Helicity dependent directional surface plasmon polariton excitation using a metasurface with interfacial phase discontinuity

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Surface plasmon polaritons (SPPs) have been widely exploited in various scientific communities, ranging from physics, chemistry to biology, due to the strong confinement of light to the metal surface. For many applications, it is important that the free space photon can be coupled to SPPs in a controllable manner. In this Letter, we apply the concept of interfacial phase discontinuity for circularly polarized SPPs on a metasurface to the design of a novel type of polarization-dependent SPP unidirectional excitation at normal incidence. Selective unidirectional excitation of SPPs along opposite directions is experimentally demonstrated at optical frequencies by simply switching the helicity of the incident light. This approach, in conjunction with dynamic polarization modulation techniques, opens gateway towards integrated plasmonic circuits with electrically reconfigurable functionalities.

Keywords: metamaterials; metasurface; surface plasmon
properties as well as polarization-dependent refractions, through careful arrangement of dipole antennas with spatially varying orientations. Here we employ a plasmonic metasurface to realize helicity-dependent SPP unidirectional excitation. By changing the helicity of the incident beam, we can achieve an asymmetric momentum matching condition of SPPs along different directions for input light at normal incidence.

**MATERIALS AND METHODS**

The unidirectional SPP coupler consists of an array of elongated apertures with a constant gradient of orientation angle $\varphi$ along the $x$ direction, as shown in Figure 1a. In general, each aperture can be considered as a combination of electric and magnetic dipoles. Each dipole, under the illumination of circularly polarized light at normal incidence, can be decomposed into two circularly oscillating components, with one component having the same helicity as the incident light and a phase that does not depend on the orientation of the aperture, and the other with opposite helicity to the incident light and a phase $2\varphi$ that is twice the orientation angle of the aperture (see Supplementary Information). For an array of apertures with a constant gradient in the orientation angle, the refraction and diffraction of light by the array show ordinary and anomalous refraction and diffraction orders. In particular, such phase discontinuity for anomalous refraction and diffraction is geometric in nature and does not rely on the incident wavelength. By taking into account the contribution from the phase gradient, the angles of the ordinary and anomalous refracted and diffracted beams for a normal incident beam are given by:

$$n_t \sin \theta = \frac{\lambda_0}{s} \left( \frac{\Delta k}{2\pi} \right)$$ (ordinary diffraction) \hspace{1cm} (1a)

$$n_t \sin \theta = \frac{\lambda_0}{s} + 2\varphi + \frac{\Delta \omega}{2\pi} = \frac{\lambda_0}{s} \left( m + 2\varphi + \frac{\Delta \omega}{2\pi} \right)$$ (anomalous diffraction) (1b)

where $n_t$ and $\theta$ are the refractive indices and angles for the transmitted (index ‘t’) beams, respectively. $\lambda_0$ is the incident wavelength in

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**Figure 1** (a) Schematic of a unidirectional SPPs coupler. The coupler consists of an array of rectangular apertures with spatially varying orientations on a metal film. (b) Ordinary and anomalous refraction and diffraction for the two circular polarization states. The anomalous diffraction orders are asymmetric about the surface normal. (c) Dispersion curve of SPPs and the momentum matching condition for ordinary and anomalous diffraction orders. (d) Only one of the anomalous diffraction orders in (b) can be matched to the SPP dispersion relation to launch unidirectional SPP due to the asymmetry in the anomalous diffraction orders. Interestingly, when the helicity of the incident beam is reversed, so is the direction of the SPP excitation. SPP, surface plasmon polariton.
SPPs can be calculated by:

\[ \text{dispersion curves for SPPs at air/metal and metal/glass interfaces, respectively.} \]

\[ \text{Figure 1c. The in-plane wave vector of light for generating} \]

\[ \text{condition for a beam at normal incidence to excite SPPs, as illu-} \]

\[ \text{Figures 2 and 3 illustrate the ordinary and anomalous refraction and} \]

\[ \text{for the two circular polarization states. For a circularly} \]

\[ \text{polarized incident beam at normal incidence, the two ordinary first-} \]

\[ \text{order diffracted beams are symmetric about the central ordinary zero} \]

\[ \text{order beam along the surface normal. In contrast, the anomalous} \]

\[ \text{refracted beam and the two first-order anomalous diffracted beams} \]

\[ \text{are shifted towards the same direction relative to their ordinary} \]

\[ \text{counterparts. As a result, the two anomalous first-order diffracted beams} \]

\[ \text{are not symmetric about the surface normal, which forms the basis of} \]

\[ \text{unidirectional SPP excitation at certain optical frequencies.} \]

\[ \text{The lattice constant between neighboring apertures s and the step of} \]

\[ \text{the rotation angle of the aperture } \Delta \phi \text{ offer the necessary phase matching} \]

\[ \text{condition for a beam at normal incidence to excite SPPs, as illustrated by Figure 1c.} \]

\[ \text{The in-plane wave vector of light for generating} \]

\[ \text{SPPs can be calculated by:} \]

\[ k_{\text{app}} = \frac{2m\pi}{s} + \sigma \frac{2A\phi}{s} \]

\[ \text{For ordinary refraction, both of the two first-order diffracted beams} \]

\[ \text{correspond to SPPs at the same optical frequency } \omega_2 (\lambda_2), \text{ but} \]

\[ \text{with opposite propagation directions. For anomalous refraction with an} \]

\[ \text{incident beam of right handed helicity } (\sigma = +1), \text{ the phase matching} \]

\[ \text{condition is shifted to a higher frequency } \omega_1 (\lambda_1) \text{ for SPPs propagating} \]

\[ \text{along } +x \text{ direction, and to a lower frequency } \omega_3 (\lambda_3) \text{ for} \]

\[ \text{propagating along } -x \text{ direction. This effect arises due to the extra} \]

\[ \text{positive in-plane momentum arising from the phase gradient. Interest-} \]

\[ \text{ingly, when the helicity of the input beam is changed to left handedness} \]

\[ (\sigma = -1), \text{ the phase matching condition is reversed, leading to unidirectional SPP} \]

\[ \text{propagation along } +x \text{ and } -x \text{ at } \omega_3 \]

\[ \text{and } \omega_1, \text{ respectively. Thus, at the two optical frequencies } \omega_1 \text{ and } \omega_3, \]

\[ \text{the propagation direction of SPPs can be reversed by simply changing} \]

\[ \text{the circular polarization of the input light, as illustrated by Figure 1d.} \]

\[ \text{For a metal film on a glass substrate, SPPs are supported at both the} \]

\[ \text{air/metal and glass/metal interfaces. In general, there is a coupling} \]

\[ \text{between the SPPs at the two interfaces to form hybrid modes. How-} \]

\[ \text{ever, as in our design the metal film is 40 nm thick, which is twice} \]

\[ \text{the skin depth, the coupling between the two interfaces is very small,} \]

\[ \text{leading to decoupled SPPs at the top and bottom interface. Here we} \]

\[ \text{only investigate the excitation of SPPs at the glass/metal interface. The} \]

\[ \text{dispersion curve of SPPs at the glass/metal interface is given by:} \]

\[ \lambda_{\text{app}} = \frac{\lambda_0}{\sqrt{\frac{\text{Re}(\varepsilon_m) + \varepsilon_d}{\text{Re}(\varepsilon_m)\varepsilon_d}}} \]
followed by metal deposition (3 nm Ti and 40 nm Au) and a lift-off process. A scanning electron microscopy image of the fabricated sample is shown in Figure 3a. The nanoapertures with variable orientation are \( \approx 200 \, \text{nm} \) long and \( \approx 50 \, \text{nm} \) wide, and the lattice constant \( s=570 \, \text{nm} \) is the same along both \( x \) and \( y \) directions. The nanoaperture array covers an area of \( 17 \, \mu \text{m} \times 100 \, \mu \text{m} \), containing five periods along the direction of SPP excitation. In order to scatter the SPPs into the far-field for simple detection, two gratings were symmetrically located on both sides of the array as outcouplers. The gratings have a pitch of 400 nm with duty cycle of 50% and a length of 100 \( \mu \text{m} \). Each outcoupler is 25 \( \mu \text{m} \) away from the edge of the nanoaperture array.

We employ far-field microscopy detection to experimentally demonstrate the directional excitation of SPPs at the glass/metal interface. The experimental set-up is schematically illustrated in Figure 3b. The CP light with left or right circular polarizations, generated by a polarizer and a quarter-wave plate, is normally incident on the front side (air/metal interface) of the sample. Two objectives are confocally aligned for the excitation and the detection of the scattered SPP wave. The scattered light emanating from the outcoupler gratings is collected with a 20\( \times \)0.40 objective and imaged to a CCD camera.

Figure 4a–4e shows the obtained far-field images of the scattered light from the SPPs by the output couplers for circularly polarized incident light at wavelength of 1020 nm, 870 nm and 780 nm, respectively. Note that the wavelengths where SPPs are observed are slightly shifted away from the designed values because of the possible deviation of geometries of the fabricated sample from the design. The excitation of the SPPs at these three wavelengths is evidenced by the elongated bright spots located at the positions of the outcoupers. Away from these wavelengths, the phase matching condition is not exactly matched, and the conversion efficiency to SPP drops correspondingly. The white saturated spots at the center correspond to the directly transmitted light through the nanoapertures and the metal film. As shown in Figure 4a and 4b for \( \lambda=1020 \, \text{nm} \), the propagation direction of the SPPs can be reversed to the opposite directions when the circular polarization of the incident beam is switched. While in Figure 4c for \( \lambda=870 \, \text{nm} \), the SPPs are excited equally along both directions, due to the fact that the momentum conservation for both directions is matched simultaneously for the two first-order ordinary refracted beams. The switchable SPP excitation is also observed for \( \lambda=780 \, \text{nm} \), despite that the contrast between SPPs propagating to the opposite directions is not as high as that for \( \lambda=1020 \, \text{nm} \). We plot the line cross-sections of the intensity corresponding to each case as well, where the helicity-dependent unidirectional excitation at anomalous diffraction orders is further verified. All these results are in good agreement with full wave simulations calculated by COMSOL Multiphysics shown in Figure 4f–4j. Due to the presence of a significant level of background optical intensity, it is difficult to accurately characterize experimentally the extinction ratio between the coupling efficiency of SPPs along the two opposite directions. Numerical simulations show that at \( \lambda_1=762 \, \text{nm} \), the extinction ratio is around 24, and at \( \lambda_2=1016 \, \text{nm} \), the extinction ratio can reach 270. It is also numerically calculated that the excitation efficiency for such a nanoaperture array is around 3.8% (see Supplementary Information). This low efficiency is mainly because that the structure we employed (holes in metal film) is not an optimized configuration, but it is chosen because of the ease of fabrication. It is expected that the coupling efficiency
would be significantly enhanced by replacing the non-resonant apertures with resonant structures, such as the magnetic antennas exhibiting a strong magnetic resonance as demonstrated by Ref. 19. Theoretically, we have investigated a metasurface consisting of metal/dielectric/metal resonators, which give rise to significantly higher efficiency of 14% (see Supplementary Information).

As any polarization state can be decomposed into left and right-handed circular polarizations, it is expected that arbitrary ratios between the excitation of SPPs propagating along opposite directions can be achieved by simply adjusting the ellipticity of the polarization state for the incident beam. This is experimentally confirmed, with the results shown in Figure 5. By rotating the axis of the quarter-wave plate while keeping the orientation of the linear polarizer fixed at 0°, the polarization state can be tuned continuously from one circular polarization, through elliptical and linear polarizations, to the opposite circular polarization. The ellipticity is defined as \( \eta = \frac{E_R - E_L}{E_R + E_L} \), with ±1 representing right (left) circular polarization, and 0 representing linear polarization. The ellipticity \( \eta \) is related to the rotation angle of the axis of the quarter wave plate \( \theta \) simply by \( \eta = \tan(\theta) \). Figure 5 shows continuously tunable SPP excitation efficiencies between the two opposite directions at \( \lambda = 1020 \) nm. For left/right circular handedness at points A and G, the SPPs are propagating at a predominant direction, while for ellipticity equal to zero (point D), equal excitation along both directions is achieved. The experimental results are in good agreement with the numerical simulation (solid curves) that is offset by the background optical intensity. Such ellipticity tunable properties can greatly facilitate transforming desired distribution of input energies into a plasmonic circuit.

### CONCLUSION

In summary, we have demonstrated polarization-dependent unidirectional SPP excitation based on phase discontinuities introduced by an array of plasmonic apertures with spatially varying orientations. The directional SPP excitation shows very high extinction for circularly polarized incident light. The ratio for the excitation of SPPs propagating to opposite directions can be simply adjusted by the ellipticity of the input light. In comparison to a previous work that uses metasurface to launch unidirectional SPP with high efficiency, our work focuses on a totally different functionality—spin switching of the direction of the surface plasmon excitation. The physics underlying our work is a Berry geometrical phase that depends solely on the
orientation of each nanoaperture, but not the structure and shape of each individual element. Importantly, as the switching of the SPP excitation is based on the polarization of input light, polarization modulator based on liquid crystals or polymers can be monolithically incorporated to form a compact, electrically controlled plasmonic circuit. The device works upon normal incidence, which would facilitate realistic experimental setup for the next generation of integrated plasmonic circuits.

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Figure 5 Experiment demonstration of continuously tunable contrast between SPP excitation along +x and –x directions by varying the ellipticity of the input light at λ=1020 nm. Points A–G correspond to the CCD images for η=−1 (φ=+45°), η=−0.364 (φ=−20°), η=−0.176 (φ=−10°), η=0 (φ=0°), η=0.176 (φ=10°), η=0.364 (φ=20°) and η=1 (φ=45°). The symbols show the y-integrated output power at the two positions for outcoupler vs. ellipticity ranging from [−1, 1]. The solid curves are calculated by using full wave simulation by COMSOL Multiphysics to investigate the peak intensities at the metal and dielectric boundaries at each side. All intensities are normalized in the range of [0, 1]. CCD, charge coupled device; SPP, surface plasmon polariton.

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