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Chiral characteristics of metasurface based on gammadion cross in THz frequency range

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The chiral properties of a metasurface made of 2-D array of twisted gammadion crosses was studied at frequencies ranging from 0.1–0.12 THz. The influences of unit cell design on the optical activity and the ellipticity of the metasurface were revealed. The maximal values of ellipticity and polarization azimuth rotation angle were obtained for the gammadion crosses with petals in the form of the truncated circles. The changing of the semi axes' relation of gammadion cross ellipses allows tuning of the operational frequency and creation of a multiband polarizer.

Keywords: metasurface, metamaterials, chiral structure, terahertz frequency.

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1. Introduction

Recently, metamaterials have become increasingly interesting for scientists, due to their smart properties and capability for extraordinary manipulation of electromagnetic waves: blocking, absorbing, enhancing, bending and polarization changing. Metasurfaces, or planar metamaterials (consisting of one or more layers of flat structures) has attracted a special interest due to their capacity for strong electromagnetic wave manipulation and small losses compared to bulk metamaterials. They can be easy fabricated by lithography or laser engraving [1]. Of particular interest is the development of chiral metasurfaces for wave polarization control [2]. Chirality is the geometric property of spatial particles, namely it is an asymmetry and distinction of an object from its mirror image. Chiral metamaterials can demonstrate some interesting properties, such as optical activity and circular dichroism [3] as well as negative index of refraction [2]. There is a large number of chiral unit cell designs (crosses [4], hammadions [5], U-shaped resonators [6] and others). The design and mutual arrangement of chiral unit cells strongly influence its ability for wave polarization. It would be particularly interesting to know the optical properties of such metasurfaces in the terahertz (THz) frequency range, which is safe for humans and sensitive to chemical changes in biomolecules, due to the deficit of polarizing components in this frequency range [7]. THz chiral metasurfaces may be used for time-domain spectroscopic polarimetry of biological objects to develop new diagnostic methods for common diseases such as cancer and diabetes. In this paper, we studied the influence of unit cell form on the metasurface's chiral properties.

2. Description of the structure

The chiral metasurface under study consists of a 2-D chiral unit cell array of twisted gammadion crosses with size of $< \lambda/4$. This size permitted us to use the effective medium theory. Two designs of crosses were considered to control of chiral effects. The first gammadion cross has "petals" in the form of the truncated circles. This was taken as a basic chiral element. The scheme of this design is shown in Fig. 1-a. The chiral element made of perfect electric conductor which is placed on a silicone (this material allowed control of the metasurface's spectral characteristics by changing its optical properties under the photoexcitation, for example) with permittivity $\varepsilon = 11.56$, substrate with thickness of $b = 150$ μm (less than $\lambda/10$) and side of $a = 450$ μm. The second cross design has "petals" in the form of the truncated ellipses with semi-axes ratio 2.2:1 (Fig. 1-b).

3. Numerical simulation

In simulations, the commercial software CST Microwave Studio was used to obtain the total scattering matrix, which relates the incident waves to the scattered waves. The Finite Difference Time Domain method was chosen from other numerical methods [8,9] due to its simplicity and versatility. The radiation source was linearly polarized electromagnetic wave for frequencies ranging from 0.1–0.12 THz. The scheme of this simulation experiment is shown in Fig. 2. A linearly polarized wave passing through the metasurface had its polarization changed to an elliptical one. An additional linear polarizer was used to determine the wave polarization ellipse. The polarizer consists of an array of perfect electric conductor strips, placed on a silicone substrate with periodic boundary

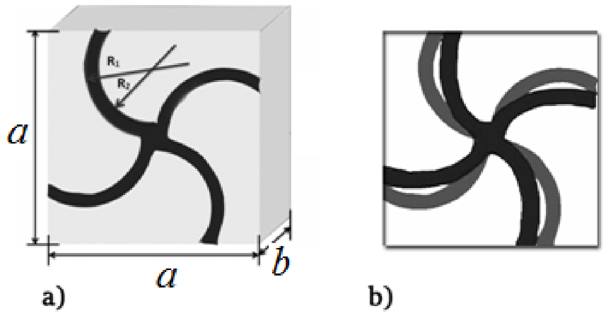

FIG. 1. a) Illustration of the basic structure. Outer radius $R_1 = 150$ μm, inner radius $R_2 = 123.3$ μm. b) The difference between basic structure (black gammadion cross) and elliptical one (gray gammadion cross)

conditions. The wave polarization was changed to linear after passing through this polarizer. Thus, it is possible to obtain the ellipse of polarization turning the polarizer. As a result, the spectra of transmission coefficients for TE and TM polarized waves were found for two linear polarizer positions.

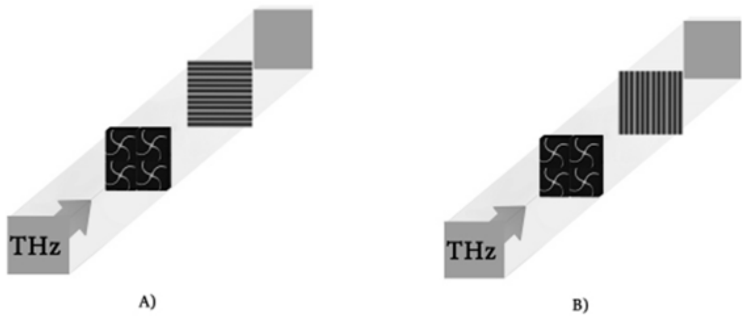

FIG. 2. The scheme of experiment for A) TE-wave, B) TM-wave

4. Results

Using the spectra of transmission coefficients, it is possible to calculate optical activity and circular dichroism of the structure. The polarization azimuth rotation angle θ and ellipticity η were used to measure optical activity and the degree of circular dichroism correspondingly. The spectra of the polarization azimuth rotation angle and ellipticity were calculated using formulas (1) and (2) [3]:

$$\theta = [\arg(T_{++}) - \arg(T_{--})], \tag{1}$$

$$\eta = \frac{1}{2}\sin^{-1}\left[\frac{|T_{++}|^2 - |T_{--}|^2}{|T_{++}|^2 + |T_{--}|^2}\right], \tag{2}$$

where T_{++} is the transmission spectrum of right-handed circularly polarized wave, T_{--} is the transmission spectrum of left-handed circularly polarized one, which can be found using the following formulas simplified for bi-isotropic chiral structures:

$$T_{++} = T_{xx} + iT_{xy}, \tag{3}$$

$$T_{--} = T_{xx} - iT_{xy}. \tag{4}$$

The transmission coefficients in (3) and (4) for linearly polarized waves can be obtained from numerical simulation results, where the first and second indices indicate the output and input wave polarizations, respectively, e.g.: $T_{xx} = E_x^o/E_x^i$ and $T_{xy} = E_x^o/E_y^i$, (E_x^o is the output x-polarized field, E_x^i is the input x-polarized field, E_y^i is the input y-polarized field).

From the numerical simulation results, the spectra of polarization azimuth rotation angle and ellipticity coefficient were found for each chiral structure design. The results are shown in Fig. 3.

As seen from Fig. 3, the changing of ellipse semi axes relation of gammadion cross allows tuning of the polarization azimuth rotation angle and ellipticity values as well as the operational frequency range. The basic

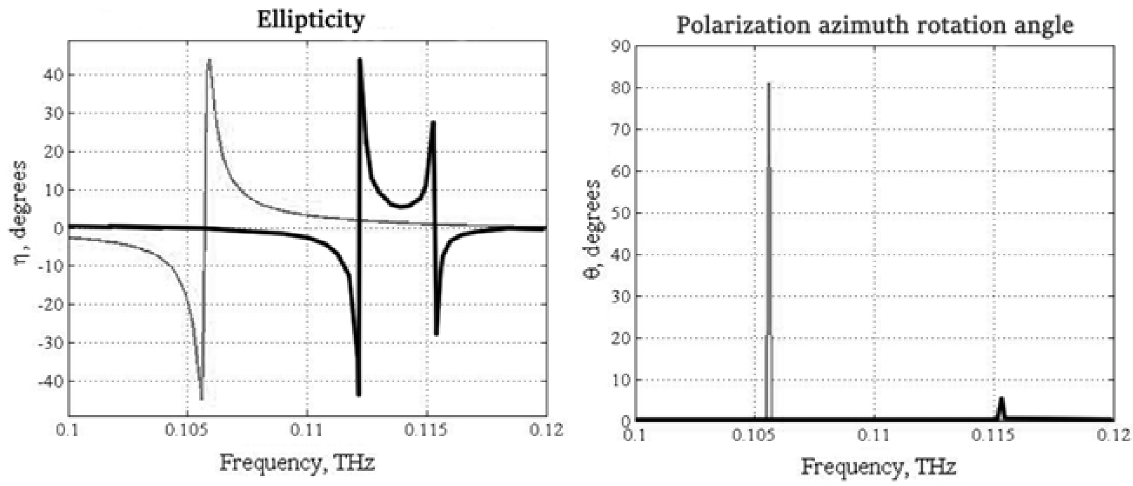

FIG. 3. Spectra of ellipticity and optical activity for the basic structure (thin gray line) and elliptical structure (bold black lines)

structure shows better chiral properties than the elliptical one, particularly, it changes the polarization of the electromagnetic wave from a linear to an elliptical one with maximum ellipticity of $|\eta| = 44.9\ ^\circ$ ($|\eta| = 45\ ^\circ$ corresponds to circularly polarized wave) as well as it is rotated the plane of wave polarization on maximum angle of $\theta = 82\ ^\circ$ vat a frequency of 0.106 THz. The structure with elliptical gammadion crosses also demonstrates chiral effects but they are not as pronounced as in the basic structure. However, it should be noted that the ellipticity and the optical activity of the second metasurface have two extreme values of $|\eta| = 43.6\ ^\circ$ at 0.113 THz and $|\eta| = 28.6\ ^\circ$ with $\theta = 5.1\ ^\circ$ at 0.115 THz, which allows its use as a polarizer at two frequencies.

5. Conclusions

Therefore, the impact of gammadion cross design on the metasurface's chiral characteristics was investigated at frequencies ranging from 0.1–0.12 THz. The gammadion cross with "petals" in the form of the truncated circles was shown to have better extreme values for the ellipticity and polarization azimuth rotation angle in comparison with the elliptical design. Also, it was shown that the changing of relation of ellipse semi axes of cross allows tuning of the polarizer's operating frequency. Additionally, the elliptical metasurface design may be used for the development of a dual band polarizer.

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