles rise as parameter L increases. When the value of L is near to zero, the chiroptical effects disappear, thus the structure is not CMM any more. Also, it is obvious that the circular dichroism has the highest value at the resonant frequency which is shifted to higher frequencies as the parameter L increases.

Further exploration of the influence of dimensions of straight wires on LCP and RCP wave propagation will be continued through analysis of group delays. As group delay describes the time at which transmitted peak reaches the second interface of the slab, it is challenging to make a design of CMM which will provide the highest difference in group delays for LCP and RCP waves. Group delay is calculated by the method of stationary phase approximation and it is given by frequency derivative of phase shift (Hauge and Støvneng 1989). Group delays in transmission (using the analogy to standard metamaterials) are:

$$\tau_{t-} = \frac{d\phi_{0-}}{d\omega} \tag{3}$$

$$\tau_{t+} = \frac{d\phi_{0+}}{d\omega} \tag{4}$$

where $\phi_{0-} = \phi_{t-} + k_0 d$, ϕ_{t-} is the phase of LCP transmitted wave and $\phi_{0+} = \phi_{t+} + k_0 d$, ϕ_{t+} is the phase of transmitted wave. k_0 is the wave vector in vacuum and d is the thickness of the slab.

Figure 3a, b show group delays in transmission for incident lCP and RCP waves in our CMM slab, respectively. When L is close to zero, the chiroptical effects do not exist and

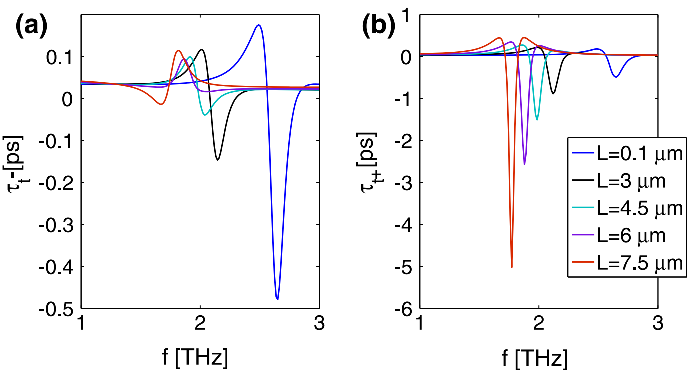

Fig. 3 **a** τ_{t-} dependence on frequency for different values of parameter L. **b** τ_{t+} dependence on frequency for different values of parameter L

the values of group delays are equal $\tau_{t+} = \tau_{t-} = -0.5$ ps. This value of group delay is the maximum for the case of LCP wave. On the other side, τ_{t+} has a maximum value for the highest value of L = 7.5 μm and it is ten times higher than τ_{t-}. This means that RCP wave has a stronger interaction with the resonance, in comparison with the LCP wave. On the other hand, the group delay of LCP wave does not show any significant change for different L which means that it interacts very weakly with the resonant elements. The τ_{t-} for $L \approx 0$ is a few times higher than CMM with higher values of L. Having in mind these results and analysis of η and θ, it can be said that RCP wave is responsible for chiroptical effects in this structure.

4 Conclusion

In this investigation, we presented a model in which circularly polarized light was illuminated on Ω particle chiral metamaterial. We analysed the chiral effects-optical activity and circular dichroism by changing the geometry of the structure. For higher values of short wires, these effects were more pronounced. The focus of our study was on the group delays and it was noticed that group delays in transmission are not the same for RCP and LCP waves. LCP wave has not shown significant changes with variations in geometry which is explained as a consequence of weak interaction with the resonant elements. Via the analysis of group delays, we realized that RCP wave is responsible for chiroptical effects in the structure. This view leads to the conclusion that THz pulses can be tuned by chirality. Furthermore, the control of the group delay with chirality can be used for THz applications, sensing and for the most popular case of wireless communications.

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