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Metasurface for characterization of the polarization state of light

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Abstract: The miniaturization of measurement systems currently used to characterize the polarization state of light is limited by the bulky optical components used such as polarizers and waveplates. We propose and experimentally demonstrate a simple and compact approach to measure the ellipticity and handedness of the polarized light using an ultrathin (40 nm) gradient metasurface. A completely polarized light beam is decomposed into a left circularly polarized beam and a right circularly polarized beam, which are steered in two directions by the metasurface consisting of nanorods with spatially varying orientations. By measuring the intensities of the refracted light spots, the ellipticity and handedness of various incident polarization states are characterized at a range of wavelengths and used to determine the polarization information of the incident beam. To fully characterize the polarization state of light, an extra polarizer can be used to measure the polarization azimuth angle of the incident light.

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1. Introduction

Polarization is one of the fundamental properties of electromagnetic radiation. Based on the measurement and interpretation of the polarization of light waves, polarimetry has found its applications in many areas of science and technology [1], ranging from ellipsometry [2], remote sensing [3] to polarization light scattering [4] and ophthalmic polarimetry [5]. Traditionally, to measure the polarization state of light, a set of polarization elements such as polarizers, waveplates and polarization modulators are usually employed and placed in a beam of light in front of a radiometer. The related polarization parameters of the incident light are then determined by measuring the flux transmitted through these polarization elements. Although the traditional measurement systems bring distinguished functionality in measuring speed and accuracy, their applications are still limited due to the various polarization elements and complicated data processing system adopted, which result in large volume and high cost. The metasurface approach described in this paper differs from previous approaches in that the phase change occurs abruptly at the interface rather than slowly evolving in, for example, a birefringent material commonly used in bulky polarization optics. Consequently, this can lead to further miniaturization and a greater potential for system integration.

Metamaterials, the artificial materials, whose optical properties are determined by their geometrical structures instead of their constituent material composition [6–12], have opened new avenues in the manipulation of the polarization of light [13–16]. The ultrathin circular polarizers [17–19] and polarization rotators [20, 21] based on metamaterials have been developed recently. As a new kind of metamaterial, metasurface [22–24] does not require complicated three-dimensional nano-fabrication techniques but can partially convert the linearly polarized incident light to its cross polarization [23] or convert a circularly polarized light to its opposite handedness [25–29]. Since an abrupt phase change occurs at the interface of the metasurface, much recent research has concentrated on utilizing the abrupt phase change to control the light propagation [30, 31]. Nevertheless, the polarization conversion function itself provides an additional degree of freedom for the use of metasurfaces in polarization measurement.

Here, we propose a novel method to measure the polarization state of a completely polarized light beam based on the metasurface. When an incident light beam passes through the metasurface consisting of nanorods with spatially varying orientations, the refracted light emerging from the metasurface is the sum of three terms with separate amplitudes: the regularly refracted light with the same polarization of the incident light, the anomalously refracted left circularly polarized (LCP) light and the right circularly polarized (RCP) light. The ellipticity and the handedness of the incident light can be deduced from the relative intensities of the last two terms. Interestingly, since the refracted LCP and RCP light diverge naturally from each other, the metasurface can also be used as a circular polarization beam splitter, whose split angle is determined by controlling the spatial distribution of the nanorods in the metasurface.

2. Materials and methods

Figure 1(a) shows the schematic of the designed phase gradient metasurface. All nanorods have the identical geometric parameters, which are 50 nm in width, 200 nm in length and 40 nm in thickness. The center-to-center distance between the two neighboring nanorods is 400 nm. The angular orientation of each nanorod varies along the x-direction with an increment of $\pi/8$ in clockwise rotation, but remains invariant in the y-direction, hence each period in x direction contains eight nanorods whose orientations change from 0 to $\pi$, with the phase shift ranging from 0 to $2\pi$. The electron-beam lithography is initially used to define the nanorod structures in a positive PMMA resist film on ITO- coated glass substrates, then a 40-nm-gold film is deposited using thermal evaporation. The thickness of the ITO layer is around 4 nm. Finally, the phase gradient metasurface consisting of the gold nanorods is obtained by a
subsequent lift-off procedure. Figure 1(b) shows the scanning electron microscope (SEM) image of the fabricated meta surface. The metasurface for generating phase discontinuity and anomalous refraction was verified by a full wave numerical simulation in previous work [27].

![Fig. 1. (a) Schematic illustration of the phase gradient metasurface. The center-to-center rod spacing $s$ is 400 nm both in $x$ and $y$ directions. The orientation of each nanorod is characterized by $\phi$, which is the angle formed by the long axis of the nanorod and $y$ axis. (b) Scanning electron microscope image of the fabricated meta surface on an ITO coated glass substrate. The scale bar is 2\(\mu\)m.](image)

In order to show the polarization conversion and the Pancharatnam–Berry phase generated by the metasurface in Fig. 1, the function of each nanorod defined in the metasurface is first analyzed. When a nanorod is illuminated by the LCP light with the electric field $E_0\hat{L}$ at normal incidence, the transmitted electric field $E_t$ can be approximated by [32]

$$E_t = \frac{t_o + t_e}{2} E_0\hat{L} + \frac{t_o - t_e}{2} e^{i2\phi} E_0\hat{R}$$

(1)

where $\hat{L}$ and $\hat{R}$ represent the normalized Jones vectors for LCP and RCP light, respectively. $t_o$ and $t_e$ are the complex scattering coefficients for components of the incident light polarized along the two axes of the nanorods. $\phi$ is the angle between the long axis of the nanorod and $y$ axis as shown in Fig. 1(a). Similarly, upon the illumination of RCP with the electric field $E_0\hat{R}$, the transmitted field $E_t$ is

$$E_t = \frac{t_o + t_e}{2} E_0\hat{R} + \frac{t_o - t_e}{2} e^{-i2\phi} E_0\hat{L}$$

(2)

The first term in Eqs. (1) and (2) represents the transmitted light which has the same polarization as the incident field, while the second term represents the scattered light with the opposite handedness and an additional Pancharatnam–Berry phase of $\pm 2\phi$.

The metasurface consisting of such a nanorod configuration is capable of splitting the refracted light into two categories, i.e. the regularly refracted light is just an attenuated copy of the incident light, while the anomalously refracted light is imparted with a local, space-variant phase change $\exp(\pm i2\phi)$. As $\phi$ changes along the $x$ axis, the anomalous refracted light follows the generalized Snell’s law [23]

$$n_i \sin \theta_i - n_t \sin \theta_t = \frac{\lambda_o}{2\pi} \frac{d\Phi}{dx} = \frac{\lambda_o}{\pi} \frac{d\phi(x)}{dx}$$

(3)

Where $n_i$ and $n_t$ are the refractive indices of the medium before and after traversing the metasurface, $\theta_i$ and $\theta_t$ are the incident and refraction angles, respectively. $d\Phi/dx$ represents the phase gradient of the metasurface.
Based on the analysis above, Fig. 2 shows the schematic of the proposed approach to measure the polarization state of light. When the RCP light is incident normally onto the metasurface, the regularly refracted light preserves the polarization status as well as the propagation direction of the incident light. However, the polarization of the anomalously refracted light is converted into LCP, which is modulated by the phase of $-2\phi$ and steered to the right when viewed from the source direction [Fig. 2(a)]. Figure 2(b) shows the case when the incident light is LCP, in which the anomalous light is shifted to the opposite side. In the general case, if the incident beam contains both LCP and RCP components (such as linearly polarized or elliptically polarized light), it is partially converted into anomalously refracted RCP and LCP light which lie on both sides of the regularly refracted light [Fig. 2(c)]. The metasurface proposed here functions like a metal-stripe polarization grating [33–35]. However, the metasurface can work in the visible and near-infrared range, while the metal-stripe polarization grating is suitable for far infrared and terahertz applications.

![Fig. 2. Schematic to show the polarization of the refracted light after a completely polarized light beam passing through the metasurface. (a-b) The polarization states of the incident light in (a) and (b) are RCP and LCP, respectively. The regularly refracted light preserves the polarization state and transmission direction of the incident light, while the anomalously refracted light changes into the opposite handedness and diverges from the incident direction. (c) The incident light is linearly or elliptically polarized light that contains both LCP and RCP components, which can be regarded as a superposition of (a) and (b) with different proportions.](image)

Since a completely polarized light is composed of LCP and RCP components with separate amplitudes, the ellipticity $\eta$ and handedness of the polarized light can be deduced by the intensity ratio $\tau$ of its LCP and RCP components: $\eta = (1-\sqrt{\tau})/(1+\sqrt{\tau})$ with $\eta = \pm 1$ representing RCP (LCP) light, and $\eta = 0$ representing linear polarization [26]. Although $\tau$ cannot be measured directly, the intensity ratio $\tau'$ of the anomalously refracted LCP and RCP light can be directly measured as shown in Fig. 2(c). We thus have $\tau = 1/\tau'$ since the anomalously refracted LCP and RCP light are obtained from the corresponding RCP and LCP components of the incident light with the same conversion efficiency [Eqs. (1) and (2)]. Therefore, the ellipticity and handedness of the incident light can be determined by $\tau'$.

### 3. Results and discussion

To experimentally demonstrate the proposed metasurface approach, various polarization states of incident light are analyzed by measuring the intensities of the refracted beams after the metasurface. The polarization states of the incident light could be varied by use of a polarizer and a quarter waveplate placed in front of the spectrally tunable laser source (NKT, SuperK Extreme). While the transmission axis of the polarizer remains fixed, the orientation of the fast axis of the quarter waveplate is rotated, so that the polarization states of the incident light change with the angle $\beta$ between the two axes. The sample is mounted on a 2D translational stage and the refracted light from the metasurface is collected by a 10x/0.30 infinity corrected microscope objective lens.

Figure 3 shows the polarization states of the refracted light on the transmission side of the metasurface upon the illumination of incident light with different polarizations. Two light
spots (one in the middle and the other on the right) are observed when the metasurface is illuminated by RCP light at normal incidence, as shown in Fig. 3(a). Using a second polarizer and quarter waveplate placed at the detection plane, the middle light spot vanishes [Fig. 3(b)] when the RCP component of the refracted light is filtered out, which implies that the right light spot and the middle light spot correspond to the anomalously refracted LCP light and regularly refracted RCP light, respectively. Similarly, Figs. 3(c) and 3(d) verify that the light spot at the left side of the observation plane corresponds to the anomalously refracted RCP light when the handedness of the incident circularly polarized (CP) light is changed to LCP. Figures 3(e) and 3(f) are the experimental results for linearly polarized (LP) incident light and the central linearly polarized beam is removed, leaving both the LCP and RCP anomalously refracted light, as expected.

Figure 4 shows the intensity distribution of the refracted light for a range of incident polarization states. Upon illumination with the linearly polarized (LP) light, which consists of equal RCP and LCP components, the intensities of the two light spots ($I_{\text{RCP}}$ and $I_{\text{LCP}}$) are equal [see Fig. 4(a)]. $I_{\text{LCP}}$ is smaller than $I_{\text{RCP}}$ when the incident light is left-hand elliptical polarized [Fig. 4(b)], and $I_{\text{LCP}}$ is negligible when the pure LCP light is incident [Fig. 4(c)]. Similarly, we can obtain the intensity relation for the right-handed elliptically ($I_{\text{RCP}}>I_{\text{LCP}}$) and circularly polarized incident light ($I_{\text{RCP}}=0$) as shown in Figs. 4(d) and 4(e). Hence the handedness and ellipticity of the incident light can be directly determined by comparing $I_{\text{LCP}}$ with $I_{\text{RCP}}$. Although the central light spot generally dominates the transmitted energy, the measurement of incident polarization relies on the ratio of $I_{\text{LCP}}$ to $I_{\text{RCP}}$, which can give clearly defined measurement in the case of the results presented in Fig. 4.
Fig. 4. Experimentally obtained CCD images of the refracted light spots versus polarization states of the incident light at 633 nm. The polarization states of incident light are chosen to be linearly polarized in (a), left-handed elliptically polarized in (b), LCP in (c), right-handed elliptically polarized in (d) and RCP in (e). The figures in the middle are the CCD images and the figures on the right are the corresponding intensity profile along a line that crosses the center of the light spots.

The experimentally obtained intensity distribution of the refracted light spots provides an accurate and simple method to measure the ellipticity of the incident light. The geometry of the nanorod is designed for a specific wavelength at which the conversion efficiency to the opposite handedness is the highest and it decreases when the wavelength of incident light deviates from this resonance frequency. However, the polarization conversion and Pancharatnam–Berry phase created by the metasurface is not affected by the incident wavelengths as implied in Eqs. (1) and (2), which means that the method proposed here should apply to a wide range of wavelengths using the same metasurface. As broadband usage is desirable for a wide range of potential applications, the light intensity distributions of the refracted light spots are measured at wavelengths of 750 nm and 850 nm, and compared to that of the wavelength of 633 nm. Figure 5 shows the ellipticity $\eta$ versus the incident polarization based on the experimentally obtained intensity distribution of the light spots. The solid curve represents the predicted value, while the red circles, green triangles and pink squares represent the experimental values for 633 nm, 750 nm and 850 nm, respectively. It is clearly shown that the experimental values agree very well with the predicted values, which unambiguously verifies the validity of the proposed approach. In addition, the sign of $\eta$ is also shown, which can be used to determine the handedness of the elliptically polarized light as we
discussed above. In the figure, \( \eta > 0 \) means that the incident light is right-hand elliptically polarized while \( \eta < 0 \) for left-hand elliptically polarized light.

![Figure 5. Experimentally obtained ellipticities \( \eta \) versus the incident polarization (a function of \( \beta \)).](image)

In many cases, only incomplete information of the polarization properties of a sample is needed, hence it is unnecessary to measure the full polarization state of the probing light [1]. For example, a determination of the degree of ellipticity of the output light can provide the measurement of the circular dichroism (the differential absorption exhibited by a sample for LCP and RCP light) [36]. The circular dichroism based measurement has been widely used in the structural studies of proteins and DNA [37], the proposed measurement method based on the metasurface may find immediate application in the circular dichroism based miniature measurement systems for bioscience research.

It is worth noting that the split angle \( \alpha \) between the anomalously refracted LCP and RCP light may vary with the phase gradient of the metasurface. Therefore this kind of metasurface is suitable for a broadband circular polarization beam splitter with the freedom of controlling the split angle, which is dependent on the orientation and distribution of the nanorods. It can be derived from Eq. (3) that the split angle \( \alpha \) equals to 22.8° at the wavelength of 633 nm. By measuring the distance between the metasurface and the observation plane \( d_1 \) and the distance between the left (or right) light spot and middle light spot \( d_2 \), the actual split angle \( \alpha \) can be calculated by using the equation \( \alpha = 2\arctan(d_2/d_1)\approx 22.6^\circ \), which is in good agreement with the above designed value.

In order to fully characterize the polarization of the polarized light, the polarization azimuth angle (PA) of the incident light is needed apart from the ellipticity and handedness. As the middle light spot (Fig. 3) has exactly the same polarization as the incident light, PA can be detected by placing a polarizer in front of the middle light spot, then rotating it to the position where the field appears the darkest. The polarization azimuth angle is then exactly 90° from the darkest position. By further experimentally measuring PA of the middle light spot, the polarization states of the incident light can be fully characterized as shown in Fig. 6. The polarization measurement method proposed here does not need the quarter-wave plate, whose phase retardation cannot maintain \( \pi/2 \) over a wide range of wavelengths. In addition, the low cost, miniature and broadband polarizer can be easily obtained. Hence the method proposed may pave the way for realizing the miniature, broadband polarization measurement.
system. Very recently, the dielectric metasurface consisting of a single layer of amorphous silicon elliptical posts [38] has been demonstrated to function as a beam splitter for linear polarization, which can be used to measure PA. If such a device and a dielectric phase gradient metasurface are fabricated onto the same substrate, the Stokes parameters can be determined by measuring the transmitted intensities of the light spots of different polarizations.

![Fig. 6. Poincaré sphere to show the experimentally measured polarization states of the incident light. With the measured polarization azimuth angle $\rho$ of the middle light spot, the normalized Stokes parameters ($S_0 = 1$) are calculated by $S_1 = \cos^2 \chi \cos^2 \rho$, $S_2 = \cos^2 \chi \sin^2 \rho$, $S_3 = \sin^2 \chi$, where $\chi = \arctan(\eta)$. The blue solid line and the red triangles represent the theoretical curve of the Stokes parameters and the experimental values at 750 nm.](image)

The conversion efficiency of the metasurface is an important parameter, which is defined by the power of the anomalously refracted light divided by that of the input power. Figure 7 shows the experimentally measured conversion efficiency versus wavelength. The maximum conversion efficiency is around 7.6% at 940 nm. It is obvious that the enhancement of the conversion efficiency can improve the measurement accuracy. Dielectric metasurface [39] or reflective-type metasurface [40] can be used to greatly increase the conversion efficiency and minimize the measurement error.

![Fig. 7. Experimentally measured conversion efficiency versus wavelength of the incident light. The red dots represent measured efficiencies at different wavelengths.](image)

4. Conclusion

In conclusion, we have demonstrated a novel method to measure the polarization state of the completely polarized light by using the metasurface consisting gold nanorods with spatially...
varying orientation. Based on the measured intensities of the anomalously refracted LCP and RCP light, the experimental values of the ellipticity and handedness of the incident light agree very well with predicted values. This work shows remarkable potential to address major issues typically associated with the current polarization measurement systems, by virtue of its simplicity, miniaturization, compactness and broadband nature. Use of the metasurface approach can simplify future polarization measurements and lead to much improved optical system integration.

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