Spin-controlled directional launching of surface plasmons at the subwavelength scale*

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In this paper, we demonstrate a spin-controlled directional launching of surface plasmons at the subwavelength scale. Based on the principle of optical spin's effect for the geometric phase of light, the nanostructures were designed. The inclination of the structures decides the spin-related geometric phase and their relative positions decide the distance-related phase. Hence, the propagation direction of the generated surface plasmon polaritons (SPPs) can be controlled by the spin of photons. Numerical simulations by the finite difference time domain (FDTD) method have verified our theoretical prediction. Our structure is fabricated on the Au film by using a focused ion beam etching technique. The total size of the surface plasmon polariton (SPP) launcher is 320 nm by 180 nm. The observation of the SPP launching by using scanning near-field optical microscopy is in agreement with our theory and simulations. This result may provide a new way of spin-controlled directional launching of SPP.

Keywords: surface plasmon, spin-controlled, directional launching, subwavelength scale

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1. Introduction

Surface plasmon polaritons (SPPs) are propagating excitations that arise from the coupling of light with collective oscillations of the electrons at the surface of a metal.[1] Because of their ability to break the diffraction limit, SPPs are believed to be promising candidates for constructing the next generation ultracompact integrated photonic circuits, and have been widely used in nano-optics, including surface plasmon focusing,[2–5] subwavelength waveguiding,[6–9] and surface plasmonic crystals.[10,11] However, due to the wavevector mismatching, the SPPs cannot be directly launched onto the smooth metal surface from the free-space light. Thus, unidirectional SPP couplers which can couple the SPPs from the free-space light to a desired direction or region are very important for the on-chip plasmonic devices. Over the past few decades, many schemes have been proposed to achieve unidirectional SPP launching.[12–18] Furthermore, some schemes have also been proposed to actively tune the propagation direction of SPPs by additional external control, such as fishbone-like metasurface and slit by changing the handedness of the incident light (spins of photons),[19–23] graphene-loaded antenna pair by changing applied voltage.[24] In above schemes which tune the propagation direction of the SPPs by the optical spin, the structure unit does not have the ability of controlling the direction of propagation of photons by spin. It can be realized only when a periodic structure of units arranged in a column with a spacing equal to half of the SPP wavelength, the interference among these structure units can result in that the propagation direction of the SPP excited by the column can be tuned by spin. Therefore, most of the above unidirectional SPP launchers have large longitudinal dimensions ($> 10\lambda$, perpendicular to the SPP propagation direction on the metal surface). This would significantly limit the on-chip integration density of the plasmonic devices and bring large crosstalk between different plasmonic devices in high-integration plasmonic circuits.

In this paper, we report a method for realizing a spin-controlled directional SPP launcher at the subwavelength scale. Our designed launcher does not depend on the coupling of the multiple structure units and need not be arranged in arrays. Therefore, the total size of the spin-controlled directional SPP launcher is far smaller than those already reported structures.[19–23]

2. Theory and simulation

The principle of our design is based on geometric phases of light which originate from the coupling between spin angular momentum and coordinate frame rotations. In the simplest circumstances, for circularly polarized waves which propagate in the z direction and carry spin angular momentum s (Planck

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constant $\hbar = 1$), rotation of the coordinates by an angle θ (about the z axis) would induce a geometric phase $\Phi_{\rm G} = s\theta$ given by the product between the spin angular momentum and the rotation angle. As is shown in Fig. 1(a), the slit is clockwise rotated θ (along the direction of light) and slit 1 becomes slit 2. According to the above principle, in the slit coordinate, the light which is incident on slit 1 and the light on slit 2 would have a phase difference $s\theta$. In the circumstance as shown in Fig. 1(b), the total phase difference is the sum of spin-related phase difference $s\theta$ and distance-related phase difference kd (on the right side) or $-kd$ (on the left side), equal to

$$\begin{aligned} \Delta_{\rm right} &= kd + s\theta, \\ \Delta_{\rm left} &= -kd + s\theta, \end{aligned} \tag{1}$$

where k is the wave vector and s is the spin quantum number. The distance-related phase difference has opposite signs in two sides of the structure, and the spin-related phase difference keeps the same. Thus, the total phase difference of two sides is different.

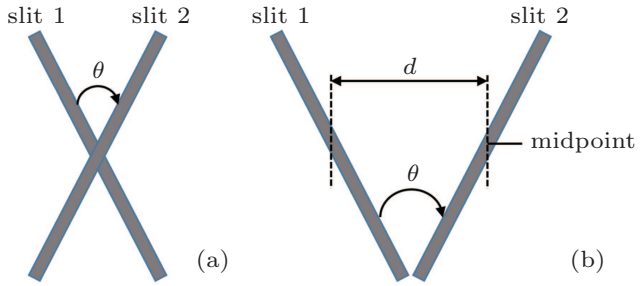


Fig. 1. (a) Two intersecting slits with the intersection angle θ. (b) Two intersecting slits with the intersection angle θ. d indicates the distance between the midpoint of two slits.

Let us consider a more complex system as shown in Fig. 2. The right part of the curve is defined by the expression $x = (1/k_{\rm spp})\arccos(\mathrm{e}^{-y/k_{\rm spp}})$ and the left part is defined by the expression $x = -(1/k_{\rm spp})\arccos(\mathrm{e}^{-y/k_{\rm spp}})$. We differentiate the equation $x = (1/k_{\rm spp})\arccos(\mathrm{e}^{-y/k_{\rm spp}})$ in both sides, then obtain

$$\cot\theta = x' = \frac{\mathrm{e}^{-y/k_{\rm spp}}}{\sqrt{1-\mathrm{e}^{2y/k_{\rm spp}}}}, \quad \theta \in \left(0, \frac{\pi}{2}\right). \tag{2}$$

Given $\cos\varphi = \mathrm{e}^{-y/k_{\rm spp}}$, the above equation becomes

$$\cot\theta = \frac{\mathrm{e}^{-y/k_{\rm spp}}}{\sqrt{1-\mathrm{e}^{2y/k_{\rm spp}}}} = \frac{\cos\varphi}{\sin\varphi} = \cot\varphi,$$

$$\theta \in \left(0, \frac{\pi}{2}\right) \varphi \in \left(0, \frac{\pi}{2}\right). \tag{3}$$

Therefore,

$$\theta = \varphi = \frac{1}{k_{\rm spp}} \arccos(\mathrm{e}^{-y/k_{\rm spp}}) = k_{\rm spp} x. \tag{4}$$

We consider each point of the curve in Fig. 2 as a small slit and then apply the formula (1) to analyze the phase of the SPPs excited by the curve. In Fig. 2, the angle between the tangent of the point A and the transverse axis is θ. According to the principle in the formula (1), on the right side, the phase of the SPPs excited by the point A consists of spin-related phase $s(\pi/2-\theta)$ and distance-related phase $k_{\rm spp}|x|$, and the phase of the SPPs excited by the point C consists of spin-related phase $-s(\pi/2-\theta)$and distance-related phase $-k_{\rm spp}|x|$ (setting the phase of the longitudinal axis as 0). Thus, the total phase difference between the SPPs excited by the point A and the SPPs excited by the point C on the right side is $s(\pi-2\theta)+2k_{\rm spp}|x|$, and the total phase difference on the left side is $s(\pi-2\theta)-2k_{\rm spp}|x|$. Applying the formula (4), the total phase difference for the spin $\sigma = +1$ photon on the right side is π and the total phase difference on the left side is $\pi-4\theta$ at this time. In the same way, the total phase difference for the spin $\sigma = -1$ photon on the left side is π. Thus, the destructive interference occurs on the right side for the spin $\sigma = +1$ photon and on the left side for the spin $\sigma = -1$ photon. In this way, we can control the propagation direction of the generated SPPs by spin of photons.

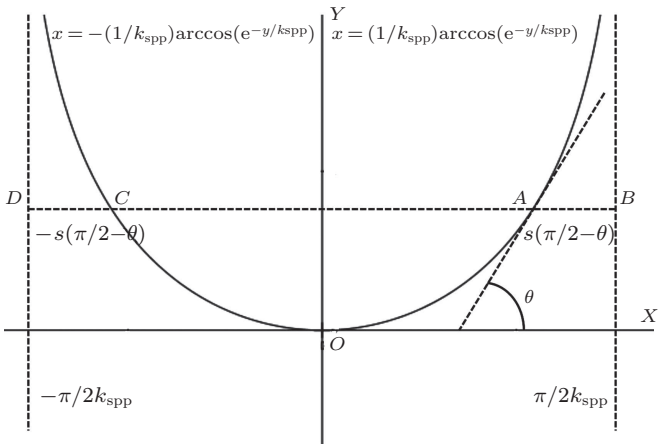


Fig. 2. (a) Schematic diagram of the defined curve above. The inclined dashed line in point A stands for the tangent line at A.

Table 1. The phase of the SPPs excited at points A and C in Fig. 2. The phase of the vertical axis is defined as 0.

The right side	The spin-related phase	The distance-related phase
light scattered by the point A	$s(\pi/2-\theta)$	$k_{\rm spp}\|x\|$
light scattered by the point C	$-s(\pi/2-\theta)$	$-k_{\rm spp}\|x\|$
The left side	**The spin-related phase**	**The distance-related phase**
light scattered by the point A	$s(\pi/2-\theta)$	$-k_{\rm spp}\|x\|$
light scattered by the point C	$-s(\pi/2-\theta)$	$k_{\rm spp}\|x\|$

When the destructive interference occurs on one side, the total phase difference on the other side is π–4θ. If θ is $\pi/2$ or 0, π–4θ is $-\pi$ or π and destructive interference also occurs on this side. Therefore, the part which θ is close to $\pi/2$ or 0 can be removed. It not only can decrease the size of the structure but also can improve the directionality of the SPPs.

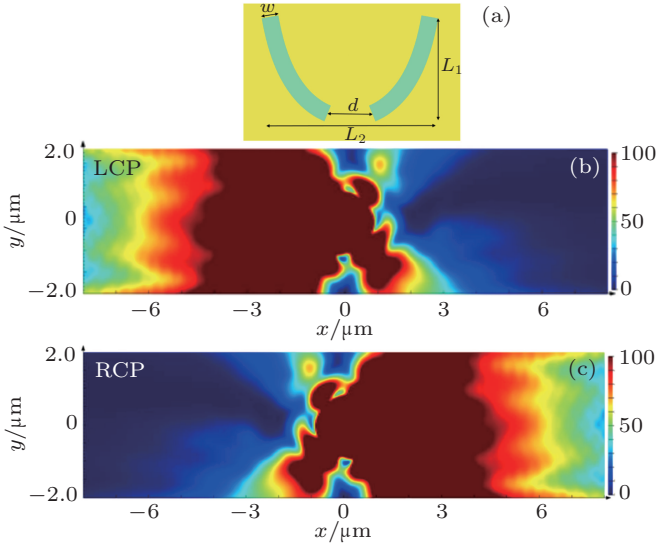


Fig. 3. (color online) (a) Schematic diagram of our proposed structure. (b) and (c) FDTD simulation of the near-field intensity (arbitrary units), calculated from the structure under the LCP and RCP illuminations, respectively. In these pictures, LCP stands for left-handed circularly polarized light, and RCP stands for right-handed circularly polarized light.

Numerical simulations were performed by using the finite difference time domain (FDTD) method to testify the above analysis. According to the above analysis, the structure was truncated at the bottom and top, relative to the curve in Fig. 2(a), to decrease the size of the structure and improve the directionality of the SPPs. The geometrical parameters of the structure in Fig. 3(a) were $w = 35$ nm, $d = 80$ nm, $L_1 = 180$ nm, $L_2 = 320$ nm. The structure was etched into a thin Au film deposited on a glass substrate (SiO_2). A laser beam was normally incident on the structure from the bottom and its wavelength was 671 nm. The relative permittivity of Au was $-12.3+1.13$i, and that of the glass substrate was 2.25, based on the experimental data reported by Palik.[25] The results in Fig. 3(b) and 3(c) show good agreement with the theoretical predictions. When the structure was illuminated by left-handed circularly polarized light (spin $\sigma = +1$ photon), most of the SPPs propagated to the left side. When the structure was illuminated by right-handed circularly polarized light (spin $\sigma = -1$ photon), most of the SPPs propagated to the right side. Further simulations were run to test the sensitivity to the change of structure parameters. Deviations in width ($w = 30$ nm–50 nm), gap ($d = 70$ nm–90 nm) and thickness ($h = 150$ nm–300 nm) have been testified to create not much effect on the directionality of the SPPs. The results are obviously helpful to conduct the following experiment. Due to the limit of fabrication techniques, slight deviation from the perfect structure may not have a significant effect on the experiment results.

3. Experiments

The experiment was conducted by using scanning near-field optical microscopy (SNOM) (Nanonics, Multiview 2000). The sample was illuminated from the bottom by a 671-nm laser beam with its polarization (LCP and RCP) set by using a polarizer and a $k/4$ wave plate (QWP). The SNOM probe was an Al-wavelength, tapered cantilever optical fiber. The SPPs light was acquired by using an Avalanche Photo Diode system (APD). The structure was fabricated by focused ion beam (FIB) milling in a 200-nm thick gold film, which was evaporated on a glass substrate. Figure 4 shows the scanning electron microscope (SEM) image of the sample structure. The parameters of the structure were the same as that of the simulation except for thickness $h = 200$ nm in order to weaken the transmitted light and improve the noise-signal ratio. We arrange four structures as a group to increase the credibility of the experiment phenomenon and the distance between adjacent structures is 5.5 μm, which is enough large to ignore the interaction of these structures.

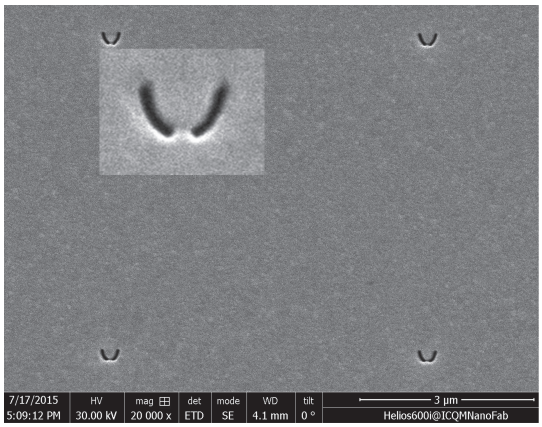


Fig. 4. SEM image of our structure. Four structures are arranged as a group and the distance between adjacent structures is 5.5 μm. The inset is an enlarged view of one structure.

Figures 5(a) and 5(b) show the SNOM images of SPPs intensity distributions of the sample under the RCP and LCP illuminations, respectively. In Fig. 5(a), under the LCP illumination, most of the SPPs generated from the structures are clearly observed to propagate towards the left side. In Fig. 5(b), under the RCP illumination, most of the SPPs generated from the structures are clearly observed to propagate towards the right side. The SNOM micrographs exhibit fringe patterns that result from the interference of the SPPs with incident light directly transmitted through the film, confirming that the measured optical signal corresponds to the near-field and also indicating their plasmonic nature. In Figs. 5(a) and 5(b), the intensity distributions of four structures have a little difference, it may result from the slight difference in the fab-

rication process of the sample. Generally speaking, the experiment is in agreement with the previous theoretical prediction and demonstrates the control of the propagation direction of the SPPs by the handedness of light (the spin of photons).

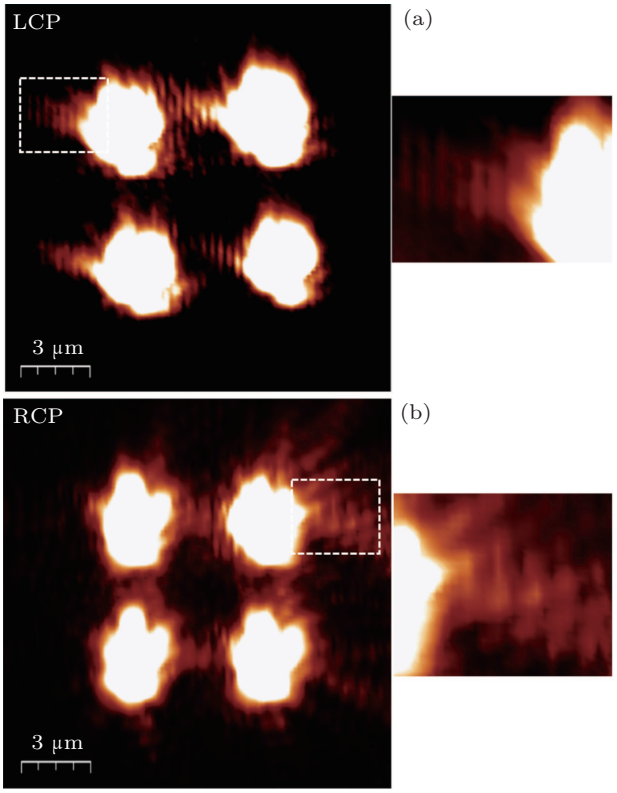


Fig. 5. (color online) (a) and (b) Near-field optical images of the proposed structure under the LCP and RCP illuminations, respectively. The insets on the right side are the enlarged view of the parts enclosed by the white dotted line.

4. Conclusion

We have designed a nanostructured spin-controlled SPP launcher with a unit size of 320 nm by 180 nm in Au thin film, and demonstrated that a tunable directional propagation of SPPs under illumination by circularly polarized light can be realized. The size of our structure is smaller than the wavelength of the incident light. By varying the inclination of the structures and their relative positions with respect to the incident light, the spin-related phase and the distance-related phase can be defined, respectively. Thus the overall phase difference of the SPPs depends on these two degrees of freedom. Hence, the propagation direction of the generated SPPs can be controlled by the spin of photons. FDTD numerical simulations and SNOM observation verified our theory. This result may provide a new way of spin-controlled directional launching of SPP. Such a subwavelength and spin-controlled SPP launcher is important for spin-controlled device's miniaturization and may develop potential applications in highly integrated plasmonic circuits and quantum information.

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