THz Twist Polarizer Based on Supramolecular Fermat's Spiral Chiral Metamaterial

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Abstract— A THz twist polarizer formed by supramolecular Fermat's spiral chiral metamaterial (SFSCMM) is reported. Twist polarizers (TPs) are the 90° polarization rotators, in which transverse magnetic linear polarization is converted into transverse electric linear polarization and vice versa. The proposed SFSCMM consists of twisted bilayered supramolecular Fermat's spiral patterns, in which each layer is chiral in nature. The design is implemented in polyimide substrate using silver as a metal. Full-wave simulations demonstrated its function of TP, where the SFSCMM shows the zero-point ellipticity with the polarization rotation angle of 89.49° at 7.765 THz. The proposed SFSCMM has a dimension of $\lambda/1.38 \times \lambda/1.38 \times \lambda/10.3$ at the operating wavelength and can be fabricated through standard layer-by-layer method for the realization of optical logic gates and THz switches.

1. INTRODUCTION

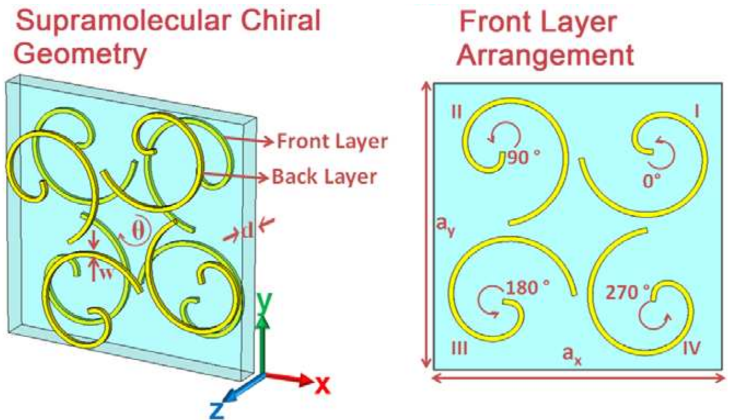
Terahertz (THz) radiation (300 GHz to 20 THz) is an inevitable tool in communication, imaging and industrial sectors due to its unique spatial and temporal characteristics [1]. For example, THz radiation can give higher contrast ratio and greater penetration depth in certain low contrast and optically opaque materials than X rays and infrared waves. At the same time, the vast range of THz spectrum is available for high-speed data transfer in communication sector. In industrial applications, THz radiation can serve as a main component in non-destructive evaluation for quality control and defect inspection. Owing to these potential applications, the development of sources, detectors and other optical components has gained greater attention over these decades. Especially, the manipulation of THz polarization state is vital for all applications. However, the realization of linear and circular polarizers using natural materials is limited for THz radiation, as many of the conventional materials do not exhibit optical activity at THz wavebands.

The advent of chiral metamaterials can overcome this limitation that one can effectively manipulate the THz radiation in the form of various polarization elements. Chiral metamaterials (CMMs) are the artificial sub-wavelength structures that lack mirror symmetry along the direction of propagation of light and they could entail giant optical activity and larger circular dichroism [2, 3]. In literature, giant optical activity of more than $2700°/\lambda$ is demonstrated using various enantiomeric chiral geometries at the microwave length scales based on the strong coupling nature of CMMs [4, 5].

In principle, one can scale any CMM geometry at any of the electromagnetic length scales. Nevertheless, the inherent metallic and dielectric losses impose constraints on the design of THz polarizing elements based on the birefringence response. For example, linear polarization rotators require pure optical activity, in which the ellipticity should be zero at the operating frequency. However, the challenging part is the requirement of zero ellipticity response of the chiral medium. For a dispersive optical medium, the linear birefringent characteristics would result in a non-zero elliptical response. So in birefringent based systems, linear polarization-rotator realization is suffering from low optical isolation values.

However, it is possible to eliminate the linear birefringence response of CMMs and one can enhance the pure optical activity based on the coupling mechanism [5]. Importantly, it is interesting to note that besides the dispersive nature of the CMMs, pure optical activity is possible with the zero-ellipticity response. For example, Kenanakis group investigated pure optical activity of CMMs at THz range with five different bilayered CMMs structures such as Z-type Gammadion structure, U-shaped split ring resonators, rotated-squares and so on [6]. However, the condition for twist polarization (i.e., 90° polarization rotation) is not met in these systems.

Twist polarizers are 90° polarization rotators, in which transverse electric (TE) polarized light is converted into transverse magnetic (TM) polarized light and vice versa. The degree of twist polarization (i.e., the optical isolation between TE and TM waves at the input and output ports)



(a) (b)

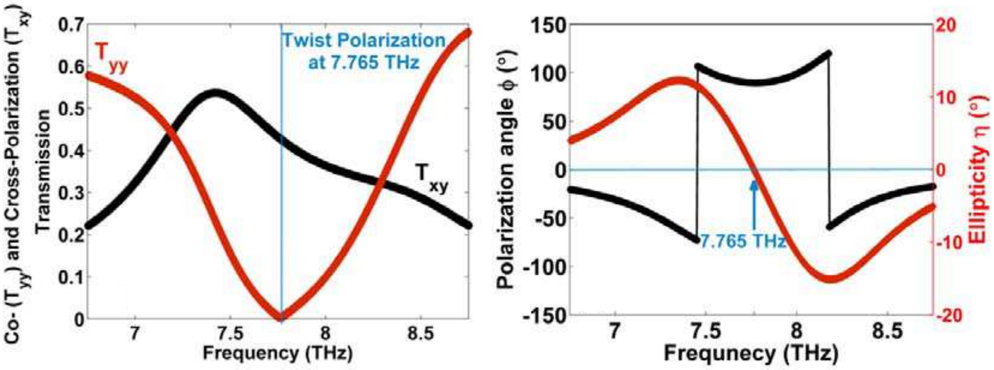
Figure 1: (a) Geometry of the single unit cell of the proposed SFSCMM. (b) Front layer arrangement of the proposed SFSCMM. The positions of the four rings are I $(-s/l, s/l)$, II $(-s/l, -s/l)$, III $(s/l, -s/l)$, IV $(s/l, s/l)$, where s and l are taken as 20 μm and 2.75 μm, respectively. The position parameters are chosen based on the parameter studies for maximum coupling.

represents the quality of the twist polarizer. At THz regime, various wire grid polarizers are currently employed for the realization of linear polarization rotators in the frequency range of 0.1 THz to 3 THz [7]. Suppose, one could design a twist polarizer directly from a chiral metamaterial response with the 100% polarization purity, then ultrafast THz optical switches and polarization logic gates can be developed and such components are highly warranted for integrated photonic devices.

It is observed that several reports have successfully synthesized CMMs for twist polarizer applications at microwave frequencies [4, 8, 9]. Nevertheless, scaling such structures to THz length scale drastically reduces the amplitude of the twist polarized light. In general, the cross polarized light amplitude for any CMMs is low at zero-ellipticity point. Unless the amplitude is high-enough at microwave frequencies, scaling procedure of CMMs may not be meaningful. For example, the C_4 symmetry cut-wire pair structure shows 90% transmission at microwave frequencies [4], whereas the same structure scaled at THz frequencies shows a transmission less than 30% [10]. Similarly, the combination of Gammadion and cut-wire pair structure [9] shows higher transmission at microwave frequencies, but the infrared scaling of Gammadion structure provides transmission only around 30% [11]. Even though, transmission is a constraint in CMM based twist polarizer, the purity of twist polarization is nearly 100%. In line of these aspects, we propose the bilayered supramolecular chiral metamaterial formed by Fermat's spirals and study its twist polarization properties at the far-infrared spectrum.

2. DESIGN AND OPTICAL ACTIVITY OF THE PROPOSED CHIRAL METAMATERIAL

Figure 1 shows the geometry of proposed supramolecular Fermat's spiral chiral metamaterial (SFSCMM). The proposed SFSCMM structure consists of twisted bilayered supramolecular patterns. Supramolecular patterns are themselves chiral in nature [12]. For example, the front layer geometry indicated in Fig. 1(b) shows four segments of Fermat's spirals, where each segment is rotated in such a way that adjacent rings maintain an angular difference of 90°. This operation enhances the additional coupling between the adjacent neighbors and the layer lacks both x- and y-in-plane mirror symmetries. The Fermat's spiral present in the design has a functional dependence of $r = A\sqrt{\theta}$, where A is the spiraling constant taken to be $2.8\,\mu\text{m}/\sqrt{\text{rad}}$. Each Spiral is traced out of a metal with the thickness and width of 0.5 μm, respectively. The metal is modeled as Silver with the conductivity of $\sigma = 6.3012 \times 10^7\,\text{S/m}$. The back metal layer of the proposed SFSCMM is a mirror structure of the front layer. Moreover, the back layer is rotated by 22.5° for enhanced coupling. The front and back layers are separated by a dielectric spacer of thickness $d = 2.75\,\mu\text{m}$. The dielectric is modeled as polyimide substrate with the dielectric permittivity $\varepsilon_r = 2.9$ and $\tan\delta = 0.03$. The lattice constants of the proposed SFSCMM are taken as $a_x = a_y = 28\,\mu\text{m}$. Total thickness of the free standing SFSCMM unit cell is 3.75 μm.



(a) (b)

Figure 2: (a) Co- and cross-polarization transmission spectra of SFSCMM. (b) Polarization angle (φ) and ellipticity (η) responses of the proposed SFSCMM.

The optical activity of the proposed SFSCMM is studied through full-wave electromagnetic simulations using commercial solver CST Microwave Studio with frequency domain calculations. Unit cell boundaries are applied along the x- and y-directions of the proposed SFSCMM and Floquet ports are applied along the propagation direction. The co- ($T_{yy} = E_y^t/E_y^i$) and cross-polarization ($T_{xy} = E_x^t/E_y^i$) transmissions are computed by exciting the first two cut-off modes of the Floquet port, which are TE and TM polarizations respectively. Here E_x^t and E_y^t are the x and y components of the transmitted electric field respectively and E_y^i is the input electric field of the y-polarized incident wave. The polarization rotation angle (ϕ) and ellipticity (η) of the transmitted wave are computed as follows;

$$\begin{aligned} \phi &= \frac{1}{2}\left[\arg\left(T_{++}\right) - \arg\left(T_{--}\right)\right], \\ \eta &= \frac{1}{2}\tan^{-1}\left(\frac{\left|T_{++}\right|^2 - \left|T_{--}\right|^2}{\left|T_{++}\right|^2 + \left|T_{--}\right|^2}\right), \end{aligned} \tag{1}$$

where $T_{++} = T_{yy} + iT_{xy}$ and $T_{--} = T_{yy} - iT_{xy}$ are the transmission coefficients of RCP and LCP waves, respectively.

From Fig. 2(a), we can observe that at 7.765 THz, the computed co- and cross polarized transmissions are $T_{yy} = 0.003$ and $T_{xy} = 0.427$, respectively. This corresponds to the cross over point on the ellipticity spectrum given in Fig. 2(b), where the computed polarization rotation angle is 89.49° at 7.765 THz. The optical isolation between the co- and cross-polarized transmissions is found around 43 dB at 7.765 THz. This represents a high degree of spectral purity around 99% at 7.765 THz, which is the desired criterion for the realization of ultrafast THz optical switches despite its higher transmission loss. The overall dimension of the proposed SFSCMM is $\lambda/1.38 \times \lambda/1.38 \times \lambda/10.3$ at the operating wavelength.

3. MECHANISM OF TWIST POLARIZATION

To probe the mechanism behind the twist polarization function of the proposed SFSCMM, surface current distribution is plotted at 7.765 THz in Fig. 3. The dashed and solid arrows represent surface current directions at the front and back layers of the SFSCMM, respectively. It is clear that at twist polarization frequency, both layers are oscillating anti-symmetrically. It is also observed that smaller arrows indicate the presence of symmetric current distribution at some parts of the structure. However, the anti-symmetric current distribution is dominant in the structure (For example, one can refer segments I to IV in Fig. 3). The surface current in each ring induces a magnetic dipole for the E-polarized incident wave and such dipoles present in the adjacent neighbors are interacting transversely [13]. Moreover, the magnetic dipole distribution at the front and back layers are interacting longitudinally. Similarly, one can analyze various interactions of electric dipoles but it is noticed that their contribution is weaker compared to the magnetic dipole interaction as the 90° rotational arrangement of the segments cancelled out mostly the electric dipole contribution since their inner product is zero [13]. Hence for a given anti-symmetric current

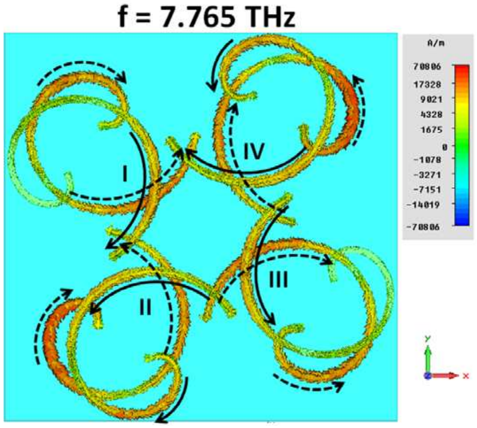
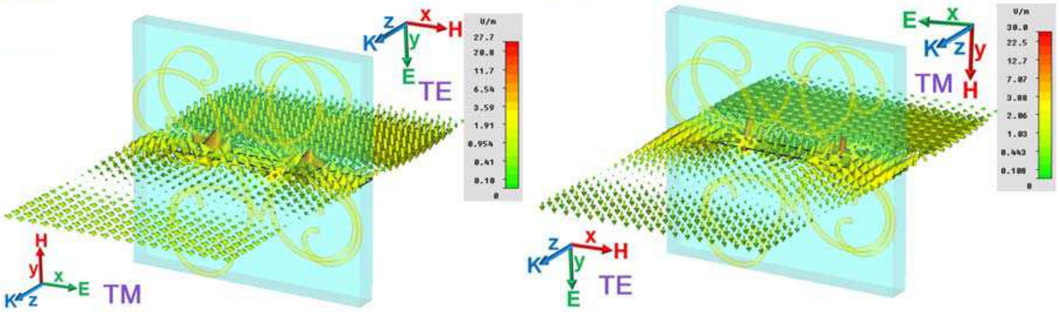


Figure 3: The surface current distribution of the proposed SFSCMM at 7.765 THz. The oscillating currents in this figure correspond to a phase of 90°. The solid and dashed arrows represent the current directions at the front and back layers, respectively.



(a) (b)

Figure 4: (a), (b) show TE to TM and TM to TE conversion functionalities of the proposed SFSCMM at 7.64 THz, respectively. In both cases, the arrow plots show a 90° rotation of the electric fields.

distribution, the induced magnetic dipoles aligned along the direction of the applied electric field of the input wave will couple strongly and will result in a twist polarized field at the output port.

4. TE TO TM CONVERSION: PLANE WAVE EXCITATION RESULTS

To visualize the twist polarization functionality of the proposed SFSCMM, additional simulations are carried out. Plane waves with TE and TM polarizations are excited and their field distributions are solved through transient electromagnetic computations. Figs. 4(a) and 4(b) present the electric field map at 7.64 THz, in which the proposed FSCMM structure clearly demonstrates TE to TM (Fig. 4(a)) and TM to TE (Fig. 4(b)) conversion function. Since the field computations are done with transient solver using different mesh settings, the twist polarization frequency is slightly shifted with respect to that in frequency domain calculations.

5. PERSPECTIVES AND CONCLUSIONS

There are three directions, in which the current research needs to be further carried out: 1) On the requirement of zero ellipticity response, the proposed SFSCMM is an ample candidate for the realization of twist polarizer. However, the intensity aspect of the proposed SFSCMM needs to be further improved. At the same time, this is a universal problem, where all CMMs at zero-point ellipticity witness lower amplitude. To overcome this problem, one may counter to balance the impedance mismatch by electromagnetic tunneling (EMT) concept [8, 14]. For example, EMT is reported at microwave frequencies but its extension to higher frequencies must balance all loss factors [15]. Some group also suggests the use of gain media to enhance the intensity of cross polarizers [16]. 2) Twist polarizers in the form of metasurfaces are well known in reflective configurations [15]. The transmission type exhibits high loss but metasurface approach may be useful for bandwidth enhancement. 3) Combining the first two perspectives, unit transmittance accompanied with the zero-ellipticity is an ideal target for the THz twist polarizers. This can be fulfilled by introducing newer analytical approaches and optimization methods. For example, the current analytical approach in the literature [17] based on the coupling picture gives excellent physical intuition but still it needs numerical simulations and rigorous optimizations. Conclusively, our present investigations on the THz twist polarizer formed by the supramolecular Fermat's spiral chiral metamaterial will find applications in the development of ultrafast THz switches, polarization logics and spectroscopic elements with the aforementioned perspectives.

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REFERENCES

1. Tonouchi, M., "Cutting-edge terahertz technology," *Nat. Photon.*, Vol. 1, No. 2, 97–105, 2007.
2. Svirko, Y., N. Zheludev, and M. Osipov, "Layered chiral metallic microstructures with inductive coupling," *Appl. Phys. Lett.*, Vol. 78, No. 4, 498–500, 2001.
3. Papakostas, A., A. Potts, D. M. Bagnall, S. L. Prosvirnin, H. J. Coles, and N. I. Zheludev, "Optical manifestations of planar chirality," *Phys. Rev. Lett.*, Vol. 90, No. 10, 107404, 2003.
4. Ye, Y. amd S. He, "90° polarization rotator using a bilayered chiral metamaterial with giant optical activity," *Appl. Phys. Lett.*, Vol. 96, 203501, 2010.
5. Decker, M., R. Zhao, C. M. Soukoulis, S. Linden, and M. Wegener, "Twisted split-ring-resonator photonic metamaterial with huge optical activity," *Opt. Lett.*, Vol. 35, 1593–1595, 2010.
6. Kenanakis, G., R. Zhao, A. Stavrinidis, G. Konstantinidis, N. Katsarakis, M. Kafesaki, C. M. Soukoulis, and E. N. Economou, "Flexible chiral metamaterials in the terahertz regime: A comparative study of various designs," *Opt. Mat. Exp.*, Vol. 2, No. 12, 1702–1712, 2012.
7. Yan, F., C. Yu, H. Park, E. P. J. Parrott, and E. P. MacPherson, "Advances in polarizer technology for terahertz frequency applications," *J. Infrared Milli. Terahz Waves*, Vol. 34, No. 9, 489–499, 2013.
8. Mutlu, M. and E. Ozbay, "A transparent 90° polarization rotator by combining chirality and electromagnetic wave tunneling," *Appl. Phys. Lett.*, Vol. 100, 051909, 2012.
9. Song, K., Y. Liu, Q. Fu, X. Zhao, C. Luo, and W. Zhu, "90° polarization rotator with rotation angle independent of substrate permittivity and incident angles using a composite chiral metamaterial," *Opt. Exp.*, Vol. 21, 7439–7446, 2013.
10. Xi, C., "Terahertz angle-insensitive 90° polarization rotator using chiral metamaterial," *Physica B*, Vol. 422, 83–86, 2013.
11. Kwon, D.-H., P. L. Werner, and D. H. Werner, "Optical planar chiral metamaterial designs for strong circular dichroism and polarization rotation," *Opt. Exp.*, Vol. 16, 11802–11807, 2008.
12. Valev, V. K., J. J. Baumberg, C. Sibilia, and T. Verbiest, "Chirality and chiroptical effects in plasmonic nanostructures: Fundamentals, recent progress, and outlook," *Adv. Mater.*, Vol. 25, 2517–2534, 2013.
13. Liu, N. and H. Giessen, "Coupling effects in optical metamaterials," *Angew. Chem. Int. Ed.*, Vol. 49, 9838–9852, 2010.
14. Zhou, L., W. Wen, C. T. Chan, and P. Sheng, "Electromagnetic-wave tunneling through negative permittivity media with high magnetic fields," *Phys. Rev. Lett.*, Vol. 94, 243905, 2005.
15. Grady, N. K., J. E. Heyes, D. R. Chowdhury, Y. Zeng, M. T. Reiten, A. K. Azad, A. J. Taylor, D. A. R. Dalvit, and H.-T. Chen, "Terahertz metamaterial for linear polarization conversion and anomalous refraction," *Science*, Vol. 340, 1304–1307, 2013.
16. Zhu, W., I. D. Rukhlenko, F. Xiao, and M. Premaratne, "Polarization conversion in U-shaped chiral metamaterial with four-fold symmetry breaking," *J. Appl. Phys.*, Vol. 115, 143101, 2014.
17. Niemi, T., A. O. Karilainen, and S. A. Tretyakov, "Synthesis of polarization transformers," *IEEE Trans. Anten. Propag.*, Vol. 61, 3102–3111, 2013.