The impact of terahertz chiral metasurface resonator rotation on polarization properties of transmitted wave

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Abstract. In this paper the influence of one and two chiral metasurfaces on polarization of the transmitted wave has been studied. The numerical simulation in CST Microwave Studio confirms the influence of the resonator rotation in the unit cell on polarizing properties of the metasurface. The ability of changing the polarization of the terahertz wave by two layers of such metasurfaces was shown. Thus, such metasurface can be used in development of mechanically-tunable polarization converter.

1. Introduction
Metamaterials is a class of composite structured materials with specific properties which cannot be found in nature. Usually these materials consist of unit cells, or meta-atoms, consequently the properties of metamaterial depend on the array of such unit cells. The ability of transformation of the unit cell allows to design and scale metamaterials for the necessary frequency range. Applications of metamaterials in terahertz frequency range attract more and more attention due to an ability to cover a lack of simple and chip elements and systems for terahertz frequencies, such as multispectral imaging systems[1-2], magneto-tunable devices[3-6], tunable reflectors[7], switches[8], filters[9-11], phase shifters[12], perfect absorbers[13], left-handed media [14-15], polarization converters[16-18], mirrors, etc. Such problem is being solved by using chiral metamaterials. In this work we studied the possibility of the transmitted wave polarization changing by using one and two layers of chiral metasurfaces with different angle position of the chiral resonators. The results of the research can be used for THz polarimetry biomedical diagnostics [19-20].

2. The structure under the investigation
The sketch of the unit cells of metasurfaces under study is shown in Figure 1-a). The resonant rosette consists of four planar aluminium half-rings rotated around the normal to the unit cell plane at its central point. The outer radius Rmax of the rosette petals is 150 μm, the inner one is 125 μm. The rosette is patterned on a dielectric (ε=3.5) substrate, which thickness is h=65 μm and the side size is a=600 μm. The angle α corresponds to the angle of rotation between the y-axis and the edge of the rosette.

In this paper, four different cases have been studied: α=0 degrees, α=15 degrees, α=30 degrees, α=45 degrees (Fig.1-b). The metasurfaces with angle of chiral element rotation α=0 degrees is considered to be a basic one. Also four types of metasurface stacks created by two metasurfaces under each other were studied (Fig. 1-c). In this case, the top metasurfaces chiral element was rotated by the
same angles $\alpha_1=0$ degrees, $\alpha_2=15$ degrees, $\alpha_3=30$ degrees, $\alpha_4=45$ degrees, while the bottom metasurface was the basic one ($\alpha_1=0$ degrees). The air gap between two metasurfaces was $d=5\mu m$.

![Diagram of metasurfaces](image)

**Figure 1.** The unit cell of the metasurface: a) the original unit cell, b) rotated resonator in single metasurface; c) stack of two metasurface.

3. **Numerical simulation and calculation approach**

The numerical simulations were performed in CST Microwave Studio based on Finite Difference Time Domain (FDTD) method. The linearly polarized waves from Port 1 become elliptically polarized ones after the propagation through the metasurface (Fig.2), and then they are received by Port 2. (Fig. 2). To characterize the polarization state of the transmitted wave the co- and cross-polarization spectra $T_{xx}$ and $T_{xy}$ were found.

Transmission spectra (matrix $T_{cir}$) for right-handed circularly waves ($T_{++}$) and left-handed circularly polarized waves ($T_{--}$) can be found using the next formula [21]:

$$
T_{cir} = \begin{pmatrix}
T_{++} & T_{+-} \\
T_{-+} & T_{--}
\end{pmatrix} = \begin{pmatrix}
T_{xx} + iT_{xy} & 0 \\
0 & T_{xx} - iT_{xy}
\end{pmatrix}
$$

(1)

where $T_{+-} = T_{-+}=0$ due to four-fold symmetry of the unit cell.

After that, the ellipticity angle $\eta$ is used to evaluate the transmitted wave polarization changes:

$$
\eta = \frac{1}{2} \sin^{-1} \left( \frac{|T_{++}|^2 - |T_{--}|^2}{|T_{++}|^2 + |T_{--}|^2} \right),
$$

(2)

The ellipticity angle shows a type of polarization: thus, the value of $|\eta|=45$ degrees corresponds to the circular polarization of the electromagnetic waves, and sign “+” or “−” before the value refers to the right-handed or left handed type of polarization state respectively; values between $\eta=\pm 45$ degrees are related to elliptical polarization state, except the case when $\eta=0$ for linear polarization.
Figure 2. Scheme of numerical calculation.

4. Results
The ellipticity angle spectra for the single metasurface are shown in Fig. 3. It can be noticed that there are few resonance frequencies, i.e. frequencies where the ellipticity angle is not equal to zero and has extreme value (maximal or minimal). For each case of metasurfaces design the resonant frequencies are almost the same, meanwhile the ellipticity angle changes its values.

Figure 3. Ellipticity angle spectra for single chiral metasurface.
Then the influence of the combinations of metasurfaces (Fig. 1-c) with differently rotated chiral rosettes of the top metasurface on polarization state of the transmitted wave was studied. For this case the ellipticity angle spectra are shown in Fig. 4.

![Ellipticity angle spectra](image_url)

**Figure 4.** Ellipticity angle spectra for the stack of metasurfaces.

As can be seen from Fig. 4, the stack of two metasurfaces changes the polarizing properties of the transmitted wave more efficiently than the single metasurface. A few similarities in behavior of ellipticity angle spectra may be noticed: absolute values of ellipticity in four different cases are about the same at the frequencies of $f_1=0.1$ THz, $f_2=0.25$ THz, $f_3=0.35$ THz, while their signs are different. The nature of this phenomenon is connected with interaction between gammadion petals of the neighbor unit cells.

5. Conclusions

The single chiral metasurfaces and their stacks with different angles of rotation of the chiral unit cell were studied. It was shown that ellipticity angle spectra of single metasurface have several resonant frequencies, where linear polarization transforms into elliptical one. Ellipticity angle spectrum depends on rosette position at the unit cell. Hence, the rotation of the chiral element leads to the changing of the ellipticity angle at these frequencies. It was shown that the ellipticity angle $\eta=25$ degrees can be reached at frequency $f=0.35$ THz by rotation of the chiral resonators in the single metasurface. Significant increment of ellipticity angle at the resonant frequencies is achieved by adding the second metasurface. The ability of changing the handedness of polarization by combination of metasurfaces with differently rotated resonators was demonstrated. Thus, it is possible to make multiband polarization converter using several different chiral metasurfaces.

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