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Metallic stereostructured layer: An approach for broadband polarization state manipulation

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In this letter, we report a full-metallic broadband wave plate assembled by standing metallic L-shaped stereostructures (LSSs). We show that with an array of LSSs, high polarization conversion ratio is achieved within a broad frequency band. Moreover, by rotating the orientation of the array of LSSs, the electric components of the reflection beam in two orthogonal directions and their phase difference can be independently tuned. In this way, all the polarization states on the Poincaré sphere can be realized. As examples, the functionalities of a quarter wave plate and a half wave plate are experimentally demonstrated with both reflection spectra and focal-plane-array imaging.

Our designing provides a unique approach in realizing the broadband wave plate to manipulate the polarization state of light. © 2014 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License.

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frequency and \( \omega_2 \) is the damping constant. For gold, the characteristic frequencies are taken as \( \omega_p = 1.37 \times 10^{16} \text{ s}^{-1} \) and \( \omega_a = 1.2 \times 10^{13} \text{ s}^{-1} \). The permittivity of the glass substrate and the L-shaped interior structure is taken as 2.00 and 2.25, respectively.\(^{34}\)

The incident light is reflected by the LSS array. The amplitude and the phase difference between the two orthogonal components of the reflected light are calculated, as illustrated in Figs. 1(c) and 1(d), respectively, so that the polarization state of the reflected light is fully described. In Figs. 1(c) and 1(d), \( r_{m,n} \) stands for the complex amplitude of the \( m \)-component of reflected light for which the incident light is polarized in \( n \) direction. For the LSS array, the symmetric axes of the structure are in 0° and 90° directions, respectively. When the incident light is polarized in 0° direction (\( x \)-direction) or in 90° direction (\( y \)-direction), the polarization state of the reflected light remains unchanged. Simulation indicates that the reflectance amplitudes \( |r_{0,0'}| \) and \( |r_{90,90'}| \) are identical and nearly dispersion-free in the range of 1550–2100 cm\(^{-1}\). The phase difference \( \Delta \phi \) between \( r_{90,90'} \) and \( r_{0,0'} \) is 90° in 1550–2100 cm\(^{-1}\). When the polarization of incident light is in 45°, the polarization state of the reflected light will be deviated. The amplitudes of reflectance, \( |r_{45,45'}| \) and \( |r_{135,135'}| \), are identical and are dispersion-free in the range of 1550–2100 cm\(^{-1}\). The phase difference \( \Delta \phi' \) between \( r_{45,45'} \) and \( r_{135,135'} \) is 90° in 1550–2100 cm\(^{-1}\). In this scenario, a right-handed circular polarized (RCP) light is achieved when the incident light is polarized along 45°. Due to the topological symmetry of the LSS unit, when the incident light is polarized along 135°, the reflected light is left-handed circular polarized (LCP). The calculations in Figs. 1(c) and 1(d) indicate that in the frequency range of 1550–2100 cm\(^{-1}\), the LSS array indeed serves as a quarter wave plate, with the fast axis of the LSS quarter wave plate along \( y \)-direction (i.e., 90° direction).

We should emphasize that a quarter wave plate constructed with LSS array can realize all the polarization states, which can be illustrated clearly with the Poincaré sphere.\(^{1}\) On the surface of Poincaré sphere, point \((2\psi, 2\chi)\) represents a state of polarization, where \( \chi \) is the ellipticity angle as illustrated in the inset of Fig. 2(c) and the angle \( \psi \) represents the direction of the major axis of the ellipse polarized light.

**FIG. 1.** (a) The schematic diagram of the designing of LSS array. The up left inset shows the top view of the LSS unit. (b) The detailed topography of the designed LSS unit: \( L = 3 \mu m, h = 1.7 \mu m, a = 2.1 \mu m, w = 0.3 \mu m \), and the thickness of the metal film \( t \) is 35 nm. \( \theta \) is the polarization angle. (c) and (d) The calculated amplitudes of reflected light and the phase difference for different polarization arrangements.

**FIG. 2.** (a) The schematic micrograph to show the Poincaré sphere. (b) The diagram to show the setup of LSS array. The polarization angle of incident light is \( \theta_1 \) respected to \( x \)-axis, and the whole device is rotated around \( z \)-axis for \( \theta_2 \) angle. (c) The ellipticity angle \( \chi \) as a function of \( \theta_1 \). (d) The orientation angle \( \psi \) as a function of \( \theta_2 \).
To experimentally verify this expectation, we fabricate the LSS array sample with two-photon polymerization system (Nanoscribe GmbH) on a glass plate (Menzel-Glaser) 170 μm thick. The femtosecond laser beam is focused to a diffraction limited spot, which is then controlled to scan in 3D space to form the LSSs. The exposed negative photoresist (IP-L, Nanoscribe GmbH) is polymerized and generates the backbone of standing L-shaped patterns, while the unexposed photoresist is removed in the developing process. Thereafter, the polymerized L-shaped structures are coated with a homogeneous layer of gold 35 nm in thickness by magnetron sputtering to finalize the metallic stereostructured layer. Figure 3(a) illustrates the field emission scanning electron micrographs (FESEM) of the LSS array, with details shown in Fig. 3(b). Fourier transform infrared (FTIR) spectrometer (Bruker Vertex 70v) is employed to characterize the optical property of LSS array. A pair of ZnSe polarizers is applied to tune the polarization of the incident light and analyze the reflected light. The incident light propagates perpendicularly to the LSS array, with its polarization along 45° direction. The reflectance collected along the polarization direction 0°, 45°, 90°, and 135°, respectively, is illustrated in Fig. 3(c). One may find that when the incident light is polarized in 45°, the amplitude of reflectance \( r_{45°,45°} \), \( r_{90°,45°} \), \( r_{135°,45°} \), and \( r_{0°,45°} \) is identical and is dispersion-free in the range of 1550–2100 cm\(^{-1}\). When the incident light is polarized in 135°, the amplitude of reflectance \( r_{135°,135°} \), \( r_{0°,135°} \), \( r_{45°,135°} \), and \( r_{90°,135°} \) shown in Fig. 3(d) is identical and dispersion-free in the range of 1550–2100 cm\(^{-1}\) as well. Figure 3(e) illustrates the retrieved \( \Delta \phi_{45°} \) (the phase difference of \( r_{45°,45°} \) and \( r_{135°,45°} \)) and \( \Delta \phi_{135°} \) (the phase

![Figure 3](image-url)
difference of $r_{135°,135°}$ and $r_{45°,135°}$).\textsuperscript{35} One may find that in the range of 1550–2100 cm$^{-1}$, $\Delta \phi_{45°} = 90°$ and $\Delta \phi_{135°} = -90°$. The measured amplitudes and the retrieved phase difference (from measured amplitudes\textsuperscript{35}) confirm that a RCP light is achieved when the polarization of incident light is set in 45°. With a similar approach, a LCP light is achieved when the polarization of incident light is set in 135°. We also measure the amplitude of reflected light with the incident light polarized in x- and y-directions (i.e., 0° and 90°). The measured amplitudes of $r_{0°,0°}$ and $r_{90°,90°}$ are in good agreement with the simulated results shown in Fig. 1(c). Therefore, LSS array works as a quarter wave plate in the frequency range of 1550–2100 cm$^{-1}$.

To directly demonstrate that LSS array indeed works as a quarter wave plate, focal plane array (FPA) detector (Hyperion 3000, Bruker) is applied to collect the infrared image of the sample. Figure 4(a) shows the topography of the LSS array for FPA measurement. The x- and y-directions are in two diagonal directions, respectively, as that defined in Fig. 1, and $\theta$ is the angle between the polarization direction of incident light and x-axis. In Figs. 4(b)–4(h), the FPA image is collected by integrating the signal in 1550–2100 cm$^{-1}$. The warmer hue indicates that more energy has been collected by the FPA detector. To analyze the polarization state of the reflected light with FPA imaging system, the polarization of incident light is set along $\theta_{\text{inc}}$ direction. The component in $\theta_{\text{ref}}$ direction of reflected light is collected by the FPA detector. When the incident light is polarized in the two symmetry directions of the structure (i.e., $\theta_{\text{inc}} = 0°$ and 90°), the polarization of the reflected light remains unchanged in 1550–2100 cm$^{-1}$. This means that no energy is switched to the orthogonal polarization direction. Figures 4(b) and 4(c) correspond to the scenarios that the incident polarization angle is set as $\theta_{\text{inc}} = 0°$ and 90°, respectively. Most of energy has been reflected back and collected in the same polarization direction. For this reason, the color of the sample area in Figs. 4(b) and 4(c) is bright red. In Fig. 4(d), the incident polarization ($\theta_{\text{inc}} = 0°$) and the collection polarization ($\theta_{\text{ref}} = 90°$) are orthogonal. No energy is converted to the orthogonal polarization direction. As a result, the color shown in Fig. 4(d) is dark blue.

In Figs. 4(e)–4(h), the incident polarization is set as $\theta_{\text{inc}} = 45°$, and the FPA images are collected with different polarization direction $\theta_{\text{ref}}$ of the reflected light. The color in the sample areas in Figs. 4(e)–4(h) is nearly identical, suggesting that the reflected light is circularly polarized when the incident direction is set in $\theta_{\text{inc}} = 45°$. In Fig. 4(e), the surrounding area is bright red and in Fig. 4(g) the surrounding area is dark blue. This is due to the fact that the polarization of light reflected by the surrounding flat surface remains unchanged.

The broadband optical device with different functionalities can be achieved by tuning the structural parameters of LSS. By setting the lattice constant $L$ and the height of LSS $h$ as 3.6 μm and 1.4 μm, respectively, a broadband half wave plate can be realized. Figure 5(a) illustrates the fabricated LSSs for half wave plate, and Fig. 5(b) illustrates the detail morphology. Figure 5(c) indicates that the energy of incident light is converted from 45° polarization direction to 135° polarization direction when the incident light is polarized in...
45°. Here, the frequency range varies from 1870 cm$^{-1}$ to 2170 cm$^{-1}$. The polarization conversion ratio (PCR)$^{14,36}$ is defined as $\text{PCR} = \left| r_{135.45} \right|^2 \left| r_{145.45} \right|^2 + \left| r_{145.45} \right|^2$ and the measured PCR is illustrated by the blue dotted line in Fig. 5(c). In 1870–2170 cm$^{-1}$, PCR is larger than 90%. Simulation shown in Fig. 5(d) further confirms the validity of the measurement.

To verify the spectrum measurement, we apply FPA imaging system and collect the infrared image of LSS with half wave plate feature. The topography of the LSS array is shown in Fig. 5(e), and the FPA images of Figs. 5(f) and 5(g) are integrated from 1870 cm$^{-1}$ to 2170 cm$^{-1}$. In Fig. 5(f), the incident polarization and the collection polarization are both in 45° direction. The color of the sample area is dark blue, yet the color of the surrounding area is bright red. In Fig. 5(g), the collecting polarization has been rotated to the orthogonal direction. It follows that the sample area becomes bright red, whereas the surrounding area turns to deep blue. Therefore, Figs. 5(f) and 5(g) confirm that this LSS indeed converts the power of the incident light to the orthogonal polarization direction; at the same time, the surrounding area works as a flat mirror with the polarization of reflected light unchanged.

Control the polarization state of light in an extremely limited space has been an important topic in developing integrated optics and on-chip photonics.$^{35}$ The work presented here experimentally demonstrates a full-metal broadband stereostructured wave plate. Our stereostructure is basically a continuous metal film and is electrically conductive. So it can be applied as an electrode simultaneously when it plays the role of wave plate. This function may have applications in active opto-electric device$^{27}$ and display technology.$^{28}$

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35See supplementary material at http://dx.doi.org/10.1063/1.4902405 for the retrieval method of phase differences and the discussion of conjugation relation.
