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Abstract. In a lossy media, anisotropic chiral metamaterial (MTM) structures with normal incidence asymmetric transmission of linearly polarized electromagnetic (EM) waves are investigated and analyzed in both microwave and terahertz frequency regimes. The proposed lossy structures are used to perform dynamic polarization rotation and consist of square-shaped resonators with gaps on both sides of dielectric substrates with a certain degree of rotation. Asymmetric transmission of a linearly polarized EM wave through the chiral MTMs is realized by experimental and numerical studies. The dynamic structures are adjustable via various parameters to be tuned for any desired frequency regimes. From the obtained results, the suggested structure can be used to design new polarization control devices for desired frequency regimes. [DOI: 10.1117/1.OE.53.7.075109]

Keywords: metamaterials; chirality; terahertz; tunability.

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1 Introduction

Approximately 40 years ago, the curiosity of a Russian scientist, Veselago, began the negative index metamaterials (MTMs) process.[1] Thirty years later (around the 1990s), a British scientist, Sir John Pendry, presented a proposal which soon gained concreteness.[2]

MTM structures that may be produced by some artificial methods do not exist in nature. The good features of these structures are the negative index of refraction and the fact that a wave and energy in the moving axis have opposite directions. One of the most interesting features of MTMs that attracts the researchers is that these artificially manufactured structures can provide the opportunity to obtain a negative refractive index. The pioneering study in this area was theoretically proposed by Pendry.[2]

The presence of these materials was demonstrated and was experimentally manufactured by Shelby et al.[3] Their work consists of a copper wire and a split-ring resonator system. Dielectric photonic crystals were then investigated by Ozbay et al. for the first time.[4]

Application of MTMs in the terahertz (THz) range has recently gained great importance.[5–11] THz MTMs are the new class of artificial composite materials under development that work in the THz frequency regime. Generally, the THz frequency range used in the research of materials is defined in the frequency spectrum from 0.1 to 10 THz.

MTMs are a promising new concept to be used in the design and development of many new technological areas such as electronics, microwave, optical circuits, antenna miniaturization, antenna design, and so on. Working in the THz frequency range leads us to develop useful devices to be used in security screening, medical imaging, wireless communication systems, nondestructive evaluation, and development of the applications of chemical identification.

Chirality is a very important concept of MTMs for which a negative refractive index can be obtained around the resonance point through both the right- and left-hand circularly polarized waves for different transmission values.[12]

In this study, we theoretically and experimentally examined and analyzed the asymmetric transmission phenomenon for linearly polarized electromagnetic (EM) waves in both microwave and THz frequency regimes. The asymmetric characteristics of the chiral MTMs are investigated and evaluated in detail. The proposed dynamic structures that provide asymmetric transmission can easily be scaled down for any desired frequency range in order to fit any desired application.

2 Theoretical Analysis

Chirality, one of the most interesting features that MTMs have, can be used to easily obtain a negative refractive index for various transmission values around any desired resonance point compared to other procedures for both right and left circularly polarized waves. Asymmetric transmission properties allow a certain difference between the polarization states when a wave is applied to opposite sides. In this study, for theoretical analysis, an incoming plane wave propagating in the $(+z)$ direction with a time dependence e^{-iwt} of is considered[12–16]

$$E_i(r,t) = \begin{pmatrix} E_x \\ E_y \end{pmatrix} e^{ikz}, \tag{1}$$

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where the angular frequency is ω, the wave vector is k, and complex amplitudes E_x are and E_y. To understand the polarization conversion, a transmission (T) matrix expression for a given electric field can be applied as follows:

$$E_t(r,t) = \begin{pmatrix} T_x \\ T_y \end{pmatrix} e^{ikz}. \tag{2}$$

This medium is assumed to be a dielectric medium that is symmetrically embedded (e.g., vacuum). The T-matrix relates the complex amplitudes of the incident field to that of the transmitted field

$$\begin{pmatrix} T_x \\ T_y \end{pmatrix} = \begin{pmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix} = \hat{T}^f_{\text{lin}} \begin{pmatrix} E_x \\ E_y \end{pmatrix}. \tag{3}$$

The f and lin indices refer to the propagation in the forward direction and a special linear base with base vectors parallel to the coordinate axes, i.e., decomposing the field into x- and y-polarized light. T_{xx} and T_{yy} are the transmitted waves in the x- and y-directions, respectively. We calculate four linear and cross-polarization transmission coefficients, T_{xx}, T_{yx}, T_{xy}, and T_{yy}, to obtain the transmission coefficients of circularly polarized waves, i.e., T_{++}, T_{-+}, T_{+-}, and T_{--}. Transmission coefficients of circularly polarized waves were calculated from the linear copolarization measurements using the following equation:[12–14]

$$T^f_{\text{circ}} = \begin{pmatrix} T_{++} & T_{+-} \\ T_{-+} & T_{--} \end{pmatrix} \quad \text{and} \quad T^b_{\text{circ}} = \begin{pmatrix} T_{++} & T_{-+} \\ T_{+-} & T_{--} \end{pmatrix}. \tag{4}$$

This can be obtained by a change of the basis vectors from linear and circular cases, resulting in

$$T^f_{\text{circ}} = \begin{pmatrix} T_{++} & T_{+-} \\ T_{-+} & T_{--} \end{pmatrix} = \frac{1}{2}\begin{bmatrix} T_{xx}+T_{yy}+i(T_{xy}-T_{yx}) & T_{xx}-T_{yy}+i(T_{xy}+T_{yx}) \\ T_{xx}-T_{yy}-i(T_{xy}+T_{yx}) & T_{xx}+T_{yy}-i(T_{xy}-T_{yx}) \end{bmatrix}. \tag{5}$$

The linearly and circularly polarized waves of the asymmetric transmission are commonly characterized by the parameter Δ. This parameter shows the difference between transmittances in the ($+z$) and ($-z$) directions. The asymmetric transmission parameter Δ is defined as

$$\Delta^{(x)}_{\text{lin}} = |T_{yx}|^2 - |T_{xy}|^2 = -\Delta^{(y)}_{\text{lin}}, \tag{6}$$

$$\Delta^{(+)}_{\text{cir}} = |T_{-+}|^2 - |T_{+-}|^2 = -\Delta^{(-)}_{\text{circ}}, \tag{7}$$

for linearly and circularly polarized waves, respectively. $\Delta^{(x)}_{\text{lin}} = 0$ for asymmetric transmission structures, whereas $\Delta^{(+)}_{\text{circ}} \neq 0$ for the same structures. The reason for the mirror symmetry in the propagation direction is that MTMs always support the components of the transmission matrix $T_{xy} = T_{yx}$.[12–16]

However, some studies have shown that the mirror symmetry is getting lost in the propagation direction for hybridizing MTM structures.[5,17] In addition, the reason for the chirality can be explained by the fact that MTM structures that have a polarization conversion feature that the polarization state of the wave will change when it propagates through the structure. This case is called as optical activity of chiral structures. Depending on the handedness of a material, the azimuth of the polarization plane rotates clockwise or counter-clockwise when it passes through a chiral medium. This polarization conversion feature may lead to design polarization sensitive devices in any desired frequency range.

3 Numerical and Experimental Setup and Design

We numerically and experimentally investigated the asymmetric transmission properties of the proposed chiral MTM structures. The designed structures have resonator-metallic parts placed on the front and the back side of the dielectric substrate in order to provide asymmetric transmission for linearly polarized EM waves in both microwave and THz frequency regions. Furthermore, the proposed structures can also provide asymmetry by changing the parameters of the structure such as the angle, gap, and width of the metallic strips.

For a microwave frequency regime, FR4 is chosen as the dielectric substrate and the metallic patterns are modeled as copper sheets with an electrical conductivity of 5.8001×10^7 S/m and a thickness of 0.036 mm. The thickness, loss tangent, and relative permittivity of FR4 are 1.6 mm, 0.02, and 4.2, respectively. Figure 1 shows the schematic diagram of the unit cell. The unit cell dimensions of the proposed resonator are shown in Table 1.

On the other hand, for a THz frequency regime, the proposed resonators on the top and bottom layers are separated by a Quartz (fused) dielectric substrate which is selected as the substrate with the thickness of 450 μm. The loss tangent and relative permittivity of the Quartz are 0.0004 and 3.75, respectively. The metallic structures on the top and bottom layers of the substrate are chosen as silver sheets with an electrical conductivity of 6.3×10^7 S/m and a thickness of 0.2 μm. The reason for this is that silver is a soft, white, lustrous transition metal, and possesses extremely low resistivity. The unit cell dimensions of the proposed resonator for this frequency range are also shown in Table 1.

A commercial full wave EM solver (CST Microwave Studio, Darmstadt, Germany) based on a finite integration

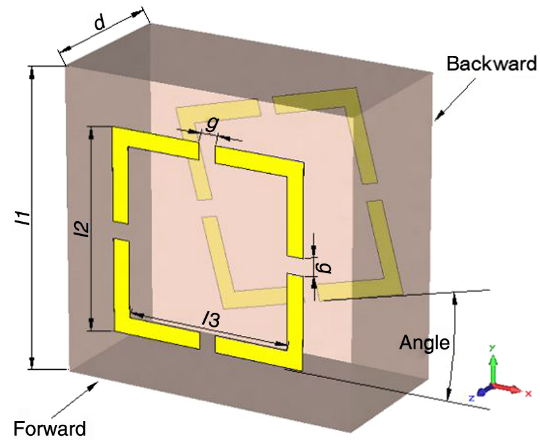

Fig. 1 The suggested chiral metamaterial (MTM) structure.

Table 1 Unit cell dimensions of the proposed resonator (Fig. 1).

Parameters	Microwave frequency regime	Terahertz frequency regime
$l1$	40 mm	900 μm
$l2$	24 mm	600 μm
$l3$	20 mm	500 μm
g	2 mm	40 μm
d	1.6 mm	450 μm
Angle	15 deg	15 deg

technique has been used for numerical studies. Unit cell and open add space boundary conditions are used in both gigahertz (GHz) and THz regions. For determining the reflection and transmission properties of the proposed structure, the numerical simulations have been implemented in both GHz and THz ranges. Transmission matrices of the proposed chiral MTMs are calculated from Eq. (8). T_{xx} and T_{yy} represent copolarized transmissions, and T_{xy} and T_{yx} define cross-polarized transmissions. These values are obtained by $T_{ij} = E_j^{\text{out}}/E_i^{\text{in}}$, relating the incident (E_i^{in}) and transmitted (E_j^{out}) waves, for example, $T_{xy} = E_y^{\text{out}}/E_x^{\text{in}}$, where E_x^{in} is the incident x-polarized electric field and E_y^{out} is the transmitted y-polarized electric field. The transmitted wave of the electric field can be written as $E^{\text{out}}(r,t) = |E_x^{\text{out}}|\cos(kz-\omega t)$, $|E_y^{\text{out}}|\cos(kz-\omega t+\phi)$ for both copolarized and cross-polarized transmissions. Transmission matrices can be found by using the following equation:[18–20]

$$\begin{pmatrix} T_{++} & T_{+-} \\ T_{-+} & T_{--} \end{pmatrix} = \frac{1}{2}\begin{bmatrix} T_{xx}+T_{yy}+i(T_{xy}-T_{yx}) & T_{xx}-T_{yy}+i(T_{xy}+T_{yx}) \\ T_{xx}-T_{yy}-i(T_{xy}+T_{yx}) & T_{xx}+T_{yy}-i(T_{xy}-T_{yx}) \end{bmatrix}, \tag{8}$$

where the first symbol represents the polarization of the transmitted field and the second one indicates the incident one. A similar equation can also be used for the reflection coefficients (R_{++}, R_{-+}, R_{+-} and R_{--}). Afterward, the numerical simulations are analyzed to determine the reflection and transmission properties of the proposed structure in the microwave frequency regime. The experimental measurement setup consists of a vector network analyzer (VNA) and two horn antennas. First, a free space measurement without the chiral structure is carried out and this measurement is used as the calibration data for VNA. Second, the structure is then inserted into the experimental measurement setup and transmission measurements are performed. The distance between the horn antennas and chiral slab is kept sufficiently large to eliminate near field effects. The VNA measures microwaves in the range of 1 to 6 GHz. Simulation and experimental results are evaluated and compared. Obtained results show that the numerical values of the sample are in good agreement with the measured ones.

4 Numerical and Experimental Results

For investigating the frequency responses of the proposed chiral MTMs, a CWS structure has been designed and fabricated in the microwave frequency regime with respect to the plane waves propagating along the $(+z)$ and $(-z)$

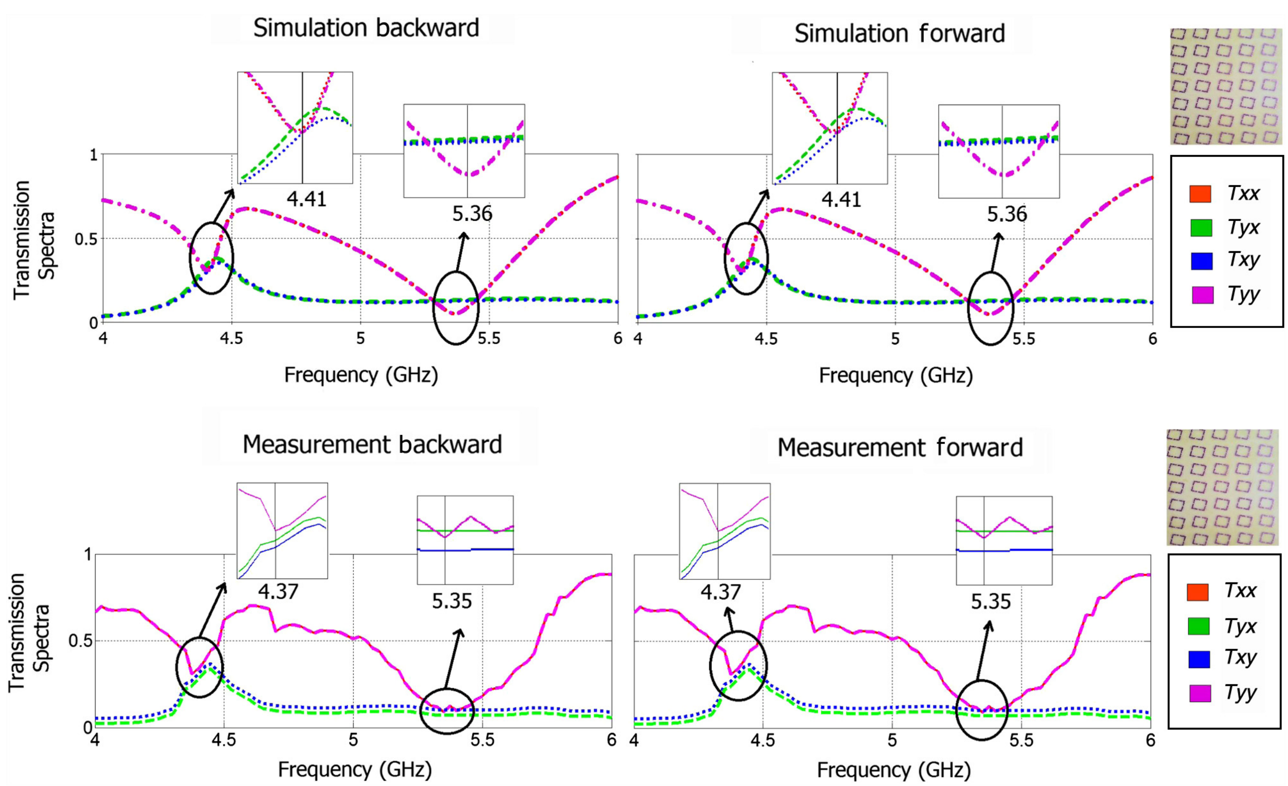

Fig. 2 Measured-simulated transmission spectra of the four matrix elements (T_{xx}, T_{xy}, T_{yx}, T_{yy}) of the slab for propagations in $+z$ (f) and (b) directions in GHz. Inset: picture of the fabricated sample.

directions. Figures 2 (numerical and experimental results in GHz) and 3 (numerical results in THz) show the results of the four transmission matrix elements (T_{xx}, T_{xy}, T_{yx}, T_{yy}) of the slab for propagations in the $(+z)$ and $(-z)$ directions, respectively. One can see from these figures that the numerical results verify the measurement results.

The resulting numerical and experimental magnitudes of T_{xx}, T_{xy}, T_{yx}, and T_{yy} are shown in Figs. 2 and 3, in order. The obtained results show asymmetric transmission for linear polarization in the resonance frequencies which may be acquired when the propagation direction is the same. This inequality confirms the presence of a circular dichroism $T_{+-} \neq T_{-+}$.

For the microwave frequency regime, the copolarization parameter of the transmission coefficient T_{xx} reaches its maximum value of 0.86 at the resonance frequency of $f = 5.99$ GHz. With this regard, the simulation and experimental results show that T_{xx} and T_{yy} are almost equal to each other. Cross-polarization parameters of the transmissions T_{xy} and T_{yx} reach a maximum value of approximately 0.38 at the resonance frequency of $f = 4.43$ GHz.

For the THz frequency regime, the copolarization parameter of transmission coefficient T_{xx} reaches its maximum value of around 0.86 at the resonance frequency of $f = 0.595$ THz. In this regard, the simulation and experimental results show that T_{xx} and T_{yy} are almost equal. In addition, cross-polarization parameters of the transmissions T_{xy} and T_{yx} reach to a maximum value of approximately 0.41 at the resonance frequency of $f = 0.583$ THz.

For both linear and circular polarizations, the asymmetric transmission parameter, Δ, is calculated and normalized using theoretical analysis via Eqs. (6) and (7), as shown in Fig. 4. It can be seen that the suggested model exhibits asymmetric transmission at two different resonance frequencies, 0.583 THz and 0.587 THz, for linear polarization. No significant change is observed in ($\Delta \approx 0$) for the circular polarization.

For the next investigation, we numerically retrieved the circular dichroism, theta degree, and chirality values of the proposed chiral MTM with constitutive relations. First,

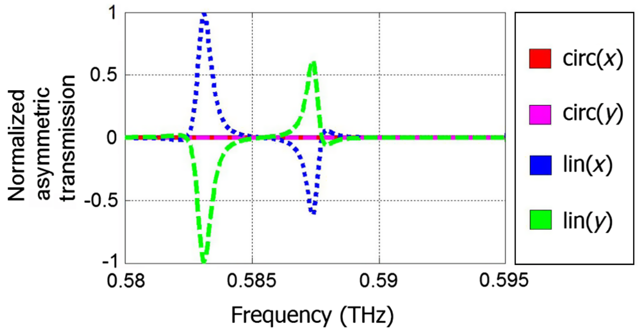

Fig. 4 Numerical results of asymmetric transmission, Δ parameter, for linear and circular polarizations.

the circular dichroism is retrieved and realized, which can be defined as the differences between RCP and LCP waves of two polarizations propagating through the medium as shown in Fig. 5. The circular dichroism is theoretically characterized by the ellipticity[18–20]

$$\eta = \frac{1}{2}\sin^{-1}\left(\frac{|T_{++}|^2 - |T_{--}|^2}{|T_{++}|^2 + |T_{--}|^2}\right). \tag{9}$$

Second, optical activity is retrieved and realized which could rotate the polarization plane of a linearly polarized wave propagating through, as shown in Fig. 5. A linearly polarized plane wave will rotate when it passes through a chiral medium. This rotation is called optical activity and is characterized by the polarization azimuth rotation angle of an elliptically polarized wave. The azimuth rotation is calculated by the copolar and crosspolar transmission data[18–20]

$$\theta = \frac{1}{2}\delta = \frac{1}{2}[\arg(T_{++}) - \arg(T_{--})]. \tag{10}$$

It can be seen that ellipticity reaches its maximum at the resonance frequencies of 0.583 THz and 0.587 THz, respectively. This means that a linearly polarized wave is weakly distorted and circular polarization is observed at these

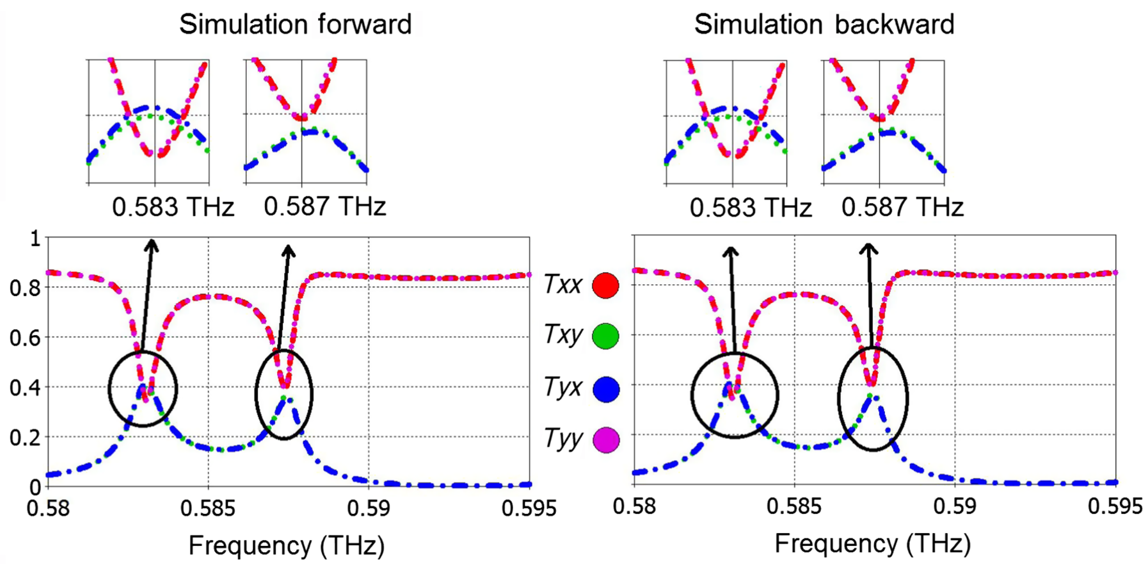

Fig. 3 Simulated transmission spectra of T-matrix elements (T_{xx}, T_{xy}, T_{yx} and T_{yy}) of the slab for propagations of $(+z)$ (forward) and $(-z)$ (backward) directions in THz.

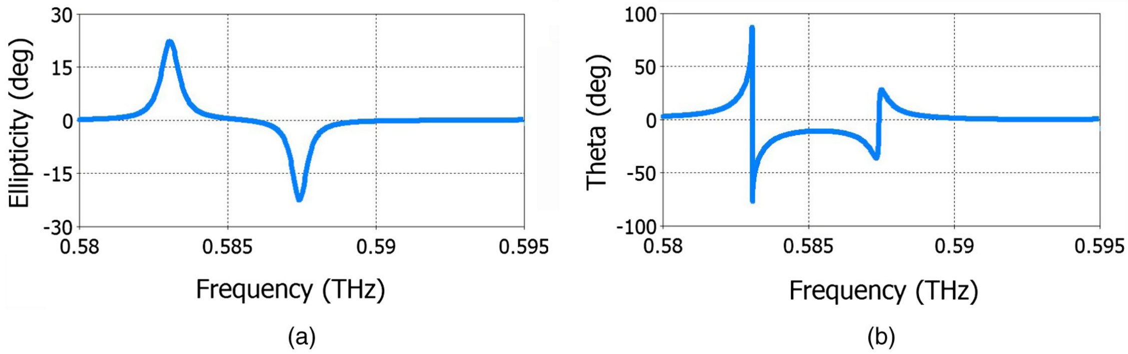

Fig. 5 Simulated circular dichroism (a) and theta degree (b) of the proposed chiral MTM.

resonance frequencies. Maximum azimuth rotation for the proposed structure is realized at the resonance frequency of 0.583 THz. This is much larger than the one observed at the second resonance frequency of 0.587 THz.

We realized a retrieval procedure to calculate the chirality parameters of chiral MTMs by using Eq. (9). Simulated chirality values calculated from copolar and crosspolar transmission data for the proposed structure between 0.58 and 0.6 THz are shown in Fig. 6 (Refs. 18–20).

$$\mathrm{Re}(\kappa) = \frac{\phi_+ - \phi_- + 2m\pi}{2k_0 d} \tag{11}$$

$$\mathrm{Im}(\kappa) = \frac{\ln|T_-| - \ln|T_+|}{2k_0 d} \tag{12}$$

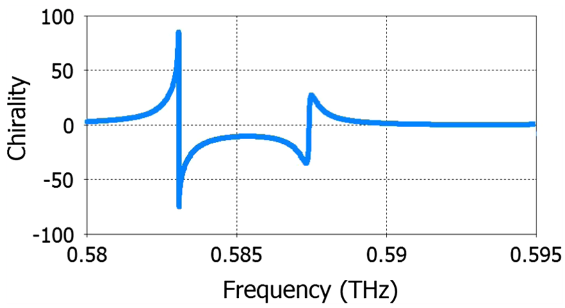

Fig. 6 Simulated chirality values of the proposed chiral MTM.

The proposed structure does not show chiral MTM characteristics between 0.592 THz and 0.594 THz. The chirality value is extremely low and near zero, but the structure shows a very large chirality value at the resonance frequencies of 0.583 THz and 0.587 THz.

Furthermore, the effects of the changes in the dimensions of the proposed resonator on the chirality are realized and evaluated. Obtained numerical results are shown in Fig. 7. The proposed geometry consists of a square-shaped resonator with gaps in the unit cell on one side and the rotated (15 deg) version of the same geometry on the other side. We have selected this shape because it is very simple, flexible, and easy to manufacture, which will allow us to adjust the structure easily by simply tuning the geometrical dimensions in order to work in any desired frequency regime. This property provides a shiftable frequency band and large chirality. The length of the wire ($l2$) is increased from 595 um to 650 um and the resonator at the back is rotated from 15 deg to 30 deg for parametric examination. It can be seen from the parametric study that the suggested structure has reconfigurable chirality values. In addition, the best value for the angle of the back resonator is found to be 15 deg. Therefore, this value is used in the design for the asymmetric transmission calculations.

Moreover, up- and down-shifts in the frequency response of the chirality value can be achieved when the dimensions of the resonator vary in any desired range. This feature provides mechanical tunability and flexibility to obtain any desired optical activity. Furthermore, this design possesses a very

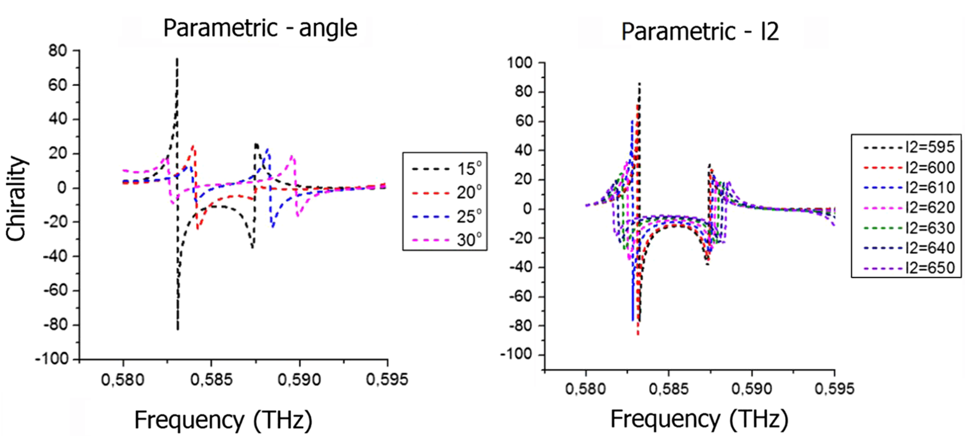

Fig. 7 Parametric numerical study results for the chirality parameter for different angles and $l2$ (Fig. 1 and Table 1) wire length values.

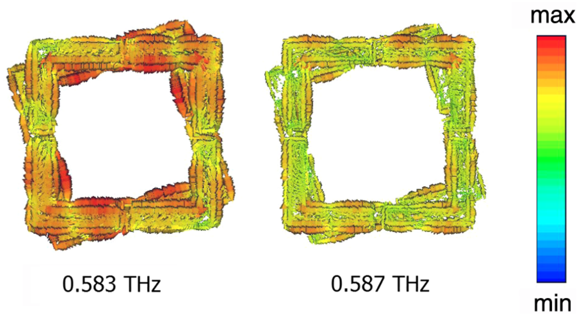

Fig. 8 Surface current distribution of the structure at the resonance frequencies.

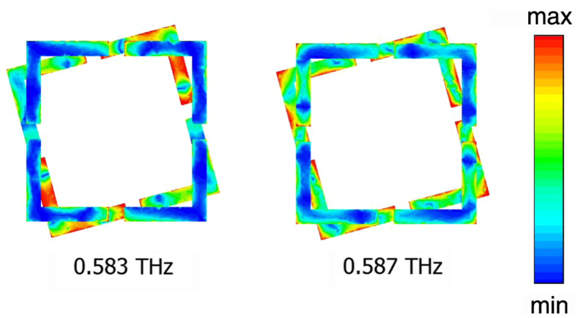

Fig. 9 Electric field distribution of the structure at the resonant frequencies.

strong and dynamic optical activity due to the features previously mentioned.

Figures 8 and 9 show the electric field and surface current distributions which verify the characteristics of the resonances of the proposed design. The electric field and surface current distributions are obtained and evaluated separately for the proposed chiral MTM at the resonance frequencies of 0.583 THz and 0.587 THz. It can be seen from the surface current distributions shown in Fig. 8 that there are parallel and antiparallel currents on the top and the bottom layers of the resonator. This means that the asymmetric resonance is directly related to the antiparallel currents excited by the magnetic dipoles and the symmetric resonance mode is realized by the parallel currents excited by the electric field (Fig. 9). Moreover, the physical mechanism of the resonance mode for 0.583 THz is different than the one for 0.587 THz.

5 Conclusion

In conclusion, the proposed chiral MTM consisting of a dielectric substrate and a square-shaped resonator with gaps are analyzed theoretically, experimentally, and numerically for both microwave and THz frequency regimes. In addition, obtained numerical results are confirmed with our experimental results in GHz and with the simulated results in THz with very good agreement. For designing novel devices in the THz frequency band, different frequency regimes can be studied based on the proposed GHz study.

Numerical simulations showed that it is possible to adjust the optical activity, for instance by actively controlling the angle of polarization of light via integrating semiconductor layers into the chiral MTM design. Moreover, a tunability feature of the proposed model provides an additional degree of freedom for polarization control. In other words, the tunable chiral MTM design enables applications such as antireflection coatings, new THz polarization rotators, polarization control devices, security screening, medical imaging, nondestructive evaluation and the development of chemical identification applications, etc., in the THz-wave frequency range.

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