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ABSTRACT
Polarization conversion devices are key components in spectroscopy and wireless communications systems. Conventional terahertz waveplates made of natural birefringent materials typically suffer from low efficiency, narrow bandwidth, and substantial thickness. To overcome the limitations associated with conventional waveplates, a terahertz quarter-wave metasurface with enhanced efficiency and wide bandwidth is proposed. The transmissive quarter-wave metasurface is rigorously designed based on an extended semi-analytical approach employing network analysis and genetic algorithm. Simulation results suggest that the design can achieve linear-to-circular polarization conversion with a 3-dB axial ratio relative bandwidth of 53.3%, spanning 205 GHz–354 GHz. The measurement results confirm that the proposed design enables a 3-dB axial ratio from 205 GHz to at least 340 GHz with a total efficiency beyond 70.2%, where the upper frequency bound is limited by the available experimental facility. This quarter-wave metasurface can cover an entire terahertz electronics band and can be scaled to cover other nearby bands under the same convention, which are technologically significant for future portable systems.

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I. INTRODUCTION
The terahertz spectral range defined between 0.1 THz and 10 THz presents a unique potential for diverse applications, including wireless communications,1 medical imaging,2 and substance identification.3 In order to harness the terahertz waves for those applications, various terahertz devices have been developed, such as modulators, filters, and antennas.4,5 Waveplates that alter the polarization state of incident beams provide additional degrees of freedom to manipulate the terahertz waves.

Birefringent materials such as crystalline dielectrics6,7 and wood provide distinct refractive indices to electric field components along two orthogonal directions, thus leading to different phase accumulations. By carefully controlling the thickness of a birefringent material, a prescribed phase difference between the two electric field components can be achieved at a given frequency. However, waveplates made of quartz using one single layer typically feature a narrow bandwidth of ~14.4% and significant reflection and absorption losses. The multi-layer quartz-based waveplate was presented to improve the relative bandwidth to 32% but exhibited a bulky configuration and an efficiency of merely 50%.11 Alternative wave-plate construction methods involving the effective medium theory13,14 or the form-birefringence methodology15,16 demand further efficiency and bandwidth enhancement. As a substitute, polarization conversions can be implemented by employing metasurfaces.

Metasurfaces formed by periodically arranged subwavelength resonators can be exploited to locally manipulate the amplitude, phase, and polarization state of waves in reflection or transmission. Metasurfaces have demonstrated their extraordinary electromagnetic properties in wavefront shaping7–20 and polarization control.21–24 More specifically relevant to this article, metasurfaces are also capable of providing designable birefringence to realize quarter-wave plates for conversion between linear and circular...
In the microwave engineering community, strip gratings were employed in a quarter-wave plate design with a limited 3-dB axial ratio relative bandwidth of 20%. A quarter-wave plate based on reactive impedance surfaces exhibited a relative bandwidth of 40%, but the six layers of metal would be prohibitively difficult to fabricate at terahertz frequencies. In the millimeter-wave region, a tri-layer quarter-wave plate exhibited a simulated 3-dB axial ratio fractional bandwidth of 40% and an efficiency above 59.2%. However, the quarter-wave plate design did not involve optimization algorithms, which leaves room for performance improvement. In the terahertz domain, split ring resonators and metal slots have been reported to realize linear-to-circular polarization conversion with an efficiency of 62% and 30%, respectively, requiring further efficiency improvement. In the optics region, waveplates typically show low transmittance resulting from the relatively high metal losses at optical frequencies.

In this work, we propose a broadband transmissive quarter-wave metasurface with enhanced efficiency. The proposed design targets coverage of the WR-3.4 waveguide frequency range from 220 GHz to 330 GHz, which is foreseen for terahertz point-to-point communications. The transmissive quarter-wave metasurface consists of three metallic layers separated by two dielectric spacers. Each metallic layer can be modeled as a parallel LC circuit along the x- or y-polarization, while the dielectric spacers are represented by transmission lines in the z-direction. Thus, a semi-analytical approach incorporating network analysis and genetic algorithm is implemented to optimize the quarter-wave metasurface. The network analysis investigates the scattering characteristics of the anisotropic metasurface, while the genetic algorithm as an optimization algorithm is employed to determine the optimal circuit parameters for the quarter-wave metasurface to achieve a low axial ratio and high transmission over a wide bandwidth. The quarter-wave metasurface is then physically realized by designing a particular pattern for each metallic layer, which reproduces the calculated optimal circuit parameters. It is worth mentioning that the extended semi-analytical approach employed in the quarter-wave metasurface design is capable of configuring transmissive metasurfaces for other functionalities.

II. DESIGN PRINCIPLE

Here, we design a transmissive quarter-wave metasurface that comprises three metallic layers separated by two dielectric spacers. Figure 1(a) illustrates a metasurface structure with identical top and bottom layers, and the two dielectric spacers having the same thickness. The induced currents on the middle layer generated by the \(-x\)-directed quasi-static magnetic field are canceled out due to the symmetric nature of the structure. As a result, the three metallic layers collectively interact with the electric field, while the magnetic response is shaped only by the top and bottom layers. Therefore, design priority is given to the top and bottom layers to manipulate the magnetic response first, while the middle layer is subsequently tailored for the electric response without affecting the magnetic field. Consequently, the electric and magnetic responses are controlled separately, and thus, each unit cell acts as a Huygens’ source that consists of crossed electric and magnetic dipoles of equal strength. Figure 1(b) depicts the electric fields generated by the electric and magnetic dipoles, where electric fields present equal strength and opposite signs in the \(z < 0\) space, but the same sign in the \(z > 0\) space.

In order to facilitate the design process and optimize the device performance, the quarter-wave metasurface is designed with the aid from an extended semi-analytical approach, which is based on the basis of the approach presented by Pfeiffer and Grbic. The extended approach implemented here involves network analysis combined with a genetic algorithm to determine the optimal frequency-independent circuit parameters so that the desired transmission coefficients can be achieved over a wide bandwidth. When the quarter-wave metasurface is illuminated by an incident wave that is linearly polarized at 45° with respect to the major principal axis, the x- and y-polarizations are equally excited. Hence, we can choose a pattern for each metallic layer that exhibits distinctive equivalent parallel LC circuit behaviors along the x- and y-axes. It should be noted that here, the equivalent parallel LC circuit is chosen as an illustrative example, and the metallic pattern could also be in other forms including equivalent series LC circuit or purely inductive or capacitive circuits. For simplicity, it is assumed that all materials employed are lossless at this stage. Based on the assumptions above, the admittance tensor of the ith metallic layer can be written as

![Figure 1](https://example.com/figure1.png)
where \( (L_{xi}, C_{xi}) \) and \( (L_{yi}, C_{yi}) \) are the pattern-equivalent inductance and capacitance along the \( x \)- and \( y \)-axes, respectively. The off-diagonal terms are equal to zero, indicating that there is no cross-coupling introduced by the pattern. Note that the analytical procedure presented by Pfeiffer and Grbic solved for the optimal admittance at the design center frequency.\(^{27,28}\) However, the optimal admittance at the frequency of interest can be physically realized by a vast number of \((L,C)\) combinations and hence diverse metallic patterns. Nevertheless, only very few metallic patterns are capable of providing a large bandwidth, enhanced efficiency, and high polarization purity performance. Hence, here, the frequency-dependent admittance at the design center frequency.

\[
Y_w = \begin{bmatrix}
\frac{1}{j\omega L_{xi}} + j\omega C_{xi} & 0 \\
0 & \frac{1}{j\omega L_{yi}} + j\omega C_{yi}
\end{bmatrix},
\]

(1)

The analytical solution can be readily calculated based on the equivalent inductances and capacitances of each metallic layer. Conversely, a stipulated \( S \)-parameter specification can be obtained by implementing the genetic algorithm to determine the required circuit parameters.

To achieve circular polarization with high efficiency and high purity, the quarter-wave metasurface requires near-units admittances for the two orthogonal electric field components, i.e., \( |S_{21}^{xy}| = 1 \) and a constant quadrature phase difference between them, i.e., \( \angle S_{21}^{xx} - \angle S_{21}^{yy} = 90^\circ \). The possible range for the inductance and capacitance within a certain unit cell size is estimated based on the simulations of metallic patterns with equivalent parallel LC circuits along the \( x \)- and \( y \)-polarizations. Considering the feasibility for fabrication of a dielectric spacer and the assumption of negligible evanescent modes, a spacer thickness range from 100 \( \mu \)m to 200 \( \mu \)m is specified for the targeted frequency range between 220 GHz and 330 GHz. With the constraints identified, a cost function is assigned in the genetic algorithm to find the optimal \((L_{xi}, C_{xi}, L_{yi}, C_{yi})\) for the \( i \)-th metallic layer and the desired thickness \( d \) for the dielectric spacers, with the aim of satisfying the objectives over a wide bandwidth. More specifically, the genetic algorithm starts from an initial group that consists of various individuals with genes formed by circuit parameters. Since the circuit parameters implemented here are frequency-independent, the scattering characteristics of the metasurface then can be numerically investigated over the frequency range of interest using Eqs. (1)-(3). Thus, the fitness of each parameter set is evaluated based on its scattering characteristics using the cost function. As such, the optimal circuit parameters are eventually selected to collectively achieve a transmission performance that closely approximates the objectives over the targeted frequency band.

### III. RESULTS

Table I shows the calculated optimal inductances and capacitances for the quarter-wave metasurface provided by the outlined extended semi-analytical approach, while the thickness of each dielectric spacer is found to be \( d = 195 \mu \)m. Once the optimal set of \((L_{xi}, C_{xi}, L_{yi}, C_{yi})\) is determined for the \( i \)-th metallic layer, a search for the corresponding physical structure is then conducted by designing a specific pattern to meet the optimal circuit parameters. Electromagnetic simulations are performed with the commercial software ANSYS HFSS. Figures 2(a) and 2(b) show the simulation settings to design each layer in the unit cell, where master–slave boundary conditions are employed in the transverse plane to imitate infinite periodicity. In order to avoid diffraction, a lattice constant of 540 \( \mu \)m is chosen, which corresponds to 0.5\( \lambda_0 \) at the design center frequency of 275 GHz. Floquet ports are

| Top/bottom layer | Middle layer |
|------------------|--------------|
| \( x \)-axis     | \( x \)-axis |
| \( y \)-axis     | \( y \)-axis |
|\( L_{x1} \) | \( C_{x1} \) | \( L_{x2} \) | \( C_{x2} \) |
|\( 170.5 \) 0.9 | 265.6 1.9   | \( 123.1 \) 0.7 | 212.6 2.7 |

Table I. Calculated optimal inductances and capacitances based on the extended semi-analytical approach. The units for inductances and capacitances are \( \mu \)H and \( \mu \)F, respectively.
FIG. 2. Electromagnetic simulation settings for the physical realization of each metallic layer and geometry of the unit cell. (a) Top and bottom layer realizations and (b) middle layer realization. The top and bottom layers are at the interface between air and dielectric spacer, while the middle layer is hosted in between the dielectric spacers. The arrows indicate port de-embedding for phase compensation. (c) Unit cell 3D view, (d) top and bottom layers, and (e) middle layer. The top and bottom layers are identical to enhance the metasurface efficiency.

implemented to impose normally incident plane waves and also to collect the scattered waves. The Floquet ports are de-embedded to the metallic layer surface to acquire the intrinsic surface response independently from propagation effects in the media. In order to reduce the material losses, gold is utilized for the metallic layers and ultra-low loss cyclic olefin copolymer (COC) is applied for the dielectric spacers. The surface impedance of gold at terahertz frequencies is described by a Drude model, while the COC dielectric spacer shows a relative permittivity of \( \varepsilon_r = 2.33 \) and loss tangent of \( \tan \delta = 0.0005 \) from 220 GHz to 330 GHz.

To realize each metallic layer, the simulation starts from a pattern with arbitrary dimensions, but its equivalent circuits along the \( x \)- and \( y \)-axes are predominately parallel LC circuits. The pattern is then evolved to reproduce the optimal circuit parameters provided by the extended semi-analytical approach. The metallic pattern equivalent inductance and capacitance along the \( x \)- or \( y \)-polarization can be calculated based on the simulated admittances. For each metallic layer, the corresponding admittance tensor can be extracted from the simulated reflection coefficients by

\[
Y_s = \left[ \frac{1 - S_{11}}{\eta_1} - \frac{1 + S_{11}}{\eta_2} \right] \left[ 1 + S_{11} \right]^{-1},
\]

where \( \eta_1 \) and \( \eta_2 \) are the wave impedances of the adjoining media. Hence, for each metallic layer and each polarization, the two unknowns of \( (L, C) \) can be analytically solved by retrieving the \( Y \)-parameters at two different frequencies. The equivalent inductance and capacitance are then compared with the optimal values from the semi-analytical approach, and the metallic pattern is altered accordingly until the obtained simulated values match the optimal ones. Note that the physical realizations of the top and middle layers are carried out separately.

Figures 2(c), 2(d), and 2(e) plot the 3D structure of a quarter-wave metasurface unit cell. As mentioned, the top and bottom metallic layers are identical to enhance the efficiency, while the equivalent circuit of each metallic layer under the \( x \)- or \( y \)-polarization is basically a parallel LC circuit as implemented in the extended semi-analytical approach. Detailed dimensions of the structure are illustrated in Table II. Notably, a strip width of 4 \( \mu m \) \( (w_{t1} = w_{m1} = 2 \mu m) \) is desired at the unit cell borders to provide the optimal equivalent inductance under the \( y \)-polarization. Simulations suggest that the metasurface exhibits a large tolerance to the strip width variation

| Parameter | Value | Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|-----------|-------|
| \( a \)   | 540   | \( w_{t3} \) | 101   | \( l_{m3} \) | 49    |
| \( d \)   | 195   | \( g_{t1} \) | 10    | \( w_{m3} \) | 20    |
| \( h_1 \) | 47    | \( g_{t2} \) | 111   | \( l_{m4} \) | 198   |
| \( w_{t1} \) | 2   | \( i_{m1} \) | 50    | \( w_{m4} \) | 10    |
| \( h_2 \) | 54    | \( w_{m1} \) | 2     | \( g_{m1} \) | 5     |
| \( w_{t2} \) | 108 | \( l_{m2} \) | 18    | \( g_{m2} \) | 199   |
| \( h_3 \) | 216   | \( w_{m2} \) | 60    | \( g_{m3} \) | 209   |

TABLE II. Detailed dimensions of the quarter-wave metasurface unit cell. The units are in \( \mu m \).
up to \( w_{\text{z}} = w_{\text{z}_{\text{opt}}} = 10 \, \mu\text{m} \). Figures 3(a) and 3(b) show the transmission coefficients of the quarter-wave metasurface as calculated using the extended semi-analytical approach and the 3D full-wave simulation. Since the calculation does not account for near-field coupling, the close agreement between the simulation and calculation results implies negligible coupling effects. Within the frequency range of interest from 220 GHz to 330 GHz, the maximum simulated insertion losses for the \( x \)- and \( y \)-polarizations are 1.45 dB and 1.04 dB, respectively, while the phase difference between the two components remains close to 90°. Moreover, simulations reveal that the reflection magnitudes for the \( x \)- and \( y \)-polarizations from 220 GHz to 330 GHz are less than \(-5.75\) dB and \(-7.41\) dB, respectively. Thus, the metasurface power loss is mainly contributed from reflections instead of material losses. However, the material losses considered in the simulation together with the deviation between the optimal and obtained equivalent inductances and capacitances collectively contribute to the discrepancy between the calculated and simulated results. Further simulations shown in supplementary A (supplementary material) suggest that the proposed design is relatively insensitive to tolerances in spacer thickness, as the relatively large electrical spacing between the metallic layers leads to a negligible near-field coupling. It is found that an axial ratio below 1.7 dB and a total efficiency above 64.6% can be maintained over the desired frequency band from 220 GHz to 330 GHz when the spacer thickness deviates by \( \pm 20.5\% \).

The complex transmission coefficients presented by the semi-analytical approach and the 3D full-wave simulation suggest that the quarter-wave metasurface realizes linear-to-circular polarization conversion upon transmission. In order to rigorously quantify the performance of the quarter-wave metasurface, the axial ratio of the transmitted wave is evaluated. The axial ratio refers to the ratio of the major axis to the minor axis of the transmitted wave polarization ellipse, which can be written as

\[
\text{AR} = \frac{E_{\parallel}^2 + E_{\perp}^2}{E_{\parallel}^2 - E_{\perp}^2} = \frac{E_{\parallel}^2 + E_{\perp}^2 + 2E_{\parallel}E_{\perp}\cos(2\Delta\phi)}{E_{\parallel}^2 + E_{\perp}^2 - 2E_{\parallel}E_{\perp}\cos(2\Delta\phi)} \left( \frac{1}{2} \right),
\]

where \( E_{\parallel} = |S_{21}^x| \) and \( E_{\perp} = |S_{21}^y| \) are the transmission amplitudes of the \( x \)- and \( y \)-polarizations, respectively, and \( \Delta\phi = \angle S_{21}^x - \angle S_{21}^y \) is the phase difference between them. It is possible to relate the axial ratio to the extinction ratio and the detailed derivation is shown in supplementary B (supplementary material). It is noted that the commonly used 3-dB axial ratio criterion corresponds to an extinction ratio of \( \sim 15 \) dB. To further evaluate the metasurface polarization conversion performance, the Stokes parameters of the transmitted wave is calculated using

\[
S_0 = |E_{\parallel}|^2 + |E_{\perp}|^2, \\
S_1 = |E_{\parallel}|^2 - |E_{\perp}|^2, \\
S_2 = 2|E_{\parallel}||E_{\perp}|\cos(\Delta\phi), \\
S_3 = 2|E_{\parallel}||E_{\perp}|\sin(\Delta\phi).
\]

The output wave ellipticity is defined as \( \chi = S_3/S_0 \), where \( \chi = 1 \) indicates an ideal left-handed circularly polarized (LHCP) output wave, while \( \chi = -1 \) denotes a perfect right-handed circularly polarized (RHCP) output wave. Figures 3(c) and 3(d) depict the axial ratio, extinction ratio, and ellipticity of the transmitted wave obtained from the semi-analytical approach and simulation, revealing that a simulated 3-dB axial ratio fractional bandwidth of 53.3% can be sustained over a frequency range extending from 205 GHz to 354 GHz. Additionally, the simulated ellipticity from 220 GHz to 330 GHz is beyond 0.99, while the axial ratio remains lower than 1.21 dB that corresponds to an extinction ratio above 23.16 dB.
Images of the fabricated free-standing prototype are given in Fig. 4 and a slight top layer misalignment can be seen from Fig. 4(b), where the top layer is shifted $-24 \mu m$ (4% of the unit cell size) along the $x$-axis and $48 \mu m$ along the $y$-axis relative to the middle and bottom layers. Simulation results suggest that the quarter-wave metasurface is robust to the slight top layer shift (see supplementary C of the supplementary material). The fabrication process is detailed in supplementary D (supplementary material), and it is also available in our previously reported linear polarization rotator design, which converts the linearly polarized incident waves to its orthogonal counterpart. To validate its performance, the manufactured quarter-wave metasurface is characterized using a Keysight Precision Network Analyzer (PNA) together with VDI WR-3.4 Extension Modules. We configure the extension modules so that they operate from 205 GHz to 340 GHz, which is beyond their typical frequency coverage of 220 GHz–330 GHz. As illustrated in Fig. 5(a), a vertically polarized incident wave is collimated by Lens 1 and then focused onto the sample after propagating through Lens 2. Lens 3 collimates the transmitted wave, while Lens 4 focuses the collimated wave onto the receiver. As a result, the fabricated sample with a size of $50 \times 50 \text{ mm}^2$ is illuminated by the incident beam with a focal spot of $\sim 1 \text{ mm}$ in diameter. In addition, the Rayleigh range of the incident beam equals 0.72 mm at the design center frequency of 275 GHz, and the three metallic layers are therefore included inside of the Rayleigh range of the focused beam. Thus, a normally incident plane wave illumination is assumed over the entire measurement.
frequency range. The employed WR-3.4 metallic waveguides have a length of 25.4 mm, and in this waveguide, the cross-polarized wave manifested as the TE_{01} mode is below its cutoff frequency. As a consequence, no polarizers are required to screen the cross-polarization component that experiences an attenuation of 31 dB/mm at 300 GHz in this waveguide. The transmission coefficients of the quarter-wave metasurface under the x- and y-polarizations are measured separately by rotating the sample. As a reference, a measurement is taken without the presence of sample.

Figures 5(b) and 5(c) depict the simulated and measured transmission coefficients of the quarter-wave metasurface, where a good agreement is confirmed. The measured results reveal that the maximum transmission loss is limited to 1.75 dB, and the phase difference between the x- and y-polarizations remains very close to 90°, leading to an axial ratio below 3 dB, an extinction ratio beyond 15 dB, and an ellipticity above 0.94 from 205 GHz to 340 GHz, as shown in Figs. 5(d) and 5(e), respectively. More specifically, the measured axial ratio from 220 GHz to 330 GHz is lower than 1.25 dB that corresponds to a measured extinction ratio beyond 22.88 dB, while the measured ellipticity is above 0.99. The maximum frequency in the measurements is constrained by the available characterization facility, but a general agreement with the simulation results is expected. The slight deviations between the measured and simulated results can be attributed to the unavoidable fabrication and experiment tolerances, the former of which could be dominant as suggested by further simulations. Moreover, Fig. 5(f) illustrates the total efficiency of the proposed design, accounting for the total transmittance of the x- and y-polarizations, i.e., ((S_{xx}^2 + S_{yy}^2)/2. The simulated total efficiency from 205 GHz to 354 GHz is beyond 77.4%, while the measured total efficiency from 205 GHz to 340 GHz is above 70.2%, corresponding to a measured insertion loss below 1.54 dB. Additional simulations shown in supplementary E (supplementary material) reveal that an axial ratio below 2.2 dB from 220 GHz to 330 GHz can be effectively maintained up to an incidence angle of 10° in the xoz and yoz incident planes, but the corresponding simulated total efficiencies decrease to 72.7% and 62.6%, respectively. It is noted that the 45° polarized incident wave with respect to the x-axis gives LHCP output waves. RHCP waves can be obtained by rotating this structure by 90° around the z-axis. Importantly, the measured results further confirm that the proposed design is robust to the metallic layer shift, which is not uncommon in microfabrication of multilayer structures.

A performance comparison of the proposed work with notable existing designs from the literature is given in Table III. To simplify the comparison, a figure of merit is included to quantify the bandwidth and total efficiency collectively. It can be seen that the existing designs exhibit a modest figure of merit. In general, microwave-based quarter-wave plates basically show a higher figure of merit than those at terahertz frequencies as a result of a relatively low material loss and ease of fabrication at microwave frequencies. In the terahertz domain, most reported waveplates have limited bandwidth or efficiency, resulting in a remarkably low figure of merit. Comparing with the existing quarter-wave plates, our proposed design involves a systematic optimization methodology and provides an advantageous bandwidth, efficiency, and figure of merit. Importantly, the design can cover a full WR-3.4 waveguide frequency band from 220 GHz to 330 GHz, which is technologically significant and foreseen for terahertz point-to-point communications. Despite the restrictions in material and fabrication, the bandwidth and total efficiency of the metasurface are the highest among other broadband terahertz quarter-wave plates. In addition, a high output wave polarization purity with an axial ratio lower than 1.25 dB is achieved within the frequency band of interest. The metasurface bandwidth and efficiency enhancement can be attributed to the optimal frequency-independent circuit parameters provided by the extended semi-analytical approach, which can deliver a constant quadrature phase difference and high transmittances for the two orthogonal electric field components over a wide bandwidth. In addition, the tri-layer metasurface manipulates the electric and

| Structure                  | Metallic layers | Spacer material | Center frequency (GHz) | Bandwidth (AR < 3 dB) (%) | Minimum efficiency (%) | FoM (%) |
|----------------------------|-----------------|-----------------|------------------------|---------------------------|------------------------|---------|
| Microwave-based            |                 |                 |                        |                           |                        |         |
| Meander line and loop      | 1               | Duroid 5880     | 24                     | 47                        | 50                     | 24      |
| Cross strips               | 2               | Taconic TLY-5   | 24                     | 74                        | 47                     | 35      |
| Strip gratings             | 5               | Duroid 5880     | 27                     | 20                        | 93                     | 19      |
| Reactive surfaces          | 6               | Duroid 6010     | 10                     | 40                        | 74                     | 30      |
| Terahertz-based            |                 |                 |                        |                           |                        |         |
| Split slot ring            | 1               | Silicon         | 325                    | 12                        | 45                     | 5       |
| Metal slots                | 1               | PEN             | 870                    | 5                         | 30                     | 2       |
| Metal gratings             | 2               | Polyimide       | 1180                   | 44                        | 42                     | 19      |
| Split ring resonators      | 2               | BCB             | 980                    | 12                        | 62                     | 7       |
| This work                  | 3               | COC             | 280                    | 53                        | 70                     | 37      |
magnetic dipoles separately, further contributing to the efficiency improvement that cannot be achieved by the single- and bi-layer designs, as presented in Table III.

IV. CONCLUSION

A broadband terahertz quarter-wave plate that allows linear-to-circular polarization conversion is constructed on the basis of metasurfaces. The device is developed and optimized using an extended semi-analytical approach that targets broadband and high-efficiency performance. A measured axial ratio of less than 3 dB can be sustained from 205 GHz to at least 340 GHz, where the highest frequency is limited by the measurement facility. In addition, the proposed design demonstrates its robustness to the metallic layer misalignments. A misaligned fabricated prototype with its top layer shifted −4% of the unit cell size along the x-axis and 8% of the unit cell size along the y-axis shows a close transmission performance with the aligned structure. As such, the proposed metasurface relaxes the fabrication requirements at terahertz frequencies. The extended semi-analytical approach can be readily implemented to design various bandwidth-enhanced transmissive metasurfaces for wavefront control and polarization manipulation.

SUPPLEMENTARY MATERIAL

See the supplementary material for further details.

AUTHORS’ CONTRIBUTIONS

X.Y. and R.T.A. contributed equally to this work.

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DATA AVAILABILITY

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

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