Analytical full complex-amplitude control strategy for metasurface

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Abstract
We proposed a meta-atom design strategy that can achieve full complex-amplitude modulation based on analytical method for circularly polarized waves. The meta-atom can be regarded as two cascaded quarter wave plates, the orientation angles of which provide two degrees of freedom for obtaining arbitrary amplitude and phase modulation through accurate analytical method. As verification, a microwave meta-atom is designed and used to realize lateral and axial dual focusing. The proposed design strategy provides a straightforward route for full, continuous control of both amplitude and phase, and can stimulate various advanced meta-devices.

1. Introduction
Metasurface has attracted great interest due to the paradigm it presents that unprecedented manipulation over electromagnetic waves along with novel functionalities, such as abnormal transmission and reflection [1, 2], perfect conversion of propagating waves to surface waves [3], flat lensing [4–6], vortex beam generation [1, 7], holography [8], can be implemented by assembling meta-atom in a two-dimensional array. The crux of meta-surface lies on the control of scattering features of meta-atom, namely, the phase, amplitude, polarization and their combinations. Recently, lots of efforts have been made to realize simultaneous amplitude and phase control. Compared to phase-only metasurfaces, full complex-amplitude modulation enables various advanced functionalities, such as quality enhanced hologram [9–16], customized radiation pattern shaping [17–22], radar cross section reduction [23], power control over different diffraction order [24], full polarization cloak [25, 26] and so on. By exploiting combination of degrees of freedom of the meta-atom such as size, orientation, position, etc, and even introducing multiple degrees of freedom through complex array [11] or introducing lossy components to absorb unwanted energy [27], various approaches have been proposed to realize full complex-amplitude modulation. However, it is still highly desirable to find an accurate and universal design strategy to realize full complex-amplitude modulation on meta-atom level. Huygens’ metasurfaces with simultaneous electric and magnetic responses can be utilized for high efficiency complex-amplitude modulation [28]. However, the meta-atom design is quite complicated and without a simple and general modulation rule.

The orientation of meta-atom is an excellent degree of freedom for amplitude and phase modulation. For mirror symmetrical meta-atoms that could convert linearly polarized (LP) wave to its orthogonal polarization state, the amplitude of cross-polarization transmission component is rigorously proportional to the sine of twice of the rotation angle. Such feature has been utilized for exotic application like Airy beam generation [29–31]. However, as only binary phase can be obtained, additional optimization on the size of...
Figure 1. (a) Schematic of two cascaded QWPs with different orientations. The red arrow labeled with ‘S’ denotes the slow axis direction; (b) the corresponding polarization evolution path on the Poincaré sphere.

meta-atom is needed to achieve full phase control and implement synthesis of complex wave front [15–17, 19–21, 24, 32]. On the other hand, the geometric Pancharatnam–Berry (PB) phase provides an analytical phase modulation approach with single meta-atom [5–8, 33]. The additional geometric phase introduced is equal to twice of the rotation angle, leaving the amplitude of the transmitted wave unchanged. So geometrical dimensions optimizing is further needed to achieve the amplitude control [14, 34]. Usually, the modulation through the size of meta-atom cannot be simply scaled to other frequency range and obtain universal modulation rule. Recently, it has been reported that the X-shaped meta-atom can support full range control of amplitude and phase [12, 22]. By superposition of two PB phase responses, analytical modulation is obtained by tuning the orientation of two arms of the X-shaped meta-atom, though the mutual coupling between them needs special attendance.

In this paper, we propose an alternative meta-atom design strategy that can achieve full complex-amplitude modulation with analytical rules. The meta-atom is generally determined as two cascaded equivalent quarter wave plates (QWPs). We have theoretically shown that the polarization state evolution route of the circular polarization conversion (CPC) component on the Poincaré sphere can be modified by tuning the orientation angles of two QWPs, leading to arbitrary combination of amplitude and phase based on analytical rules. A microwave regime meta-atom is designed to demonstrate the proposed design strategy, and is used to realize bifocal metalens that requires simultaneous phase and amplitude modulation. The calculated and experimental results validate our proposals, which may find many applications in various advanced meta-devices.

2. Theory

The PB phase refers to the geometric phase that light acquires when its polarization state undergoes a cyclic evolution [35, 36]. CPC related PB phase is commonly used in metasurface design, that is, by rotating the meta-atom by an angle of $\phi$, an additional phase of $2\sigma\phi$ is introduced to the CPC components, where $\sigma = \pm 1$ depending on the handiness of the transmitted wave. An ideal conventional PB phase meta-atom possesses perfect CPC feature, which is essentially a half-wave plate. However, only the phase can be changed by meta-atom rotation, and additional degree of freedom is needed to obtain full complex-amplitude modulation. As a typical phase retarder, a half-wave plate can be regarded as two QWPs cascaded with their slow axes aligned. Here, we consider the case that two QWPs have independent orientations. As shown in figure 1(a), the orientation angle of a QWP is defined as the angle between its slow axis and the $x$-axis, and the orientation angles of the two cascaded QWPs are marked as $\theta_1$ and $\theta_2$, respectively. For a QWP with the slow axis along the $x$-direction, its Jones calculus in circular polarization basis is

$$Q = \frac{1}{2} \begin{pmatrix} 1 + i & 1 - i \\ 1 - i & 1 + i \end{pmatrix}. \quad (1)$$

When the QWP is rotated by an angle $\theta$ about the $z$-axis, the new Jones calculus can be obtained by the following rotation operation

$$Q_\theta = R^{-1}QR = \frac{\sqrt{2}}{2} \begin{pmatrix} e^{i\frac{\pi}{4}} & e^{-i\frac{\pi}{4} - i\theta} \\ e^{-i\frac{\pi}{4} + i\theta} & e^{i\frac{\pi}{4}} \end{pmatrix}, \quad (2)$$
Figure 2. (a) Schematic diagram of the C-aperture resonator QWP; (b) calculated transmission spectra in linear basis; (c) the linear-to-circular conversion features of the C-aperture resonator QWP. The first and the second subscripts of the transmission spectra refer to the polarization states of the transmitted and incident waves, respectively. The transmission spectra are normalized to the total power of the incidence.

where \( \mathbf{R} = \begin{pmatrix} e^{i\theta} & 0 \\ 0 & e^{-i\theta} \end{pmatrix} \) is the rotation matrix.

Therefore, the total Jones calculus of the two cascaded QWPs is

\[
T = Q_{\theta_1} \cdot Q_{\theta_2}
\]

\[
= \begin{pmatrix} \sin(\theta_2 - \theta_1) e^{i(\theta_2 - \theta_1)} & \cos(\theta_2 - \theta_1) e^{-i(\theta_2 + \theta_1)} \\ \cos(\theta_2 - \theta_1) e^{i(\theta_2 + \theta_1)} & -\sin(\theta_2 - \theta_1) e^{i(\theta_2 - \theta_1)} \end{pmatrix},
\]

\[
= \begin{pmatrix} \sin \alpha e^{i\alpha} & \cos \alpha e^{-i(\alpha + 2\theta_1)} \\ \cos \alpha e^{i(\alpha + 2\theta_1)} & -\sin \alpha e^{-i\alpha} \end{pmatrix}
\]

(3)

where \( \alpha = \theta_2 - \theta_1 \) is the difference of their orientation angles. Clearly, the amplitude and phase of transmitted CPC component are \( \cos \alpha \) and \( \sigma(\theta_1 + \theta_2) = \sigma(\alpha + 2\theta_1) \) respectively, which provides an analytical approach for realizing arbitrary combination of amplitude from zero to unity and phase from 0\(^\circ\) to 360\(^\circ\). This property arises from the change in polarization state evolution path brought by rotation of the two QWPs. For example, after a right-handed circularly polarized (RCP) incident wave passes through the first QWP, it is converted into a LP wave with a polarization angle of \( \theta_1 + 45^\circ \) about x-axis. Since the second QWP is orientated at an angle of \( \theta_2 \), only LP component whose polarization angle is \( \theta_2 + 45^\circ \) will be converted to left-handed circularly polarized (LCP) state. Thus, it can be derived that the amplitude of the transmitted LCP wave is \( \cos \alpha \) by simply applying the Malus’ law. On the other hand, it is necessary to point out the phase modulation is purely by exploiting the PB geometric phase. The RCP-to-LCP polarization evolution paths of cascaded QWPs with \((0^\circ, 0^\circ)\) and \((\theta_1, \theta_2)\) orientation angles are shown in figure 1(b) with blue and red lines, respectively. Then, the phase shift introduced by PB geometric phase between two cases can be derived as \( \alpha + 2\theta_1 \), which is half of the solid angle of the area enclosed by two paths. The above discussions are also applicable to the LCP-to-RCP conversion components, only with the phase shift in opposite sign.

Therefore, in order to implement the proposed strategy with actual structures, only an equivalent QWP needs to be designed. Then, the meta-atom can be obtained simply by cascading two designed QWPs. As for realization of required complex-amplitude distribution, the distributions of orientation angles \( (\theta_1, \theta_2) \) can be determined simply according to the relationship that the complex-amplitude equals to \( \cos \alpha \exp[i\sigma(\alpha + 2\theta_1)] \). It is noteworthy that the aforementioned full complex-amplitude modulation approach purely originates from the geometric transformation and hence is frequency-independent. Thus, the proposed meta-atom design strategy can be universally applied in different frequency regime to implement diverse advanced wave front manipulations, such as enhanced holographic imaging, radiation pattern shaping, and special beams generation.
3. Meta-atom design

As discussed above, the proposed meta-atom consists of two parts that each functions as a QWP. There have been various works in realizing phase retarders or polarization converters in different frequency regimes ranging from microwave, THz to visible light [10, 37–47]. Here, two layers of identical C-aperture resonators aligned along z-axis are utilized to realize QWP in microwave regime. As shown in figure 2(a), the C-aperture resonators are manufactured on 0.018 mm thick copper films. The geometric parameters of the C-aperture resonator are the radius $r_1 = 3.5$ mm, width of the gap $g = 0.2$ mm, outer and inner radius of the C-aperture $r_2 = 3.2$ mm, $r_3 = 3$ mm, and the lattice constant $p = 9$ mm. The two layers of C-aperture resonators sandwich an F4B ($\varepsilon_r = 2.65$, tan $\delta = 0.0017$) dielectric spacer with a thickness of $d = 1.5$ mm. Transmission spectra calculated with finite-difference time-domain algorithm are shown in figure 2(b). The incident wave is set to be along the z direction. It can be found that, in the frequency range of 11.9 GHz–12.6 GHz, the two co-polarized transmission amplitude $T_{xx}$ and $T_{yy}$ is roughly the same with a phase difference $\Delta \phi = \phi_{yy} - \phi_{xx}$ around 90°, indicating that two-layer C-aperture resonator functions as a QWP with slow axis along its symmetric axis (x-axis). In addition, the linear-to-CPC functionality of the C-aperture resonators QWP is also verified. As shown in figure 2(c), the incident LP wave with polarization angle of $\pm 45$° about x-axis can be respectively transformed to RCP and LCP with efficiency above 90% through the 11.9 GHz–12.6 GHz frequency range.

Conspicuously, we can implement the proposed design strategy simply by cascading two of the designed QWPs. As shown in figure 3(a), the meta-atom is built by introducing an air gap with the thickness $l = 5$ mm between two QWPs. Same to the definition in previous section, the orientation angles of the two
Figure 4. The designed normalized amplitude and phase distributions on the (a) and (b) lateral and (c) and (d) axial bifocal metalenses aperture; (e) the photograph of the lateral bifocal metalens sample. The enlarged view (top) and the side view (bottom) are shown in the insets; (f) schematic of experimental setup.

QWPs are also defined as the angle between their slow axes and $x$-axis and labeled as $\theta_1$ and $\theta_2$. The amplitude and phase modulation features are also verified with numerical calculations. The amplitude spectra of RCP-to-LCP conversion component for meta-atom with different $\alpha$ values while $\theta_1$ fixed to be 0° are shown in figure 3(b). Obviously, the amplitude reaches maximum in the operating frequency range of the designed QWP when $\alpha$ equals to 0°. This is because the slow axes of the two QWPs are aligned and the meta-atom functions as a half-wave plate. Then, just as predicted, the amplitude continuously varies from maximum to zero as $\alpha$ increasing from 0° to 90°. In order to show complex-amplitude modulation characteristics more clearly, the normalized amplitude and the phase shift compared to the case that $\alpha$ equals to 0° are respectively shown in figures 3(c) and (d), while $\theta_1$ is still fixed to be 0°. Clearly, the calculated results show good agreement with the theoretical predictions, that the amplitude is proportional to $\cos \alpha$ and phase shift introduced by the PB phase is equal to the orientation angle difference $\alpha$. On this basis, full range of complex-amplitude modulation can be achieved by further varying $\theta_1$ from 0° to 180°. The normalized amplitude and phase shift compared with (0°, 0°) orientated meta-atom are presented at 12.3 GHz in figures 3(e) and (f), where the theoretically predicted modulation rules can be clearly observed. Specifically speaking, the amplitude of CPC components is decided by the orientation difference $\alpha$, and is proportional to its cosine value. Meanwhile, the phase shift of CPC components is decided by the summation of orientation angles of the two QWPs as $\sigma(\theta_1 + \theta_2)$. Therefore, as shown in figures 3(e) and (f), arbitrary combination of phase and amplitude can be achieved for spin waves by tuning the two orientation angles of meta-atom.
Figure 5. Calculated and measured LCP electric field intensity distributions on (a) and (b) the \( xoz \) plane and (c) and (d) the focal plane of lateral bifocal metalens at 12.3 GHz; (e) the calculated and measured LCP field intensity along the white dashed line \((y = 0 \text{ mm})\) shown in figures 5(c) and (d). All intensity distributions are normalized to their global maximum.

The proposed strategy can be implemented with structures in various different forms, such as nanopillars, gratings and other resonant structures, as long as the meta-atom is equivalent to two cascaded QWPs. Numerical calculation results of a meta-atom designed with our strategy in the near-infrared regime are shown in the supplementary material (https://stacks.iop.org/NJP/23/083023/mmedia). It can be noticed that the maximum transmission amplitude is a little less than unity. This is mainly due to the inevitable medium losses and certain impedance mismatch. The operating bandwidth and the modulation efficiency are mainly decided by the performance of the QWPs, and can be improved by impedance matching design. It should be noted that two QWPs do not have to be cascaded by introducing an air gap in between. A dielectric layer can be used instead to obtain free-standing devices. More discussion about the meta-atom design can be found in the supplementary material. In addition, since the meta-atom following our full range complex-amplitude modulation strategy essentially consists of two functional layers, it is necessary to compare it with other strategies, especially bilayer strategy. As we state above, our strategy alters the polarization evolution path by tuning the two orientation angles to achieve full range of complex-amplitude modulation. The amplitude and phase modulations are respectively based on Malus' law and PB phase, which is fundamentally different from those in references [10, 18] where amplitude and phase modulations are assigned to different layer.
Figure 6. (a)–(c) Calculated and (d)–(f) measured LCP electric field intensity distributions on the xoz plane and the two focal planes of axial bifocal metalens at 12.3 GHz; the calculated and measured LCP field intensity (g) along the optical axis (z-axis) and (h) and (i) across two focal planes (horizontal white dashed lines \( y = 0 \text{ mm} \) shown in figures 6(a) and (d)). All intensity distributions are normalized to their global maximum.

4. Bifocal metalenses design and experiment

To further demonstrate the proposed full complex-amplitude modulation approach, we design and characterize two bifocal metalenses with lateral and axial aligned foci respectively, which demands continuous full range control of amplitude and phase. The required complex-amplitude distributions on the bifocal metalens aperture can be expressed as

\[
A(x, y) e^{i\phi(x, y)} = A_1 e^{i \frac{2\pi}{\lambda_0} \sqrt{(x-x_1)^2+(y-y_1)^2+f_1^2-f_1}} + A_2 e^{i \frac{2\pi}{\lambda_0} \sqrt{(x-x_2)^2+(y-y_2)^2+f_2^2-f_2}},
\]

where \( A_1 \) and \( A_2 \) are the amplitudes of two foci with focal lengths \( f_1 \) and \( f_2 \), respectively, \((x_1, y_1)\) and \((x_2, y_2)\) are lateral positions of two foci with respect to the lens center, and \( \lambda_0 \) represents the free space wavelength of operating frequency. For both lateral and axial bifocal cases, the metalenses are designed at 12.3 GHz, and each contains a total of 1681 aforementioned meta-atoms, which form a 41 \( \times \) 41 square array. In the lateral bifocal metalenses design, the two foci are set with same amplitude and same focal length \( f_1 = f_2 = 300 \text{ mm} \), with 150 mm lateral distance \((x_1, y_1) = (-75 \text{ mm}, 0 \text{ mm})\) and \((x_2, y_2) = (75 \text{ mm}, 0 \text{ mm})\). Meanwhile, the focal lengths of the axial bifocal metalens are set as \( f_1 = 50 \text{ mm} \), \( f_2 = 150 \text{ mm} \), and the amplitudes of two foci are also different, which are \( A_1 = 1 \) and \( A_2 = 0.707 \), respectively.

Figures 4(a)–(d) shows the designed amplitude and phase distributions on apertures of the two bifocal metalenses acquired by sampling from the theoretical profiles from equation (4). Then, the distributions of the meta-atom orientation angles are determined accordingly by the relationship that the complex-amplitude is proportional to \( \cos \alpha \exp[i\sigma(\alpha + 2\theta_1)] \). Namely, parameter \( \alpha \) can be obtained by calculating the arc cosine value of the normalized designed amplitude. Then, parameter \( \theta_1 \) can be determined by the relationship that phase is equal to \( \sigma(\alpha + 2\theta_1) \). As shown in figure 4(e), the samples are...
fabricated by standard printed-circuit-board technique on F4B substrates (Taconic TLT-6) and assembled with several plastic spacers to align two printed circuit boards and ensure the air gap in between. The experimental setup is shown in figure 4(f). The performance of metalens is measured in an anechoic chamber with Keysight PNA-X 5242A Network Analyzer. An RCP wave generated by a circularly polarized horn antenna is normally incident to the sample. The LCP components of the transmitted field on the xoz plane and the focal planes are detected in steps of 1 mm with a small helix antenna used as a probe. More details about the experimental setup can be found in supplementary material.

The calculated and measured results of lateral bifocal lens at 12.3 GHz are shown in figure 5. The two maxima can be clearly observed at the preset focal plane (i.e. \( f_1 = f_2 = 300 \text{ mm} \)). The intensity distribution across the two foci on the focal plane (along the line of \( y = 0 \text{ mm} \)) is shown in figure 5(e), from which the lateral distance between two foci is calculated. It can be seen that, the measurement and calculation agree well with each other and confirming the design goals. The lateral bifocal features at other frequencies can be seen in the supplementary material.

Figure 6 shows the performance of the axial bifocal metalens. As expected, the measured results show good agreement with calculated ones. As shown in figures 6(a) and (d), the two maximum intensity along the optical axis (z-axis) occur at the two designed focal planes (\( f_1 = 50 \text{ mm} \) and \( f_2 = 150 \text{ mm} \)). The measured and calculated LCP field intensity along the optical axis are shown in figure 6(g). It can be noticed that the intensity ratio of the two foci is slightly deviated from the designed ratio of 1:0.5. This is mainly due to the different focusing capability for the finite-size lens at different axial positions. In addition, the boundary condition of a meta-atom in the real meta-devices may differ from the perfect periodic boundary condition we applied in a calculation, which may cause the phase/amplitude distribution to be different from the designed ones.

5. Conclusions

In summary, we have presented a general meta-atom design strategy for full range complex-amplitude modulation with analytical rules. By altering the polarization state evolution path through the two orientation angels of meta-atom that can be regarded as two cascaded QWPs, arbitrary combination of amplitude and phase can be achieved for spin waves. As verification, two bifocal metalenses enabled by meta-atom composed of C-aperture resonators are fabricated and characterized in microwave regime. The proposed meta-atom design strategy can be implemented with a variety of structures in different forms, and generalized to other frequency regimes such as THz, infrared and even visible light. Our findings may stimulate various novel and high-performance meta-devices, thanks to nimble design and the analytical modulation rules.

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