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Coherent control of Snell's law

J.H. Shi^{1,2,*}, X. Fang² and N.I. Zheludev^{2,3,#}

¹Key Laboratory of In-Fiber Integrated Optics of Ministry of Education, College of Science, Harbin Engineering University, Harbin 150001, China

²Optoelectronics Research Center, University of Southampton, Southampton SO17 1BJ, UK

³Centre for Disruptive Photonic Technologies, Nanyang Technological University, Singapore 637378, Singapore

*hrbeusjh@gmail.com #niz@orc.soton.ac.uk

Abstract: We demonstrate coherent control of the generalized Snell's law in ultrathin gradient metasurfaces constructed by an array of V-shaped slot nanoantennas.

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Newly invented metasurfaces with a gradient phase change along the surface hold great advantages to extraordinarily manipulate the propagation of electromagnetic waves and were demonstrated to follow the generalized Snell's law, allowing anomalous reflection and refraction [1-2]. The gradient metasurfaces sufficiently control phase, polarization and angular momentum of electromagnetic waves, however, there have been no attempts to unveil how gradient metasurfaces interact with a standing wave. It is worthwhile to study coherent control of the generalized Snell's law and explore position-dependent excitation of the anomalous beam in a standing wave. This provides a new opportunity to control the associated optical phenomena coherently by placing the gradient metasurfaces at a node or anti-node of the standing wave interference pattern.

Fig. 1. (a) Schematic of the anomalous and normal transmitted beams in the gradient metasurface for an x-polarized beam. (b) The simulated results of transmission, reflection and absorption of the total intensity and the output intensities T_{yx_ano} and T_{xx_nor} of the anomalous and normal refracted beams. (c) Scattered E_y field pattern and its phase map of the gradient metasurface for a normally incident x-polarized light at a wavelength of 635 nm. (d) Transmission phase of the anomalous refracted beam within a super cell along the dotted line in Fig. 1(c).

The negative metasurface we consider is cut from an ultrathin gold film with a thickness of $t=50$ nm shown in Fig. 1(a), exactly complementary to the positive one of V-shaped nanoantennas. The metasurface of V-shaped slot antennas exhibits a broadband anomalous refraction as well as anomalous reflection in Fig. 1(b). At a wavelength of $\lambda = 635$ nm, the output intensities T_{yx_ano} and T_{xx_nor} of the anomalous and normal transmitted beams are about 12% and 14%, meanwhile, the energy absorption is about 20%. Simulated scattered E_y field pattern and its phase map of the gradient metasurface at $\lambda = 635$ nm for a normally incident x-polarized excitation are shown in Fig.1(c). Obviously, the anomalous beam is approximate a plane wave and further the propagating directions of the

anomalous refracted and reflected beams depart from the normal direction. The refraction angle of θ_r is about 23.4° , consistent with the theoretical calculation. The eight variable slot antennas create phase shifts φ from -180° to 180° for the cross-polarized anomalous beam within a super cell, illustrated in Fig. 1(d).

Fig. 2. Coherent control of the gradient metasurface of V-shaped slot antennas at $\lambda = 635$ nm. (a) Total output intensity S and absorption A of the gradient metasurface as a function of the phase difference α between the control and signal beams. S_1 and S_2 indicate the signal and control outputs, respectively. (b) The output intensities S_{yx_ano} and S_{xx_nor} of anomalous and normal beams for the signal output as a function of the phase difference α between the control and signal beams. (c) Simulated scattered E_y field patterns of the gradient metasurface for $\alpha = 0^\circ, 90^\circ, 180^\circ$ and 270° . All color maps of the electric fields are plotted in the same scale as Fig. 1(c).

Further we investigate how this gradient metasurface response is affected by an additional coherent control beam of the same polarization as the incident signal beam. In the coherent control case, the input intensities of the signal and control beams are defined as 100% and thus the total output intensity is up to 200% without any absorption. S_1 , S_2 , S and A indicate the signal output intensity, the control output intensity, the total output intensity and absorption, respectively, in which $S = S_1 + S_2$ and $A = 1 - S$. Figure 2(a) shows that the scattered intensities of the output beams and the total absorption strongly depend on the phase difference α between the control and signal beams. The signal output intensity S_1 is chosen to check how the anomalous and normal beams are coherently controlled ($S_1 = S_{yx_ano} + S_{xx_nor}$). For in-phase electrical excitation ($\alpha = 0^\circ$) of the metasurface, in comparison to $T_{yx_ano} = 12\%$ of single beam excitation, the total anomalous beam output in the coherent control case approximately fourfold increases, i.e. about 48%. On the other hand, for anti-phase excitation ($\alpha = 180^\circ$), the anomalous beam output intensity T_{yx_ano} dramatically decreases to zero and the normal beam output intensity T_{xx_nor} are about 100%. In order to visualize the amplitude and propagating direction of the anomalous beam, figure 2(c) presents the simulated scattered E_y field patterns of the gradient metasurface for $\alpha = 0^\circ, 90^\circ, 180^\circ$ and 270° . Evidently, different from the output intensity, the propagating direction of the anomalous beam is insensitive to the phase difference α between the control and signal beams. The refracted angle of the anomalous beam is always about 23.4° except for $\alpha = 180^\circ$. The interesting feature is well understood that the metasurface's eigenmodes related to the gradient V-shaped elements remain unchanged when the phase difference α varies. Therefore, the normal and anomalous beams following the generalized Snell's law are well coherently modulated and two modes are easily switched on/off by changing the phase difference α between the control and signal beams. Although here the wavelength is fixed as $\lambda = 635$ nm, coherent control technique can be applied in a broad band [3].

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