A Broadband, Background-Free Quarter-Wave Plate Based on Plasmonic Metasurfaces

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Supporting Information

ABSTRACT: We demonstrate optically thin quarter-wave plates built with metasurfaces that generate high-quality circularly polarized light over a broad wavelength range for arbitrary orientation of the incident linear polarization. The metasurface consists of an array of plasmonic antennas with spatially varying phase and polarization responses. Experimentally demonstrated quarter-wave plates generate light with a high degree of circular polarization (>0.97) from λ = 5 to 12 μm, representing a major advance in performance compared to previously reported plasmonics-based wave plates.

KEYWORDS: Plasmonics, optical antenna, metasurface, wave plate, broadband

Considerable attention has been drawn to the properties of anisotropic metallic and dielectric structures, which can mimic the polarization-altering characteristics of naturally occurring birefringent and chiral media. Subwavelength gratings introduce form birefringence and have been used to make quarter-wave plates for infrared and submillimeter waves.1–3 Planar chiral metasurfaces change the polarization state of transmitted light.4–9 Circular polarizers based on threedimensional chiral metamaterials primarily pass light of circular polarization of one handedness, while the transmission of light of the other handedness is suppressed (circular dichroism).10–11 Because of the difficulty of fabricating thick chiral metamaterials, the demonstrated suppression ratio between circular polarizations of different handedness is quite small (<10). One way to overcome this difficulty is to use planar structures comprising strongly scattering anisotropic particles that are able to abruptly change the polarization of light. Light scattered from such particles changes polarization because the particles have different spectral responses along the two principle axes.12–23 For example, planar plasmonic wave plates have been created using arrays of identical rod or aperture metallic antennas24–30 or meander-line structures.31–35 These types of quarter-wave plates are designed by controlling the spectral responses of the plasmonic eigenmodes so their scattered waves have equal amplitudes and a π/2 phase difference at the excitation wavelength. This is achieved, for example, by tuning the length of orthogonally oriented dipolar antennas,24–30 or by adjusting the inductive and capacitive impedance along the two axes of the meander-line structures.31–33

These planar wave plates have a number of shortcomings. For example, their bandwidth is limited because of the relatively narrow resonance of the plasmonic eigenmodes. Once the structures operate away from the optimal wavelength, the amplitude ratio R between the two eigenmodes deviates from unity, and their differential phase Ψ is no longer π/2 (Figure 1a). Another limitation is that the performance of plasmonic wave plates is usually degraded by the optical background that originates from direct transmission through the empty space around the metallic structures (e.g., cross antennas or meander-lines).

In this Letter we have realized metasurfaces based on phased antenna arrays that generate scattered light waves with arbitrary polarization states. In particular, we demonstrated a quarter-wave plate that features ultrabroadband and background free performance and works for any orientation of the incident linear polarization. We have previously used metasurfaces consisting of phased antennas to demonstrate generalized laws of reflection and refraction34,35 and to generate optical vortex beams.36 Note that our metasurfaces were designed to operate in the mid-infrared wavelength range, where we primarily use plasmonic effects associated with geometry instead of those associated with the intrinsic properties of metals.

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The basic elements in our metasurface design are gold V-shaped antennas. Each antenna supports symmetric and antisymmetric eigenmodes, which are excited by the components of the incident electric field polarized parallel and perpendicular to the symmetry axis of the V-structure, respectively (Figure 2a, insets).34,37,38 For arbitrary incident polarization, both modes are excited and contribute to the antenna scattering response. The scattered waves from the eight antennas in a subunit can be written as (see the Supporting Information for derivation):

\[
\begin{align*}
\vec{E}_1 &= S_1 - A_1 \\
\vec{E}_2 &= S_2 - A_2 \\
\vec{E}_3 &= S_3 - A_3 \\
\vec{E}_4 &= S_4 - A_4 \\
\vec{E}_5 &= -(S_1 - A_1) \\
\vec{E}_6 &= -(S_2 - A_2) \\
\vec{E}_7 &= -(S_3 - A_3) \\
\vec{E}_8 &= -(S_4 - A_4)
\end{align*}
\]

\[
\begin{align*}
\sin^2(\gamma) &= \frac{1}{2} \left( \cos(2\beta - \alpha) \hat{y} + \sin(2\beta - \alpha) \hat{x} \right) \\
\cos^2(\gamma) &= \frac{1}{2} \left( \cos \alpha \hat{y} + \sin \alpha \hat{x} \right)
\end{align*}
\]

Here \(\alpha\) and \(\beta\) are the orientation angles of the incident field and the antenna symmetry axis, respectively; \(\hat{x}\) and \(\hat{y}\) are the unit vectors along the \(x\)- and \(y\)-axes, respectively (Figures 3a and b); \(S_i\) and \(A_i\) are the complex scattering amplitudes of the symmetric and antisymmetric mode of the \(i\)th antenna in the subunit, respectively (Figure 2a). Equation 1 shows that the scattered light from the antennas \(\vec{E}_i\) with \(i = 1\cdots8\) contains two terms, which are polarized along the \((2\beta-\alpha)\)-direction and the \(\alpha\)-direction of the \(y\)-axis, respectively. The antenna array is designed so that at \(\lambda = 8\ \mu\text{m}\) the \((2\beta-\alpha)\)-polarized components of all of the antennas have the same amplitude and...
same wavefronts (compare the dashed curves in the upper and lower panel of b). Variations. Even in this nonideal situation, however, one still obtains an extraordinary beam with close-to-unity degree of circular polarization and high intensity. However, at wavelengths of 8 and 5 μm, as a result of the combined responses (i.e., S − A as compared to S or A), our metasurface quarter-wave plates can provide significant scattering efficiency over a broader wavelength range, as is shown in the upper panel of a. The combined plasmonic resonances can also provide a larger coverage in the phase response (i.e., ~1.5π for S − A as compared to ~0.75π for S or A), as shown in the lower panel of a. (b) Calculated phase and amplitude responses along the antenna array. Responses for two consecutive subunits are shown (i.e., antennas 9–16 are identical to antennas 1–8). Pink and green curves are for the first and second subunits, respectively; solid and dashed curves are for excitation wavelengths of 8 and 5 μm, respectively. As designed, the phase response at λ = 8 μm exhibits an almost constant gradient (i.e., 2π over 8 antennas in the subunit); however, the amplitude response at this wavelength is quite uniform. These properties correspond to an extraordinary beam with a flat wavefront and high intensity. However, at λ = 5 μm the phase response does not follow a perfect linear profile, and the amplitude response shows large variations. Even in this nonideal situation, however, one still obtains an extraordinary beam with close-to-unity degree of circular polarization (but with reduced intensity) because the waves scattered from the two subunits always give equal contributions to the beam since they have exactly the same wavefronts (compare the dashed curves in the upper and lower panel of b).

Figure 2. (a) Amplitude and phase responses of S, A, and S − A for a representative V-antenna obtained by full-wave simulations; here S and A represent the complex scattering amplitudes of the symmetric and antisymmetric eigenmodes, respectively. The arm length of the V-antenna is 1.13 μm and the angle between the two arms is 90°. This is the second antenna from the left in a given subunit (Figure 3a). The two current eigenmodes of the antenna are shown in the insets. The arrows refer to the direction of current flow, and the colors represent current density, with darker colors representing larger currents. The scattered light from the antenna can be decomposed into two components (i.e., S − A or S + A). By properly designing the phase and amplitude responses of these components in the antenna arrays, we can spatially separate them so that (S + A) and (S − A) lead to, respectively, the ordinary and extraordinary beams propagating in different directions. Because of the much broader effective plasmonic resonance as a result of the combined responses (i.e., S − A as compared to S or A), our metasurface quarter-wave plates can provide significant scattering efficiency over a broader wavelength range, as is shown in the upper panel of a. The combined plasmonic resonances can also provide a larger coverage in the phase response (i.e., ~1.5π for S − A as compared to ~0.75π for S or A), as shown in the lower panel of a. (b) Calculated phase and amplitude responses along the antenna array. Responses for two consecutive subunits are shown (i.e., antennas 9–16 are identical to antennas 1–8). Pink and green curves are for the first and second subunits, respectively; solid and dashed curves are for excitation wavelengths of 8 and 5 μm, respectively. As designed, the phase response at λ = 8 μm exhibits an almost constant gradient (i.e., 2π over 8 antennas in the subunit); however, the amplitude response at this wavelength is quite uniform. These properties correspond to an extraordinary beam with a flat wavefront and high intensity. However, at λ = 5 μm the phase response does not follow a perfect linear profile, and the amplitude response shows large variations. Even in this nonideal situation, however, one still obtains an extraordinary beam with close-to-unity degree of circular polarization (but with reduced intensity) because the waves scattered from the two subunits always give equal contributions to the beam since they have exactly the same wavefronts (compare the dashed curves in the upper and lower panel of b).

an incremental phase of ΔΦ = π/4. That is, |S - A| is constant, with i = 1–4, and Phase (S_{i+1} - A_{i+1}) = Phase (S_i - A_i) = π/4, with i = 1–3 (Figure 2b). Therefore the (2β-α)-polarized partial waves scattered from the antenna array produce a wave propagating along the direction (i.e., α and β are the polar angles of the E-vector relative to the surface normal) and the length of the subunit. On the other hand, the α-polarized components, which have the same polarization as the incident light, have unequal amplitudes but similar phase responses (Supporting Information). Therefore, the α-polarized partial waves combine to form a wave that propagates in a direction normal to the metasurface for normally incident light and contributes to the ordinary beam.

The metasurface quarter-wave plate has a unit cell consisting of two subunits that are offset from each other in the horizontal direction by d (Figure 3a). They create two coherent waves that propagate along the direction (direction (Figure 1b)). The waves spatially overlap since the spacing between the two subunits in the y-direction is much smaller than the free-space wavelength (Figure 3a). The waves have equal amplitudes because the corresponding antennas in the two subunits have the same geometries (i.e., arm length and opening angle of the V-structures). Cross-polarization between the waves is achieved by choosing antenna orientations β_1 = 67.5° and β_2 = 112.5° so that (2β_2 - β_1) = 90° (Figure 3a and b). As a result of these properties, the waves scattered from the two subunits coherently interfere, producing a circularly polarized extraordinary beam (Figure 1b). Note that once β_2 - β_1 = 45°, the two waves will always be cross-polarized, which is independent of the orientation angle α of the linearly polarized incident light.

Our optical antenna arrays can provide phase coverage from 0° to 360° with an increment of ~45° over a wide range of wavelengths (Figure S1a in the Supporting Information). Therefore, the metasurface quarter-wave plates can generate well-defined extraordinary beams over a broad spectral range. Figure 3c shows experimental far-field scans at excitation wavelengths from 5.2 to 9.9 μm. Three samples with Γ = 13, 15, and 17 μm have been tested. For all samples and excitation wavelengths, we observe the ordinary and extraordinary beams and negligible optical background. The observed angular
positions of the extraordinary beams agree very well with the generalized law of refraction in the presence of the interfacial phase gradient, $\theta = \arcsin(\lambda/\Gamma)$ (Figure 3c). At 8 μm, close to the optimal operating wavelength, our metasurfaces scatter approximately 10% of the incident light into the extraordinary beam. The power dissipated in the antenna structures due to absorption is about 10% of the incident power.

Figure 3d shows the phase difference $\Psi$ and amplitude ratio $R$ between the two waves scattered from the subunits, as calculated via full-wave numerical simulations using the finite difference time domain (FDTD) method. It is observed that $\Psi$ and $R$ are in the close vicinity of 90° and 1, respectively, over a wide wavelength range from $\lambda = 5$ to 12 μm; correspondingly, a high degree of circular polarization (DOCP) close to unity can be maintained over the wavelength range (Figure 3e). Here DOCP is defined as $I_{LCP} - I_{RCP}/I_{LCP} + I_{RCP}$, where $I_{RCP}$ and $I_{LCP}$ stand for the intensities of the right and left circularly polarized components in the extraordinary beam, respectively.35

We observed in experiments that the extraordinary beam is circularly polarized with high purity between $\lambda = 5$ and 10 μm (Figure 3f). The experimentally demonstrated suppression ratio between $I_{RCP}$ and $I_{LCP}$ is $\sim$500, 700, and 400 at $\lambda = 9.9$, 8, and 5.2 μm, respectively. The extraordinary beam reaches its peak intensity at $\lambda \approx 7$ μm (Figure 3e). The intensity decreases toward longer and shorter wavelengths because the $S-A$ components of the scattered light from the antenna arrays start to have mismatched amplitudes and a nonlinear phase distribution. We define the bandwidth of a quarter-wave plate $\Delta \lambda_{qc}$ as the wavelength range over which DOCP is sufficiently close to 1 (e.g., $>0.95$) and an output with high intensity can be maintained (e.g., intensity larger than half of the peak value). According to this definition, the bandwidth of our metasurface quarter-wave plates is about 4 μm (i.e., from $\lambda \approx 6$ to 10 μm; see Figure 3e), which is about 50% of the central operating wavelength $\lambda_{central}$.

We have verified that the intensity and propagation direction of the extraordinary beam is independent of the orientation of the incident linear polarization (Figure 4a). The extraordinary beam maintains a high DOCP when the incident polarization changes (Figure 4b). The polarizations of the waves scattered from the two subunits are controlled by angles $\alpha$, $\beta_1$, and $\beta_2$, and their amplitudes are controlled by the scattering amplitudes, $S$ and $A$, of the antenna eigenmodes (eq 1). This decoupling between polarization and amplitude allows us to synthesize beams with arbitrary polarization states. In addition to circularly polarized beams (Figure 3), we were able to generate elliptically polarized extraordinary beams by simply changing the subunit offset $d$ (Figure 5). For example, when $d = 1\Gamma/8$ (or $3\Gamma/8$), the two waves scattered from the subunits have perpendicular polarization, equal amplitudes, and a phase difference $\Psi = \pi/
4 (or $3\pi/4$), thus forming an elliptically polarized beam. The state-of-polarization analysis of the beam shown in Figure 5b is in good agreement with analytical calculations.

Our metasurface design has a few limitations. First, it is inherently dispersive. The circularly polarized extraordinary beams created at different wavelengths propagate in different directions according to $\theta_t = \arcsin(\lambda/\Gamma)$. Second, the efficiency of the metasurface quarter-wave plate is not high. In addition to the circularly polarized extraordinary beam in transmission, which carries about 10% of the incident power, there are ordinary reflection and refraction, as well as a second extraordinary beam in reflection created by the phased antenna array. The efficiency can be increased by using denser antenna arrays or by exploiting antenna designs with higher scattering amplitude. For example, reflect-array structures consisting of phased antennas separated by a dielectric space layer from a metallic back plane are able to shape the wavefront of reflection with high efficiency.39

Wave plates are some of the most ubiquitous components in optics. Most commonly used designs are based on bulk birefringent crystals with optical anisotropy. This conventional approach has several limitations: it is relatively narrow band, and it relies on the availability of birefringent materials in the desired frequency range. Approaches exist to overcome the latter limitation, which utilize form birefringence of anisotropic structures such as plasmonic antennas. These come with their own limitations; in particular, they exhibit relatively low purities of polarization and often superimpose an optical background onto the desired signal. In addition, the bandwidth of these devices is also relatively small. Our approach, which involves spatially inhomogeneous arrays of anisotropic optical antennas, overcomes many of these limitations. We experimentally demonstrated quarter-wave plates, which are broadband and feature high polarization purity (e.g., output with DOCP larger than 0.97 over $\lambda = 5$ to 12 $\mu$m, and with intensity larger than half-maximum over $\lambda = 6$ to 10 $\mu$m). This approach requires only a single step of conventional lithography and is generalizable from the visible to the radio frequency regimes.

**ASSOCIATED CONTENT**

3 Supporting Information

Fabrication, derivation of the scattered waves from the eight antennas, broadband performance of V-antennas, Table 1, and
Figure S1. This material is available free of charge via the Internet at http://pubs.acs.org.

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**Notes**
The authors declare no competing financial interest.

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