Metasurface supporting broadband circular dichroism for reflected and transmitted fields simultaneously

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Abstract

We demonstrate significant optical activity in the near-infrared spectrum of a chiral metasurface which is designed using an array of L-shaped silver nanostructures. The far-field radiation from the plasmon-polariton surface wave currents produces combination of strong and highly dispersive orthogonal electric field components leading to the observation of broadband circular and elliptical polarization states (dichroism) for reflected and transmitted fields. Full-wave electromagnetic simulations show a linear to left hand and right hand circular polarization conversion between 200–261 THz frequency (1.15 \( \mu \)m–1.5 \( \mu \)m wavelength) range for reflected and transmitted fields. The structural chirality can be further enhanced by engraving another smaller L-dipole in nested configuration reaching near perfect polarization conversion efficiency. The nested L-dipole configuration supports circular polarization conversion between 262–306 THz frequency (980 nm–1.14 \( \mu \)m wavelength) range. Full-wave simulations suggest clear enhancement of the surface currents with helical orientation leading to increased optical activity. The proposed optical waveplate may be utilized in polarization control applications such as optical imaging, sensing, and display components.

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(Some figures may appear in colour only in the online journal)

1. Introduction

In the past two decades, engineered periodic structures known as metamaterials have been successfully designed to demonstrate phenomena that do not exist in nature altogether or transport a naturally occurring phenomenon (such as the chirality) into an applicable spectrum. The earlier metamaterial was engineered to demonstrate the negative index of refraction which is not supported by any natural medium [1]. More recently, metamaterials were designed as electromagnetic absorber [2], switches [3–5], slow-light devices [6], lensing [7, 8] and invisible cloaking [9, 10]. The advancement in metamaterial research also paved way to the design of chiral materials that demonstrated optical activity several magnitudes larger than what occurs naturally [11–20]. An interesting piece of work that showed large chiral effects was designed by using 3D nanoscale gold helices arranged in a square lattice formation [12]. Since the electromagnetic response in these chiral metamaterials is derived from strong resonant interactions, the resulting optical components (such
as the polarizers) were much more compact than their classical counterpart [12–15, 17, 18]. Additionally, the concept of superchiral electromagnetic fields in plasmonic nanostructures can lead to a significant increase in the light–matter interaction which may open opportunities to highly sensitive chiro-optical detection [15]. Some other exotic behaviours such as negative index and all-angle absorption were also demonstrated in the chiral metamaterials [19–24].

Optical activity is the rotation of the polarization of a light beam as it passes through materials having crystalline or molecular chirality. In materials like quartz, it stems from the associated crystalline structure and hence does not exist in the molten quartz when the structure is broken [25]. On the other hand, in fluids like turpentine and in solutions of sugar and tartaric acid, the chirality resides in individual molecules and hence can exist even if they are randomly oriented. By considering linearly polarized waves as superposition of the two oppositely oriented circular polarizations, Fresnel postulated that the origin of the optical activity was due to the helicoidal arrangement or the ‘chirality’ of the molecular or crystalline structures [25, 26]. The chirality exhibits itself naturally in various places in the natural world such as the amino acids and the sugar molecules, which are mostly chiral [27]. The extent of optical activity determines the structure properties such as the handedness, solubility, dissolution, and stability and hence it has been applied to analyse chiral compounds in analytical chemistry, crystallography, and pharmaceutics [28]. Given the fact that more than 50% of the drugs are chiral in nature, the measurement of optical properties is a critical step towards development, approval, and clinical use of drugs [28]. Moreover, since all proteins and DNA are also chiral, the characterization of optical activity is of critical importance in medical sciences [29].

The fascination around the concept of chirality and optical activity in natural media led to major advances in physics and natural sciences during the nineteen and twentieth century [29]. From the application point of view, optically active liquid crystals form the basis of many optoelectronic devices [30]. However, it may be noted that, in general, the optical activity demonstrated by naturally found chiral materials is weak and can only be detected when light propagates in them over large optical lengths.

Chirality and polarization control are intimately related to each other and sometimes it becomes difficult to separately identify them. The two phenomena although produce similar results are fundamentally different: one caused by the intrinsic molecular structure and the other by an external source. The first proposal of circular polarization selective structure (CPSS) was initiated by Pierrot in the year 1966 [31]. The idea was based upon an array of bended wires, with two subwavelength sized orthogonal arms connected by a vertical arm. The theoretical validation of CPSS idea was later provided by Roy and Shafai [32]. In recent works, polarization control has become a vital optical property required in several applications such as liquid crystal displays, imaging, and optical sensing [20, 33, 34]. Moreover, since chiral structures may replace 3D helical antennas, a dramatic reduction in satellite payload can be expected [35]. Note that the chiral designs are based on breaking the structure’s symmetry, thus allowing the currents to flow asymmetrically. Therefore, more planar geometries and compact designs are possible [15, 17, 18, 36–43]. Although, Faraday rotation and optical activity provided way to control polarization, the structures based on these conventional methods suffer from narrow bandwidth and weak wave interaction resulting in high profile geometries and bulky structures [35, 44–48]. These polarization control methods employ concepts like the eigenmode superposition [44], the traditional geometrical approach using helix [49], resonance-based asymmetry [45], surface plasmon destructive interference in the far-field [46, 47] and quasi-crystal approach [50, 51]. Finally, narrowband polarization control may also be achieved by designing anisotropic structures to implement the half-wave and quarter-wave plates at the infrared and/or terahertz (THz) frequencies [48, 52, 53]. Microwave antenna based metasurfaces are also becoming popular for radar and wireless communication systems [54–58].

In this paper, we manipulate the polarization of near-infrared light by using a metasurface consisting of a two-dimensional array of silver L-shaped dipoles (see figure 1). The metasurface based on nanoplasmonic chiral elements allows the generation of the localized surface plasmon modes. The metasurface design is inspired by the chiral materials which have been historically known to rotate the optical polarization of the impinging light. The general design approach can be understood by considering the mirror-symmetric arrangement of the chiral molecules or crystalline structures responsible for the optical rotation. In the metasurface design, these chiral structures are replaced by subwavelength sized metallic unit cells capable of radiating cross-polarized electric fields. In particular, we obtain a broad spectrum of linear to circular (or elliptical) field conversion, a form of optical activity also known as circular dichroism. More interestingly, the proposed design works as a partially reflecting surface as it supports the circular states simultaneously for both the transmitted and reflected fields. Here we should note that the linearly polarized wave can be considered as a vector sum of the left- or right-handed circularly polarized waves with equal contribution. The quarter-waveplate is defined as complete suppression of either the left- or right-handed component leading to a perfectly circularly polarized wave. Circular dichroism is a more general term that encompasses the frequency-dependent conversion of linearly polarized waves to a variety of elliptically polarized waves.

2. Simulation domain and Jones calculus

The chirality in our metasurface design is obtained by using metasurface based on asymmetric pattern of L-shape metallic (silver) nanostructure. The L-shape unit cell is inspired from the cross dipole structure which is a popular radiation element used in antenna applications [54, 59]. In optics, a two-dimensional array of cross-dipoles has been recently used for planar rotation of the polarized beam [60–63]. In order to enhance optical activity at subwavelength scale, the structural symmetry needs to be broken with respect
to incident polarization. Chiral light design strategy is also described by a couple of shifted nanorod dimers for transmitted fields [64]. A hybrid structure consisting of metallic nanorod embedded inside L-shaped dielectric medium is also used to demonstrate circular dichroism for transmitted fields [65]. Figure 1 depicts the design progression from the concentric cross dipole structure to the asymmetric L-dipole structure. The dipole’s arms are shifted off-axis to obtain two different metasurface designs: the T-dipole and the L-dipole unit cells. The intermediate T-dipole exhibits the two-fold symmetry and hence can still be superimposed onto its image. The L-dipole does not exhibit the reflection symmetry along the x- or y-axes, however it exhibits mirror inversion symmetry along its diagonal axis and hence can be regarded as a chiral structure. When a linearly polarized NIR 240 THz radiation impinges on the metasurface, it induces asymmetric displacement currents as a result of the excitation of the localized surface plasmon modes on L-shape metal [66]. These displacement currents produce cross-polarized field components leading to the optical rotation in the far field. Simulated electromagnetic fields determined for the design progression from the cross to the L-dipole geometry show a efficient circular polarization conversion over a broad range of frequency for the L-dipole array. The performance is shown to be considerably enhanced when an additional L-dipole is added as a nested element to the original unit cell of figure 1. The planar geometry based on plasmonic nanostructure results in much compact geometry compared to the other complex contemporary 3D approaches such that the one constructed with dielectric and metallic helical in the similar spectral region [67]. Recently, fabrication techniques based on nanoimprint lithography, hard-mask definition and metal deposition were demonstrated to yield high throughput of planar nanoparticle based array nanostructures.

The proposed chiral metasurface is supposed to work in the reflection and transmission mode simultaneously. Figure 2(a) depicts the simulation domain explaining the unit cell geometry and the boundary conditions along with an illustration of the expected metasurface’s working principle. Full wave simulations were performed using finite element method (FEM) based COMSOL Multiphysics software. Note that the silver nanostructure consisting of L-dipoles are placed on dielectric substrate (refractive index 1.48). The effect of background medium to the far-field quantities can be simply deducted by subtracting the additional phase due to the wave propagation in background medium at the far-field ports, located along the z-axis. Along the x- and y-directions, periodic boundary conditions (PBC) are implemented, such that infinite metasurface is simulated, as depicted in figure 2(b). As shown, it is expected that a polarized wave impinging on the cross dipole metasurface does not undergo the polarization conversion because of the symmetric geometry. On the other hand, the L-dipole metasurface would efficiently couple incident fields to induce circularly polarized reflected and transmitted field components. The optical properties of silver used in the simulation were extracted from the Johnson and Christy (JC) experiment for optical constants of the noble metals [68].

Fresnel laid down the foundation of the optical rotational analysis by proposing the mathematical representation of linearly polarized fields in the form of the two rotational field components. Jones represented the polarization effects in a more elegant form through the mathematical formulism known as Jones calculus [69]. The Jones matrix relates the x- and y-directed incident fields $E_{xi}$ and $E_{yi}$ to the reflected and transmitted fields in terms of a set of scattering coefficients:

$$\begin{pmatrix} E_{xR} \\ E_{yR} \end{pmatrix} = \begin{pmatrix} S_{xx} & S_{xy} \\ S_{yx} & S_{yy} \end{pmatrix} \begin{pmatrix} E_{xi} \\ E_{yi} \end{pmatrix}. \quad (1)$$

Here, subscript $s = r, t$ may refer to reflected $E_{xR}/E_{yR}$ or transmitted $E_{xT}/E_{yT}$ electric fields where applicable. The terms $S_{xx} = E_{xx}/E_{xi}$ and $S_{yy} = E_{yy}/E_{yi}$ are the co-polarization scattering coefficients for x- and y-polarized incident fields respectively, whereas, $S_{yx} = E_{yx}/E_{yi}$ and $S_{xy} = E_{xy}/E_{xi}$ are the cross-polarized coefficients. Here, generalized scattering coefficient term $S = R; T$ may refer to reflection $R$ or transmission $T$ coefficients.
Figure 2. A schematic view of simulation domains of the L-dipole chiral metasurface. Inset shows metasurface unit cell utilized for simulation domain surrounded by periodic boundary conditions (PBC) on each side. The lengths of the arms of two dipole are given by $L_x = L_y = 320$ nm, period $p = 400$ nm and width $w = 80$ nm, thickness of metasurface is $25$ nm and substrate height $h = 50$ nm. The linearly polarized waves impinging on the L-dipole array are converted into circular polarized reflected and transmitted fields depending on the frequency.

To facilitate the determination of the amount of linear to rotational field conversion, it is useful to express the Jones Matrix in the circular bases. Prior to doing that, we define the right handed circularly polarized (RHCP) ($E^{+}$) and left hand circularly polarized (LHCP) ($E^{-}$) components and the four rotational transmission coefficients:

\begin{align}
    E^{+} &= E_{xx} + jE_{yx}, \quad E^{-} = E_{xx} - jE_{yx} \quad (2)
\end{align}

\begin{align}
    S_{\pm x} &= 1/\sqrt{2}(S_{xx} \pm jS_{yx}), \quad S_{\pm y} = 1/\sqrt{2}(S_{xy} \pm jS_{yy}) \quad (3)
\end{align}

Subsequently, the rotational electric fields in terms of the Jones matrix can be written as:

\begin{align}
    \begin{pmatrix}
        E^{+} \\ E^{-}
    \end{pmatrix} =
    \begin{pmatrix}
        S_{++} & S_{+y} \\ S_{-x} & S_{--}
    \end{pmatrix}
    \begin{pmatrix}
        E_{xx} \\ E_{yi}
    \end{pmatrix} \quad (4)
\end{align}

By incorporating the above-mentioned definitions of the rotational fields and the coefficients, the LHCP and RHCP polarized fields can be extracted from equation (4):

\begin{align}
    E^{+} &= 1/\sqrt{2}(S_{xx} + jS_{yx})E_{xx} + 1/\sqrt{2}(S_{xy} + jS_{yy})E_{yi} \quad (5)
\end{align}

\begin{align}
    E^{-} &= 1/\sqrt{2}(S_{xx} - jS_{yx})E_{xx} + 1/\sqrt{2}(S_{xy} - jS_{yy})E_{yi} \quad (6)
\end{align}

To accomplish ideal circular polarized fields, the reflected or transmitted fields requires x- and y-components and must have identical magnitude ($|E_{xx}| = |E_{yi}|$) with phase difference of ±90°. The extent of the linear to circular polarization conversion or the quarter waveplate action is represented by the polarization extinction ratio (PER):

\begin{align}
    PER &= 20\log_{10}\left(\frac{|S_{+x}|}{|S_{-x}|}\right) \quad (7)
\end{align}

The rotational tilt of linear or major axis of elliptical polarization for reflected and transmitted fields can be found with respect to incident polarization:

\begin{align}
    \tau &= \frac{1}{2}\tan^{-1}\left(\frac{2S_{xx}S_{xy} - S_{yx}^2 \cos \delta}{S_{xx}^2 - S_{yx}^2}\right) \pm \frac{\pi}{2} \quad (8)
\end{align}

Here, $S_{yx} = E_{yi}/E_{xx}$ and $S_{xx} = E_{yx}/E_{xx}$ are the co- and cross-polarization coefficients respectively, $\delta$ is the phase difference between x- and y- components of electric fields. The phase can be unwrapped by choosing appropriate stepwise jumps ±π/2 to all frequencies after which the phase of scattering reaches ±π/2.

3. Results

3.1. Demonstration of circular dichroism

Going back to our designed nanoplasmonic metasurfaces, consider the reflection and transmission responses of the x-polarized waves incident on the T-dipole and L-dipole metasurfaces. It is noted that the concentric cross dipoles or T-dipoles metasurface does not support cross-polarized field
components (i.e. $|R_{yx}| = |T_{yx}| = 0$) throughout the spectrum. On the other hand, the reflection and transmission responses and the associated phase difference for the L-dipole metasurface clearly indicate the presence of circular dichroism for broad range of frequencies, as depicted in figures 3(a)–(d). For example, significant amplitude of cross-polarized components i.e. $R_{yx}$ and $T_{yx}$ can be noted in the frequency ranges of interest i.e. 167 THz–350 THz. The analysis of the reflection and transmission magnitude and the phase characteristics characterize the polarization state and the type of circular dichroism.

The quarter waveplate action of the metasurface is identified by nearly equal co- and cross-polarized field components and concurrent phase difference of odd multiples of $\pm 90^\circ$ between them so that the transmitted and reflected waves are purely circularly polarized. In the spectral vicinity of the quarter-waveplate frequency, different forms of dichroism shall be observed. As discussed earlier that the unique structural symmetry prohibits the chiral response in the cross-dipole and T-dipole arrays leading to a zero PER throughout the spectrum. The introduction of structural asymmetry with respect of incident polarization enhances the chiral response. In order to characterize the circular dichroism response of the L-dipole array, the PER is calculated from equation (7) and is shown in figure 4(b) for reflected and transmitted fields. For transmitted fields, it can be observed that the LHCP ($T_{xx}$) dominates in the frequency range between 199–262 THz where a PER of lower than $-10$ dB is noted. The peak of LHCP polarization reaches $-24$ dB at 231 THz. Similarly, for reflected fields the RHCP dominates and peaks of RHCP polarization reaches $+35$ dB at 231 dB. The reason for small difference between reflected and transmitted PER is the background medium due to dielectric substrate of refractive index 1.48. As a result, the magnitude of PER values for reflected and transmitted fields are close but not identical.

To show the orientation of the fields in the transmitted spectrum, the polarization states of the electric field vectors are depicted for three different frequencies in the inset of figure 4(b). At the resonant frequency of 231 THz, the incident x-polarized incident field is fully converted into LHCP transmitted fields, thus validating the high PER of $-24$ dB. This corresponds to a resonant frequency near the quarter of the incident wavelength compared to the arm size of the L-shaped metasurface. The intrinsic losses contribute to broadening of resonance and therefore reduce the overall Q-factor of the resonance. On the other hand, reflected fields at 231 THz are fully converted to RHCP polarization. At 250 THz, however, the
Figure 4. Quarter waveplate action of the L-dipole metasurface. (a) Surface current distribution on unit cell of L-dipole metasurface at respective frequencies (viewed from the top). The magnitude of surface current distribution is presented by the size of arrows, and its orientation is presented by the direction of arrows. (b) The PER showing the efficiency of circular polarization conversion. Inset shows the time varying orientation of reflected and transmitted electric field at 231 THz, 250 THz and 287 THz frequencies (see supplementary material (stacks.iop.org/JPD/53/435106/mmedia)). (c) Rotational tilt for major axis of polarization for reflected and transmitted fields.
polarization conversion is not fully circular indicated by the elliptical polarization state for reflected and transmitted fields. Similarly, at 287 THz, the transmitted fields are nearly linear having rotational tilt towards $-45^\circ$, consistent with the PER $= 0$ dB. However, at the same frequency the reflected fields are elliptically polarized, validating PER value of $+5$ dB. The animations used in the supplementary materials were generated by plotting the locus traced by the tip of electric field vector at a given time and space.

Returning to our earlier assertion that the polarization states in our metasurface arise from the flow of the localized surface plasmon modes that supports the asymmetric surface currents. The resonance mechanism can be best understood by plotting the distribution of the surface current density over the metallic layer, as given in figure 4(b) for the elliptical and circular polarizations described in figure 4(a). At 231 THz the clockwise surface current distribution over L-dipole metasurface element lead to RHCP and LHCP for reflected and transmitted fields respectively. Similarly, at 250 THz the currents are clockwise relating to right- and left-hand elliptical polarization in the reflected and transmitted fields respectively. Finally, at 287 THz the surface currents are originating from the junction point and spreading to two arms of dipoles leading to linearly polarized $-45^\circ$ tilted transmitted fields.

The tilt due to orientation of scattered electric field vector for L-dipole metasurface is calculated from equation (8) is provided in figure 4(c). It can be observed that the tilt angle matches with the inset plot for orientation of the electric field vector for both reflected and transmitted fields.

The L-shaped nanostructure retains mirror symmetry along the diagonal axis and therefore $y$-polarized incident waves will have equal response but in the opposite direction in terms of handedness to the $x$-polarized incident waves. Hence, due to the incident polarization along $y$-axis the currents along the L-shaped nanostructure will be flipped in equal amplitude but opposite direction to the $x$-polarized incidence. As a result, the PER spectrum for an L-shaped metasurface for $y$-polarized incident fields possesses equal but opposite direction for circularly polarized output (i.e. RHCP transmitted fields) when compared to $x$-polarized incident fields. On the other hand, the diagonally polarized fields at 45 degree can be decomposed into equal $x$- and $y$-components and therefore superposition of optical activity due to both these components will cancel the overall chiral response. Similarly, the response of metasurface to either LHCP or RHCP incident waves can be found by applying the superposition principle and the reciprocity theorem. The LHCP and/or RHCP can be constructed by adding together $x$- and $y$-components of incident fields having phase difference of $\pm 90$ degree between them. The individual response of two linear components (along $x$- and $y$-axes) are equal in amplitude but opposite in direction. Therefore, the phase difference of 90 degrees will cancel the orientation of electric field along either $x$- or $y$-direction leading to linearly polarized transmitted or reflected fields. Finally, the flipping of the L-shaped geometry of the unit cell along the diagonal axis is equivalent to changing the incident polarization from $x$- to $y$-polarized.

The L-dipole metasurface is sensitive to geometrical variations in the unit cell. For example figure 5(a) provides the PER response of metasurface as we change the length (L) of arms of L-shape dipoles. A resonant blueshift can be observed in the PER spectrum as the length of arms of the dipole is increased from $L = 280$ nm to $L = 360$ nm. Similarly, the periodicity plays important role in the design of metasurface as the coupling between adjacent unit cells depend upon the distance between successive meta-atoms. On the other hand, the peak magnitude of PER is reduced below $\pm 20$ dB for $L = 360$ nm, 280 nm for both reflected and transmitted fields. Figure 5(b) provides the variation in the PER response of metasurface as we change the arm width (w) of the L-shaped dipole. A resonant redshift can be observed as the arm width is increased from $w = 60$ nm to $w = 100$ nm. The polarization state response of the metasurface is evaluated for oblique incidence where the incident angle is varied between $0^\circ$ and $60^\circ$ for $s$-polarized condition. Figure 5(c) presents the resulting change in PER for both reflected and transmitted waves at a fixed frequency of 231 THz. Polarization state variation is also demonstrated to have stable response for transmitted fields under oblique incidence.

### 3.2. Nested L-dipole unit cell for enhanced optical activity

To enhance the optical activity, the aperture of the metallic part is increased by adding another smaller L structure nested with the existing L-dipole, as shown in figure 6. It is evident that the new unit cell remains mirror-symmetric about the diagonal axis. The result of full-wave field analysis is depicted in figures 7(a) and (b). The co- and cross-transmission coefficients and their respective phase differences ($\angle T_{xx} - \angle T_{yy}$) shows the dispersive nature of chiral metasurface response. The reflection and transmission plots reveal broadband spectral range where large optical activity can be noted.

Our particular interest lies in the circular polarization control because of the underlying myriad applications in the field of polarization control and sensing. The points of linear to circular conversions can be further highlighted by extracting the polarization extinction ratio (PER) and the associated polarization states. Note that the large cross-polarized fields do not essentially correspond to an enhanced PER. The conversion efficiencies rather point to the full suppression of one of the orthogonal components. For example, the $-40$ dB efficiency point in figure 8(a) correspond to the transmission coefficients of nearly 0.5 amplitude. The high PER corresponds to a perfectly circularly polarized transmitted wave at 282 THz, as shown in figure 8(a). Spectral bands around 282 THz are of importance from the application point of view as it supports strong LHCP and RHCP polarization conversion for transmitted and reflected fields respectively. In addition, an efficient PER $< -10$ dB is maintained for broad range of frequencies between 264–306 THz. On the other hand, the lower value of
Figure 5. Variation in PER due to change in (a) length ($L$) of arms of L-dipole array, (b) period ($p$) of unitcell, (c) arm width ($w$) and (d) oblique incidence at 231 THz frequency.

Figure 6. The schematic illustration of the nested L-shaped chiral metasurface design. Inset shows metasurface unitcell with geometric features similar to L-dipole structure. Smaller L-dipole of arm length $L_{x2} = L_{y2} = 224$ nm, width $w_2 = 56$ nm and inter-element gap $g = 16$ nm nested inside larger L-dipole.
PER, e.g. at 255 THz, corresponds to elliptical polarization as shown in figure 8(a).

Surface current distribution can also be analysed for nested L-dipole metasurface as shown in inset of figure 8(a). At 282 THz the currents flow in a helical fashion that corresponds to the direction of the polarization state. The surface distribution has a dominant clockwise pattern formed by large currents giving the transmitted electromagnetic wave a right hand clockwise circular polarization. In a similar manner, the currents at 255 THz shows clockwise current in the inner and outer arms that leads to elliptical polarization state for reflected and transmitted fields. Furthermore, it can be observed that the calculated tilt angle for scattered fields agrees with the inset plot for orientation of the electric field vector for both reflected and transmitted fields.

It is often noted that the inter-element gap of plasmonic materials is difficult to control during the fabrication process and precise gap of 16 nm between the nested L-dipole might not be realizable. The interelement gap of different sizes i.e. $g = 16$ nm, 24 nm, 32 nm are simulated, and the result is compared in figure 9(a) for the corresponding PER spectrum. The increase in gap size ($g$) leads to blueshift in the resonant peak of PER spectrum. Similarly, the fabrication of sharp edges of L-shape dipole is hard to realize and the corners of the nanostructures are often rounded. The effect of rounded corners of the nested L-shape dipole array is investigated in figure 9(b). It is clear from the PER spectrum that the rounded corners lead to blue shift in the resonance frequency compared to sharp edges.

The bandwidth and mode of operation of chiral metasurfaces are important from application point of view. Achieving broadband CD remains a challenging task. Table 1 provides a comparison among various types of nanostructured metasurfaces to achieve chiral mode of operation. The comparison can be made in terms of structure shape, mode of operation either in reflection or transmission mode and the operational bandwidth of the chiral response. The distinct feature of the L-shaped design of chiral metasurface is to support broadband of operation and works in transmission and reflection mode simultaneously. On the other hand the operational bandwidth of chiral operation ranges between 1.15 $\mu$m–1.5 $\mu$m and 980 nm–1.14 $\mu$m wavelength range for L-shaped and nested L-shaped nanostructures respectively. It is emphasized that the fractional bandwidth of single L-dipole array is slightly wider compared to nested L-dipolar array. The main advantage of is that the proposed L-shaped metasurface can offer

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**Figure 7.** (a) Reflection coefficient of nested L-dipole metasurface and (b) their phase difference ($\angle R_{xx} - \angle R_{yx}$). (c) The transmission coefficients of nested L-dipole metasurface and (d) their phase difference ($\angle T_{xx} - \angle T_{yx}$).
Figure 8. (a) PER in dB for the chiral metasurface with the nested L-dipole metasurface. Inset shows the time varying orientation of reflected and transmitted electric fields at 255 THz and 282 THz frequencies (see supplementary material). Another inset shows surface current distribution on unit cell of nested L-dipole metasurface at respective frequencies (viewed from the top). The magnitude of surface current distribution is presented by the size of arrows, and its orientation is presented by the direction of arrows. (b) Rotational tilt for major axis of polarization for reflected and transmitted fields.
Figure 9. Variation in PER due to change in (a) inter-element gap \( g \) between nested L-loops. (b) Variation in PER due to rounded corners of L-shape nanostructure.

Table 1. Comparison between bandwidths and mode of operation for chiral metasurfaces at optical frequencies.

| Reference | Structure type                  | Operation mode          | Operational bandwidth frequency/wavelength range |
|-----------|---------------------------------|-------------------------|--------------------------------------------------|
| [38]      | Single Layer Gammadion Shaped   | Transmission            | 230 THz–272 THz (1.1 µm–1.3 µm)                   |
| [39]      | Multilayer Rods                 | Reflection              | 35.2 THz–40 THz (7.5 µm–8.5 µm)                   |
| [40]      | Single Layer Etched Z-Shaped    | Transmission            | 181 THz–206 THz (1.45 µm–1.65 µm)                 |
| [41]      | Single Layer Eta Shaped         | Transmission            | 40 THz–50 THz (6 µm–7.5 µm) 70 THz–80 THz (3.75 µm–4.28 µm) |
| [42]      | Single Layer Ramp Shaped        | Reflection              | 413 THz–480 THz (625 nm–725 nm)                   |
| Present Study | Single Layer L-Shaped       | Transmission/Reflection | 200 THz–261 THz (1.15 µm–1.5 µm)                 |
| Present Study | Single Layer Nested L-Shaped | Transmission/Reflection | 264 THz–306 THz (9.803 µm–1.136 µm)               |

broadband of chiral operation and works in transmission and reflection mode simultaneously. The main disadvantage of using plasmonic nanostructure is that the large-scale fabrication of nanoparticle array is challenging due to lack of precise control over dimensions of the overall structure.

4. Conclusion

We propose a nanoplasmonic metasurface that demonstrates significant optical activity (circular dichroism) in the near-infrared THz spectrum. The chirality which is an essential property to produce the optical activity is achieved by designing an asymmetric unit cell consisting of L-dipole silver nanostructure array. When an electromagnetic wave impinges on the 2D L-dipole array, localized surface plasmon modes originate on the metal-dielectric interface leading to strong disproportionate current distributions that radiate large cross-polarized electric field components. Consequently, interesting polarization state is obtained in the far field region. Full-wave electromagnetic simulations show an efficient circular polarization conversion between 200–261 THz frequency range for reflected and transmitted fields simultaneously. To further enhance the chirality, the unit cell is modified such that a smaller L-dipole is engraved in nested configuration. These two asymmetric nested metallic surfaces support mutually exclusive non-coupled current distributions leading to a substantially increase in the optical activity. Full-wave simulations suggest clear relation between the localized surface plasmon currents and the respective polarization states. Given the strong chiral effects demonstrated by the nanoplasmonic waveplate, we anticipate several novel designs by exploiting the underlying polarization control in the areas of optical imaging, sensing and display components.

Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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