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Interferometric Control of Signal Light Intensity by Anomalous Refraction with Plasmonic Metasurface

Zhaocheng Liu[1] · **Shuqi Chen**[1] · **Hua Cheng**[1] · **Zhancheng Li**[1] · **Wenwei Liu**[1] · **Jianguo Tian**[1]

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Abstract We propose a new method of controlling signal light intensity by changing the polarization direction of pump light that is incident on a phase-gradient metasurface. Theoretical analyses and simulations demonstrate that, when the incident angles for signal and pump light sources conform to a certain relationship, the anomalous refraction of the pump light superposes with the signal light. The intensity of the signal light can be fully tuned across a broadband range by varying the polarization direction of the pump light. Our methods will contribute to the development of promising techniques to be used in photonics devices such as amplitude modulators and photoswitches.

Keywords Metamaterials · Surface plasmons · Electromagnetic optics

Introduction

Controlling light intensity is a crucial task in fields such as optical communication and computation. The traditional methods usually involve nonlinear properties of matter, wherein light and other forces interact, resulting in changes in the intensity, phase, and polarization. However, the nonlinear coefficients of the media are rather small compared with the linear polarizability, and the volume of nonlinear matter has to be large enough to ensure sufficient interaction. Considering certain unwanted effects—such as the walk-off effect leading to divergence of interacted waves in nonlinear matter—effective modulation using weak light at the nanoscale is hardly possible. As a result, applications in highly integrated photonics are restricted in this manner.

With the development of nanofabrication techniques, metamaterials have provided approaches for controlling light wavefronts with impressive degrees of freedom. Metasurfaces, which represent a variety of metamaterials with either a single layer or a few layers of artificial metallic structures, possess the ability to manipulate the intensity, phase, and polarization of incident light in the waveband from the terahertz region to the visible region [1–6]. The rapidly expanding applications of metasurfaces include anomalous refraction [2–8], vector and vortex beams [9–11], aberration-free quarter-wave plates [12], ultra-thin flat lenses [13, 14], optical spin-orbital interactions [15, 16], and high-resolution three-dimensional metasurface holograms [17, 18]. The dynamic control of light intensity has also been achieved by introducing electric-sensitive, thermal-sensitive and Kerr dielectric materials [19–22]. However, the design usually comprises complex geometry and multiple materials, resulting in high-accuracy requirements and difficult fabrication processes. Furthermore, the response time is also a constraint for metamaterials made of thermal-sensitive materials. Interferometric control of refractive light through changing the phase of another incident light is an alternative method to modulate light intensity [23, 24]. However, the phase difference between the two light sources is not easily controlled, which limits to tuning light intensity.

✉ Shuqi Chen
schen@nankai.edu.cn

Hua Cheng
hcheng@nankai.edu.cn

Jianguo Tian
jjtian@nankai.edu.cn

[1] The Key Laboratory of Weak Light Nonlinear Photonics, Ministry of Education, School of Physics and Teda Applied Physics Institute, Nankai University, Tianjin 300071, China

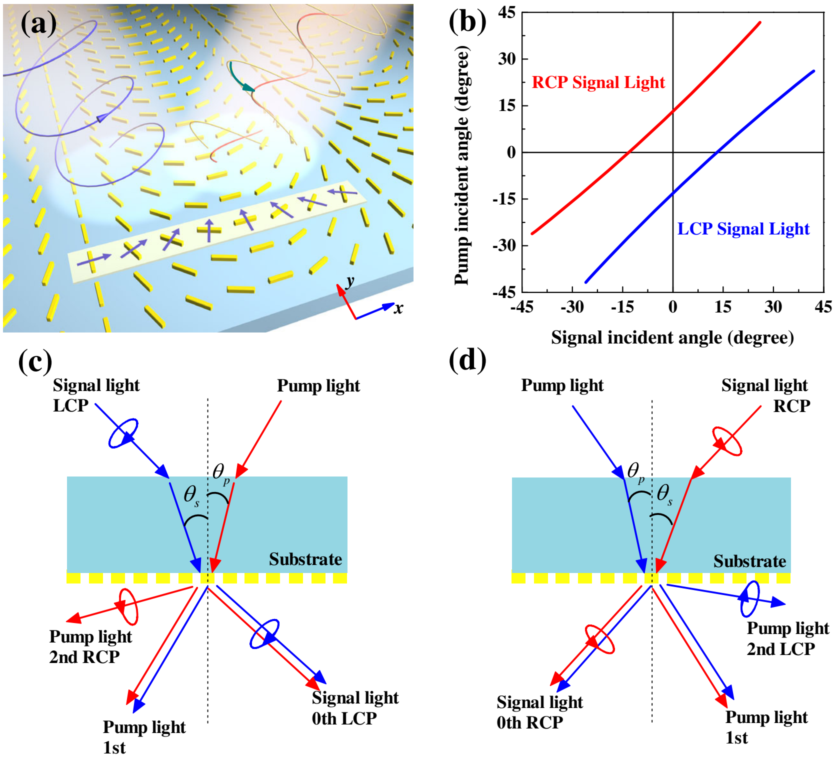

Fig. 1 **a** Schematic illustration of a representative plasmonic metasurface used as a model in our theory and simulation. *Blue arrows* indicate the polarization direction of each nanorod. **b** The incident angle requirements for CP signal light and LP pump light. The *red and blue lines* are circumstances when signal light is RCP and LCP, respectively. **c**, **d** show distributions of refracted light. When incident angles meet the requirement indicated by Eq. 5, the signal light (0th order) will superpose with pump light, resulting in intensity-modulated light with the same propagation direction and polarization as the incident signal light

In this paper, we propose a novel method of modulating light intensity by exploiting the anomalous refraction with phase-gradient metasurfaces. The circularly polarized (CP) signal light will be superposed with linearly polarized (LP) pump light after they transmit the plasmonic metasurface at certain incident angle relationship. As the polarization direction of LP pump light changes, the intensity of CP signal light will accordingly vary. With the proper selected amplitude ratio of the two incident lights, fully tuning the light intensity across a broadband range can be readily achieved.

Theoretical Analysis

Figure 1a shows the chosen phase-gradient plasmonic metasurface, which can be capable of generating ordinary and anomalous refractions. This metasurface consists of arrays of identically shaped gold nanorods (length l = 300 nm, width w = 50 nm, and thickness t = 50 nm), which exhibit a resonance at the wavelength of 1.3 µm. They are arranged evenly along the x-direction with an orientation angle φ that increases in 22.5° increments. The length and width of the unit cell, indicated by a white rectangle in Fig. 1a, are L = 3800 nm and W = 475 nm, respectively. The optical constants of gold are adopted from [25], and the refractive index of the glass substrate is taken to be 1.5. All numerical simulations were carried out using the finite-element method (FEM)-based commercial software, COMSOL Multiphysics [26].

This metasurface can be regarded as a device P that can generate anomalous light and split it away from the ordinary light [10]. If we define right-handed circularly polarized (RCP) and left-handed circularly polarized (LCP) waves as $|R\rangle = [1\ \ i]^T$ and $|L\rangle = [1\ -i]^T$, this process can be expressed as [23, 27]:

$$P|L\rangle = \alpha|L\rangle + \beta|R\rangle e^{-i2\varphi}, \tag{1}$$

$$P|R\rangle = \alpha|R\rangle + \beta|L\rangle e^{i2\varphi}, \tag{2}$$

where α and β are the amplitudes of the refracted beams; they maintain $\alpha + \beta = 1$ after normalization. The phase factor $e^{\pm i2\varphi}$ indicates that the anomalous light carries an extra phase, which is two times of the orientation angle of each nanorod. We refer to β as the conversion efficiency because it represents the capacity of the metasurface to convert the polarization to its opposite. φ can be specified as $\varphi(x) = \pi x/L$ because of the linear arrangement of nanorods in Fig. 1a. Two light sources with incident angles meeting certain eigenstate requirements will lead to superposition in the transmission direction [23]. Similarly, if we substitute one of the incident light sources with LP light—denoted in terms of Jones matrices as $|J\rangle = [\cos\phi\ \ \sin\phi]^T$, where ϕ is the polarization direction—we could also obtain the superposition in the transmitted light. However, in this

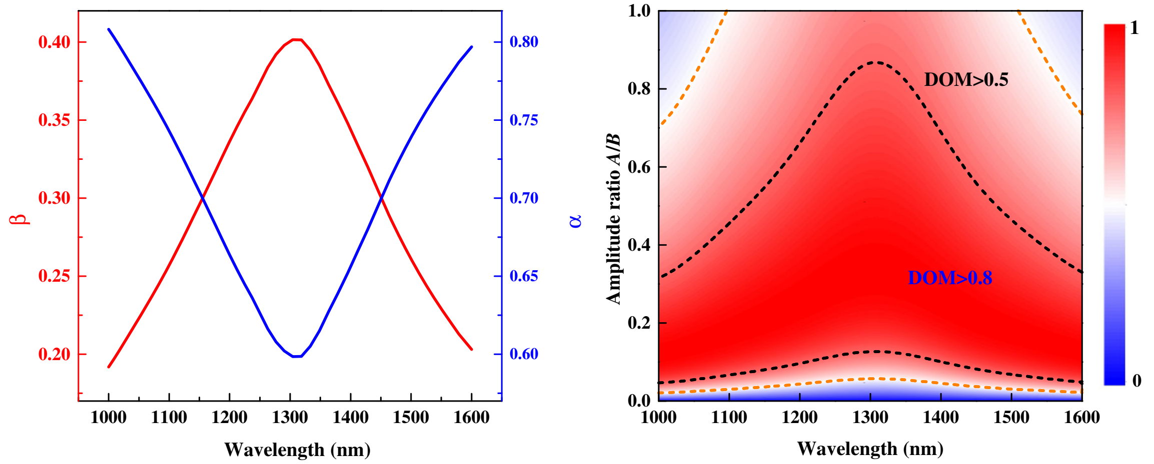

Fig. 2 **a** The values of β and α of the nanorods. β depends on how well each nanorod eliminates the incident light when its polarization direction is parallel to the nanorod. Thus, β has a maximum of about 0.4 at a wavelength of 1300 nm, where the nanorod has the strongest resonance. When the incident light deviates away the resonant wavelength, the value of β will decrease because of the weak reaction between light and nanorod. **b** DOM versus incident wavelength and amplitude ratio A/B (signal/pump)

case, the angle requirements are dependent on the helicity of the signal light, so we construct two states as:

$$|\psi_L\rangle = A|L\rangle + Be^{-i2\varphi}|J\rangle, \tag{3}$$

$$|\psi_R\rangle = A|R\rangle + Be^{i2\varphi}|J\rangle, \tag{4}$$

where A and B are the amplitudes of the signal light and pump light, respectively. The subscripts of ψ indicate the helicity of the signal light. The angle requirement of the two cases can be easily derived by performing a Fourier transformation on the phase factor $e^{\pm i2\varphi}$, which results in:

$$\sin\theta_P = \sin\theta_S + \sigma\frac{\lambda_0}{n_1 L}, \tag{5}$$

where θ_P and θ_S are the incident angles for pump and signal light, λ_0 is the wavelength of light in vacuum, n_1 is the refractive index of the substrate, and $\sigma = +1$ and $\sigma = -1$ correspond to signal lights that are RCP and LCP respectively. Figure 1b presents the angle requirements of pump and signal light at the wavelength of $\lambda_0 = 1.3$ µm.

The amplitudes and propagation directions of transmitted light, including signal and pump light, can be found by imposing the operator P on Eqs. 3 and 4. Because of the similarity between the two results, we only show the result of LCP signal incident circumstance as:

$$\begin{aligned} P|\psi_L\rangle = &\left(A\alpha + \tfrac{1}{2}B\beta e^{-i\phi}\right)|L\rangle e^{i0} \\ &+\left[\left(A\beta + \tfrac{1}{2}B\alpha e^{-i\phi}\right)|R\rangle + \tfrac{1}{2}B\alpha e^{i\phi}|L\rangle\right]e^{i2\varphi}. \\ &+\tfrac{1}{2}B\beta e^{i\phi}|R\rangle e^{i4\varphi} \end{aligned} \tag{6}$$

Accordingly, three orders of refractive light can be obtained. The first term denotes the signal light with the same propagation direction and polarization as the incident light, which is corresponding to the 0th order refractive light in Fig. 1c. The second and third terms represent pump light deflected away from the signal light, which are corresponding to the first- and second-orders diffractive light in Fig. 1c respectively. The first-order light is no more LP light because part of CP light from signal light is superposed with it. The second-order light has the opposite helicity compared to the signal light, but it is not modulated. The case when the signal light is RCP is also presented in Fig. 1d.

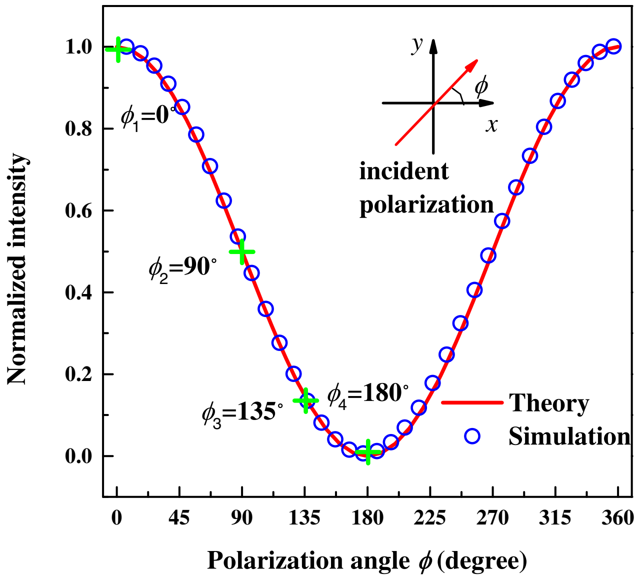

Fig. 3 The theoretical (*red line*) and simulated (*blue points*) intensities (normalized) for signal light upon changing the polarization direction of the pump light. The inset shows the polarization direction of the pump light with polarization angle ϕ

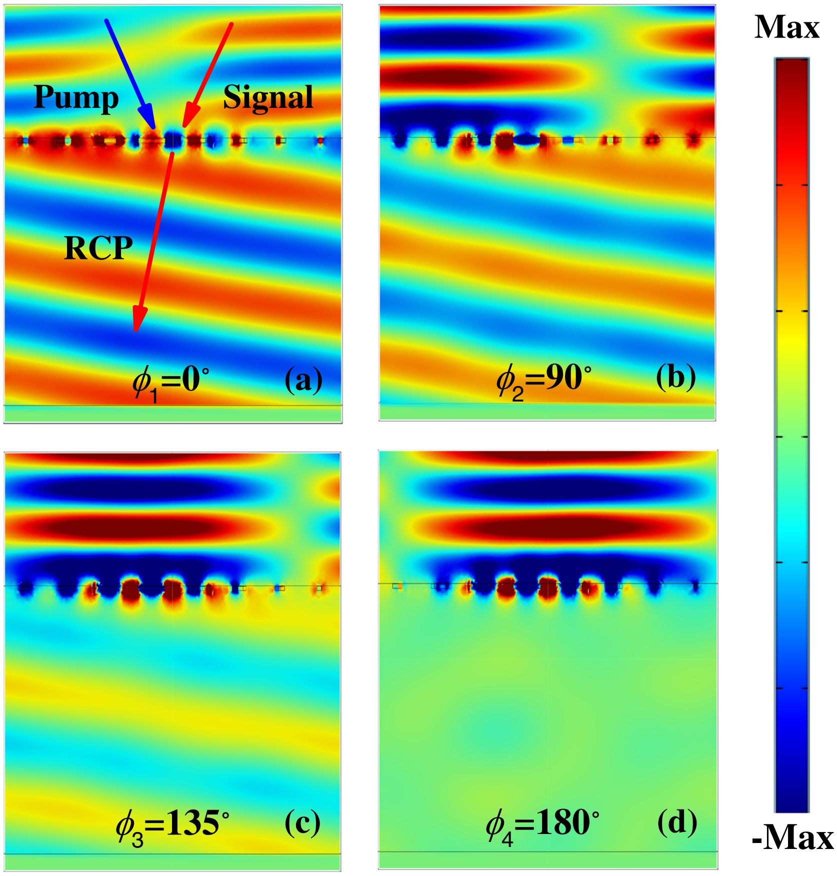

Fig. 4 Panels **a–d** show the electric field distribution of fully modulated right-handed circularly polarized (RCP) signal light. The adopted polarization directions correspond to the *green marks* shown in Fig. 3. When ϕ is 0°, the intensity of the signal light reaches its maximum. It then decreases upon varying the polarization direction of the pump light, and finally disappears as ϕ reaches 180°

The amplitude of the modulated signal light thus can be calculated from Eq. 6 as:

$$|E_s(\phi)| = \sqrt{A^2(1-\beta)^2 + B^2\beta^2/4 + AB(1-\beta)\beta\cos\phi}, \tag{7}$$

It is apparently a periodic function of the polarization angle ϕ, which means that we can tune the intensity of the signal light solely by changing the incident polarization of the pump light. Because of the phase-gradient, the incident pump light is converted to anomalous light with a refractive angle and polarization identical to those of the signal light. Therefore, any change in its polarization direction will alter the phase difference between the two superposing light sources. In this manner, interferometric modulation of signal light intensity by anomalous refraction can be achieved.

According to Eq. 7, except for the polarization angle of LP light ϕ, the parameters affecting the amplitude of the transmitted signal light are the conversion efficiency β and the incident amplitude ratio A/B. The former parameter is involved with the incident wavelength and the properties of the nanorods. In our case, the metallic nanorod has the conversion efficiency displayed by the red line in Fig. 2a; also in this figure is the value of α (blue line), which is determined by the normalization condition. At the resonant wavelength of the nanorods (i.e., $\lambda_0 = 1.3$ μm), the conversion efficiency is about 0.4. The influence of A/B on the degree of modulation (DOM, defined as $\eta = 1 - |E_{\min}|^2/|E_{\max}|^2$) from 1000 to 1600 nm is presented in Fig. 2b. The region bounded by the black dashed lines indicates a DOM larger than 0.8, whereas the region bounded by the orange dashed lines indicates a DOM larger than 0.5. For any wavelength, DOM = 1 can be achieved by selecting the proper amplitude ratio A/B based on the conversion efficiency at that wavelength. It is relatively easy to achieve the ideal modulation effect when A and B have values that are not significantly different from each other.

Simulation Demonstration

A full three-dimensional simulation was performed at the wavelength of $\lambda_0 = 1.3$ μm to demonstrate our theory. The RCP signal light and LP pump light were incident on the metasurface at the angle $\theta_s = -\theta_p = 6.5°$, which meets the angle requirement given in Fig. 1b. The only RCP signal light that is detected occurs at the zeroth-order transmission direction. The amplitude ratio A/B in all following circumstances is properly chosen (here: $A/B = 0.42$) to ensure that the DOM is 1. Figure 3 gives the theoretical and simulated normalized intensities for signal light by changing the polarization direction of the pump light. The red line is the theoretical results when the DOM = 1. The blue circles represent simulated points that result from changing the polarization direction ϕ from 0 to 2π. We can see that the simulated results are in good agreement with our theoretical results. In this case, the polarization angles ϕ and $\phi + \pi$ are two different polarization states because the directions of their electric field oscillations are reversed. Here, we neglect the effect of the relative phase δ of the two incident light sources. If the relative phase is considered, the modulation effect should be expressed as $|E_s(\phi + \delta)|$. Therefore, the true total modulation curve in Fig. 3 might shift toward the right or left; nevertheless, the curve will always maintain a sinusoidal form with a period of 2π.

Figure 4a–d shows the simulated electric field distributions of RCP signal light when the pump light takes on different polarization directions ϕ, which are indicated by green markers in Fig. 3. The wavefront and amplitude of the RCP signal light are distinct and maximal in the case of $\phi = 0$, as shown in Fig. 4a. The converted RCP light from pump light and signal light has no relative phase different, so the refracted RCP light is largely strengthened. With the increasing of the polarization angle ϕ, the relative phase between pump light and signal light becomes larger, resulting in the destructive interference to the signal light. Consequently, the RCP refracted light gradually becomes weak, which can be seen in Fig. 4b, c. The relative phase difference of pump light and signal light will reaches π when the polarization angle $\phi = \pi$. The refractive RCP light will be totally eliminated, as shown in Fig. 4d.

Conclusion

In conclusion, we have demonstrated that the CP signal light intensity can be manipulated by the anomalous refraction of LP pump light that is introduced on a metasurface. By changing the polarization direction of the pump light, the intensity of the signal light will vary accordingly; total control is achieved across a large waveband rang when the amplitude ratio of signal light and pump light is properly selected. Our work therefore provides a novel technique for controlling the intensity of signal light by changing the polarization of pump light. This study will therefore lead to promising applications in optical communications, intensity measurement, polarization detection, photon computing, and other photonic devices at the nanoscale.

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