Synthesis and Dynamic Switching of Surface Plasmon Vortices with Plasmonic Vortex Lens

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ABSTRACT The generation of surface plasmon vortices with arbitrary higher order vortex topological charges with novel plasmonic vortex lens is experimentally demonstrated. It is shown that the polarization sensitivity of the plasmonic vortex lens can be utilized for the dynamic switching of the surface plasmon vortices with different topological charges. A simple algebraic rule related to the vortex topological charge change in the dynamic switching is formulated, and its proof is provided with theory and experiment. The synthesis and dynamic switching of higher order surface plasmon vortices have profound potential in optical trapping, optical data storage, and other related fields.

KEYWORDS Surface plasmon, surface plasmon vortex, plasmonic vortex lens, circular polarization

Such as excitation, guiding, and focusing are being unveiled, and practical plasmonic devices and systems are actively researched as well.

The local excitation of SPs is one of the fundamental elements in plasmonics, for which nanoholes,^{5–8} nanoslits,⁹ and curved nanoslits^{10–12} are normally used. Besides, nanoparticles,¹³ channel waveguides,¹⁴ and surface gratings¹⁵ can also be used for local excitation of SPs. The combination of these SP generators can generate various useful SP interference patterns on metal/dielectric interfaces. The interferometric or diffractive SP pattern generation is a fundamental research area of plasmonics initiated very recently. Although research on SP patterning started from the formation of SP focal spots, namely, hot spots on a subwavelength scale,^{8,10–12,16–19} diffractive synthesis of complex SP fields as well as single hot spots^{9,11} and dynamic control of SP fields^{16,19} for various applications appear in the front of plasmonics research.

In this Letter, we report a method for the diffractive formation of SP vortices with a novel proposal of plasmonic vortex lens (PVL). The SP vortex refers to an optical vortex of plasmonic waves with a dark spot and phase singularity at its center. The SP vortex is of particular

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interest due to the fact that the SP vortex has a strong optical angular momentum in the evanescent field region; thus it is useful for various nanophotonics applications such as trapping,²⁰ soliton,²¹ data storage,²² and quantum computation. The proposed PVL takes the form of a set of split curved slits, which are designed to produce SP vortices with arbitrary vortex topological charges. The synthesis and dynamic control of the SP vortices with the proposed PVL are demonstrated with theory and experiment.

Let us first understand the mathematical structure of the SP vortex that shows all concepts addressed in this Letter very clearly. The *z*-directional electric field of the SP vortex on a flat metal/dielectric interface (x-y plane) is mathematically represented by the *l*th order Bessel function with the spiral phase profile of $l\varphi$

$$E_{z,l}(r,\varphi) \propto J_l(k_{\rm SP}r) \exp\left[jl\left(\varphi + \frac{\pi}{2}\right)\right]$$
 (1)

where $k_{\rm SP}$ is the wavenumber of the SP wave given by $k_{\rm SP} = 2\pi l \lambda_{\rm SP}$ and $\lambda_{\rm SP}$ is the wavelength of the SP. (r, φ) is the polar coordinate corresponding to the Cartesian coordinate(x, y). Here, the index l, which is the proportional constant of the azimuthal angle φ in the phase around the dark spot, is referred to as the topological charge of the SP vortex. The whole vectorial field representation of the SP vortex is presented in Supporting Information. The angular spectrum representation of eq 1 unveils the physical origin of the SP vortex²³

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$$J_{l}(k_{\rm SP}r) \exp\left[jl\left(\varphi + \frac{\pi}{2}\right)\right] = \frac{1}{2\pi} \int_{0}^{2\pi} \exp(jm\phi) \exp\left[jk_{\rm SP}(x\cos\phi + y\sin\phi)\right] d\phi \quad (2)$$

where l = m. Throughout this Letter, ϕ denotes the azimuthal angle associated with the SP angular spectrum and the geometry of PVL, whereas φ indicates that of the resultant SP vortex field. The superposition of the infinitesimal SP plane waves converging to the center with the spiral phase exp(*jm* ϕ) results in the SP vortex taking the form of the *l*th order Bessel function with the spiral phase profile of exp[*jl*(φ + $\pi/2$)] with the phase difference $l\pi/2$ from the spiral phase profile of the angular spectra (l = m).

The objective of PVL is to make such a converging angular spectrum with the spiral phase profile $\exp(jm\phi)$ to synthesize SP vortex around the converging center. The design equation of PVL is directly derived from eq 2. The spiral phase profile of the angular spectrum plane wave can be provided by the PVL having the specific curved slit pattern on thin metal film given by

$$r_m(\phi) = r_i + \frac{\lambda_{\rm SP} \mod(m\phi, 2\pi)}{2\pi}, \quad \text{for } 0 \le \phi < 2\pi \quad (3)$$

The notation mod(a, b) represents the remainder of the division of *a* by *b*. The inner radius r_i is the distance from the center to the nearest point of the slit. The outer radius $r_{\rm o}$, defined as the distance from the center to the farthest slit point, is given by $r_i + \lambda_{SP}$. Figure 1a shows the relative phase differences between the converging angular spectra of the SP waves generated from each infinitesimal curved slit of the PVL under radial polarization. If the radial polarization beam illuminates the PVL from the bottom, it induces SP point sources with the same phase on the curved slit pattern of $r_m(\phi)$, as shown in the light red arrows in Figure 1a. However, as the SP waves travel from the slit pattern to the center, they experience the phase retardations, which are proportional to the distance from the slit to the center region, as indicated in the arrows with light colors in Figure 1a. Owing to the spiral geometry of the slit pattern, the SP waves excited on the PVL comprise the angular spectrum with the spiral phase along the circumference of the dashed circle in Figure 1a. Note that there are $\pi/2$ phase delays between the points A, B, C, and D on the circle. Consequently, the spiral phase profile of the resultant SP vortex field has $\exp(j2\varphi)$; i.e., the topological charge of the SP vortex is l = 2. It is noteworthy that this spiral phase originates from the geometric structure of the slit pattern. In this sense, we can say that the PVL shown in Figure 1a has the geometric vortex topological charge of m = 2 for this example PVL. Throughout this Letter, we adopt a convention that the plus and minus signs of the geometric vortex topological charge



FIGURE 1. Schematic diagram of the converging angular spectrum of the SP waves inside the plasmonic vortex lens with m = 2 under (a) the radial polarization, (b) the right-handed circular polarization, and (c) the left-handed circular polarization. The black arrows in upper right corners show the polarization states. The red, green, blue, and yellow arrows correspond to the out-of-plane electric field E_x with the relative phase difference of 0, $\pi/2$, π , and $3\pi/2$, respectively. The dark colors are used to give emphasis on the phases along the circumference of a circle.

correspond to the right- and left-handed rotation direction of the PVL slit patterns looking from the top, respectively. In other words, if the geometric vortex topological charge *m* is positive, the distance from the center to the slit increases as the azimuthal angle ϕ increases and vice versa. Note that the plasmonic lens for making a single SP hot spot can be regarded as the simplest PVL with m = 0.10

The proposed PVL has interesting polarization sensitivity for the illumination of circular polarization beams. In contrast to the case of the radial polarization, the phases of the

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SP waves generated at the slit pattern depend on the azimuthal angle ϕ . In Figure 1b, we illustrate the SP angular spectrum under the illumination of the right-handed circular polarization. Since the direction of the SP wave generated at an infinitesimal part of a slit is always normal to the part of the slit,^{3,11,12,24} the initial phases of the SP waves arriving at the points B, C, and D in Figure 1b are led by $\pi/2$, π , and $3\pi/2$ compared with that at the point A, respectively. In other words, the right-handed circular polarization beam induces the SP point sources with $\exp(j\phi)$. This is the key difference from the case of the radial polarization where the SP point sources have the same phase. The arrows with dark red and dark yellow colors in the points A and B show the phase difference of $3\pi/2$ at the circumference. In a similar way, one can also construct the phase relation between the points C and D. The resulting spiral phase profile of the SP angular spectrum exhibits $\exp(j3\varphi)$, and then the topological charge of the synthesized SP vortex is l = 3. Figure 1c illustrates the SP angular spectrum for the left-handed circular polarization beam. The initial phases of the SP waves at the points B, C, and D are led by $\pi/2$, π , and $3\pi/2$ compared to that at the point A, respectively. It can hence be inferred that illumination of the left-handed circular polarization beam on the PVL induces the SP point sources with $\exp(-i\phi)$. It is seen in Figure 1c that the spiral phase profile of the SP angular spectrum is obtained as $\exp(j\varphi)$, i.e., l = 1.

This phase structure induced by the circular polarization beams leads to interesting effect on the synthesis of SP vortex by the PVL. The synthesis of SP vortices by the rightand left-handed circular polarization beams can be mathematically represented as

$$J_{l}(k_{\rm SP}r) \exp\left[jl\left(\varphi + \frac{\pi}{2}\right)\right] = \frac{1}{2\pi} \int_{0}^{2\pi} \exp[j(m \pm 1)\phi] \exp[jk_{\rm SP}(x\cos\phi + y\sin\phi)] \,\mathrm{d}\phi \quad (4)$$

where $l = m \pm 1$, respectively. When the rotational direction of the circular polarized beam is the same as (opposite to) the rotational direction of the PVL, the topological charge of the obtained SP vortex is increased (decreased) by 1. Therefore, the dynamic switching of SP vortices with topological charges of l = m + 1 and l = m - 1 can be performed on the PVL of geometric vortex topological charge *m* by the dynamic change of the polarization state of circular polarization excitation beam, respectively.

To prove the aforementioned properties of the synthesis and switching of SP vortices, we provide the experimental demonstrations with numerical simulations. The schematic diagram of the experimental setup is shown in Figure 2a. The sample was illuminated from the bottom by the laser with the free space wavelength of 660 nm (Newport, LQA660-110C) and the SP evanescent field intensity distribution was measured by the near-field scanning optical microscope



FIGURE 2. (a) Experimental setup for the NSOM. Illuminated from the bottom is the laser with the free space wavelength of 660 nm and the circular polarization. (b) SEM image of the PVL with the geometrical vortex topological charge m = 4. The inner (r_i) and outer (r_o) radii are 4.00 and 4.64 μ m, respectively.

(NSOM) (Nanonics, Multiview 4000). For the sample fabrication, first, the Ag layer with the thickness of 300 nm was evaporated on a fused silica wafer (MUHAN, MHS-1800). Then the PVL slit patterns with the geometrical vortex topological charges *m* ranging from 0 to 4 were inscribed on the Ag layer by using the focus ion beam (FIB) (FEI, Quanta 200 3D). Figure 2b shows the scanning electron microscopy (SEM) image of the PVL with the geometric vortex topological charge of m = 4. The inner radius r_i is 4 μ m. The slit width is set to be 250 nm, which was found to result in the maximum SP excitation efficiency through numerical simulations. For the free space wavelength λ_0 of 660 nm, the relative permittivity of the silver, ε_m , is given by -17.7 + 1.18j²⁵ The relative electric permittivity values of the glass and air are 2.25 and 1, respectively. The effective refractive index of the SP at the interface between the Ag layer and air is $n_{SP} = 1.03$, resulting in the SP wavelength $\lambda_{\rm SP}$ of 641 nm. The propagation length of the SP is $L_{\rm P} = 25.7$ иm

Located under the sample was the microscopic objective lens with a magnification of 10×, a numerical aperture of 0.28, a working distance of 33.5 mm, and a depth of focus of 3.5 μ m. To illuminate the whole area of PVL uniformly, the beam was slightly defocused on the sample.¹² The SP field inside the PVL was detected by the cantilever type metal-coated (Cr/Au) NSOM tip with a diameter of 250 nm.

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The feedback mode in the NSOM system we used is the noncontact intermittent mode (or tapping mode), in which the tip is tapping over the sample and touches it with the resonance frequency of the tip during the scan. The main benefit from this mode is that there is less chance to damage the sample or the tip compared with the contact mode while the tip is in close proximity (\sim 50–100 nm) to the sample enough to detect the SP field, the decay length of which is \sim 430 nm. The photomultiplier tube (PMT) (Hamamatsu, H7422-20) with a gain of 10^7 was used to convert the light intensity transmitted by the optical fiber into electric signal. The image processing was done with the WSXM.²⁶ The quarter wave plate was used to achieve the circular polarization beam. Unfortunately, the experimental result for the radial polarization is not presented, because in our experiment setup it was impossible to achieve sufficient accuracy in the alignment between the centers of the radial polarizer and the PVL.

The experimental results are presented with simulation results in Figure 3. For the simulation, we employed the rigorous coupled wave analysis (RCWA) with the 63 Fourier harmonics for the *x*- and *y*-directions, respectively. The size of the computation cell was chosen to be 14 μ m \times 14 μ m. The absorbing boundary layer was used to simulate aperiodic structure, by which the influence from the adjacent periodic cells is prohibited.^{11,27} In parts a and d to Figure 3 are the experiment and simulation results for the case in which the rotation direction of the circular polarization beam is the same as that of the geometric vortex topological charge. Parts a and b of Figure 3 show the field intensity of the SP vortex measured by the NSOM, and the field intensity $|E|^2$ obtained by the RCWA at the interface between the Ag layer and air, both of which prove the formation of SP vortex clearly. The white arrow denotes the direction of the rotation of the circular polarization beam looking in the top view. In Figure 3a, it is observed that the dark spot surrounded by the bright circumference, which is called the primary ring of a vortex, is generated at the center of the structure.^{28,29} Outside the primary ring, we can see the interference pattern with the period of $\lambda_{SP}/2$. In our experiment, the NSOM signal level at the brightest point on the primary ring is 2.4 V. In our NSOM equipment, a signal level of 1 V indicates that the optical fiber connected to the NSOM tip carries the power of about 1.25 μ W. The power measured through the NSOM tip-fiber at the primary ring is hence about 3 μ W. Considering that the power of the incident laser beam is 40 mW, the focusing efficiency of the PVL is estimated as 3.13×10^{-5} . Note that, however, since there is some coupling loss of the SP field into the tip, it is difficult to estimate the exact field intensity at the NSOM tip itself as well as the exact focusing efficiency of the PVL. Thus the intensity scales in parts a and e of Figure 3 are in arbitrary units. In Figure 3c, the E_z field calculated by the RCWA, one can see five node lines around the center of vortex clearly, which indicates the rotation of the SP vortex. The topological charge of the SP vortex extracted from the E_z field intensity distribution is l = 5. In Figure 3d, the intensity distribution of the SP vortex in the experiment is compared with the results of the analytic model and the RCWA simulation. The SP vortex profiles expected from the theory (eq 4), the experimental result (along the dashed line in Figure 3a), and the RCWA simulation result (along the dotted line in Figure 3b) are plotted by the red dashed line, the blue solid line, and the black dotted line, respectively. The primary ring size of SP vortex is defined as the distance between two peaks surrounding the SP vortex shown in Figure 3d. The experimental result coincides well with the simulation result as well as the analytic model. Note that the topological charge of the SP vortex is l = 5, whereas the geometric vortex topological charge of the PVL is m = 4. This shows that the right-handed circular polarization beam increases the topological charge of the SP vortex by 1.

Second, the experiment and simulation results on the use of a left-handed circular polarization beam are shown in parts e-h of Figure 3. In this case, the excitation beam rotates in the counterdirection to the PVL geometry. Parts e and f of Figure 3 present the field intensity measured by the NSOM and calculated by the RCWA, respectively. It is first observed that the diameter of the primary ring of the SP vortex is smaller than that of the right-handed circular polarization beam (parts a and b of Figure 3). The E_z field intensity distribution shows that there are three nodal lines, indicating that the topological charge of the SP vortex is l =3. In Figure 3h, the intensity distributions of the SP vortex in the experiment are compared with the results of the analytic model and the RCWA simulation. The SP vortex profiles expected from the theory (eq 4), the experimental result (along the dashed line in Figure 3e), and the RCWA simulation result (along the dotted line in Figure 3f) are plotted by the red dashed line, the blue solid line, and the black dotted line, respectively. As shown in Figure 3h, the field intensity distributions measured by the NSOM and calculated by the RCWA are in good agreement with the theoretical prediction with l = 3. It has been shown that the right- and left-handed circular polarization beams upon the PVL with the geometric vortex topological charge of m = 4give rise to the topological charges of the SP vortices with l = 5 and l = 3, respectively.

The aforementioned algebraic rule on the change of SP vortex proved for the PVL with the geometric vortex topological charge m = 4 can be extended to PVLs with arbitrary higher order topological charge. We examined the SP vortices generated by the PVLs with various geometric vortex topological charges. Figure 4 plots the diameter of the primary ring of SP vortex as a function of the geometric vortex topological charge *m* for circular and radial polarizations. Considering that the primary ring size



FIGURE 3. Experiment and simulation results under the right-handed circular polarization in (a)–(d) and the left-handed circular polarization (e)–(h). (a) Near-field intensity distribution measured by the NSOM. (b) Near-field intensity distribution calculated by the RCWA. The dark spot is clearly observed in both images. (c) E_z distribution of the near-field calculated by the RCWA. The number of node lines is five, which indicates that the topological charge of the SP vortex is l = 5. The white arrows in (a)–(c) denote the directions of the rotation of the polarization. (d) Comparison of the intensity profiles. The red dashed line corresponds to the result of the theoretical model, i.e., the square of the absolute value of the fifth order Bessel function of the first kind. The blue solid line depicts the field intensity along the dashed line in the NSOM image (Figure 3a). The black dotted line shows the field intensity along the dotted line in the RCWA image (Figure 3b). (e), (f), (g), and (h) correspond to (a), (b), (c), and (d), respectively, but from the left-handed circular polarization beam.



FIGURE 4. Size of the primary ring of the SP vortex as a function of the geometric vortex topological charge m for various types of the polarization states. The straight lines with markers are from the simulation results, whereas the error bars are from the experimental data. The horizontal dotted lines show the sizes of the primary rings from the theoretical prediction given by the Bessel function of the first kind. The topological charge of the SP vortex l is given by l = m + 1 for the right-handed circular polarization, l = m for the radial polarization, and l = m - 1 for the left-handed circular polarization, respectively.

may vary slightly depending on the direction of the crossline, we comparatively plotted the primary ring size obtained from the RCWA simulation (indicated by markers on straight lines) and that from the experimentally measured data with the error bars indicating maximum and minimum values of the primary ring size. The black horizontal dashed lines indicate the theoretical primary ring size of SP vortices with various topological charges obtained from eq 4. The rotation direction of the PVLs is kept right-handed ($m \ge 0$). The red solid line with diamond markers and the blue dashed line with circle markers correspond to the results for the right- and lefthanded circular polarizations, respectively. The primary ring size of the SP vortex for the right-handed circular polarization increases monotonically with the geometrical vortex topological charge of the PVL and matches the theoretical result of l = m + 1. On the other hand, the size of the SP vortex for the left-handed circular polarization reaches its minimum for m = 1 and then increases monotonically. It is clearly seen that the SP vortices synthesized by the PVL of the geometric vortex topological charge *m* with the left-handed circular polarization beam have a topological charge of l = m - 1. The result for the radial polarization is also noteworthy. The PVLs with the geometric vortex topological charge *m* under the radial polarization produces SP vortices with l = m, as indicated by the green dotted line with cross markers in Figure 4. This linear dependence of the primary ring size on the topological charge arises from the fact that the radial field distribution of the SP vortex presented here is ascribed to the characteristics of the Bessel function of the first kind. Whereas the optical vortices having the form of the Laguerre-Gaussian function exhibit the primary ring size proportional to $(l + 1)^{1/2}$, ^{28,29} those related to the Bessel function of the first kind show the primary ring size

proportional to l.³⁰ The linear property offers useful insight in design and analysis of the PVL.

It is noteworthy that the SP vortex carries the orbital angular momentum proportional to the topological charge l. In the Supporting Information, it is proved that the orbital angular momentum of the SP vortex, Γ_z , is proportional to the topological charge l as

$$\Gamma_z \propto \frac{P}{\omega}l$$
 (5)

where *P* and ω are the power of the SP vortex field and the angular frequency of SP. This is also in agreement with the result of Volke-Sepulveda et al.³¹ It is therefore expected that the higher-order evanescent vortices generated by the PVLs could offer a way to gain more optical torque keeping the incident power.^{32–34}

Here, one may be curious about the maximum topological charge that can be achieved in a PVL. If the primary ring size exceeds the diameter of the PVL, then the SP vortex field inside the PVL vanishes. Thus it appears that the topological charge in practical applications should be limited so that the primary ring appears inside the PVL with a finite diameter. To obtain higher orbital angular momentum, we can increase both the diameter of a PVL and the geometric vortex topological charge *m*. However, as has been reported in ref 10, the propagation loss of the SP wave becomes dominant for a PVL with a large diameter. Therefore it seems that the extraction of an exact maximum topological charge in the general PVL geometry is not possible.

The relationship between the SP vortex and the PVLs under various polarization states can be understood by the terms of photon angular momentum. Light is described by its wavefront and polarization, which correspond to the orbit angular momentum and the spin angular momentum, respectively.^{35,36} The orbit angular momentum per photon is obtained by taking the angular momentum operator $L_z =$ $-j\hbar(\partial/\partial\varphi)$ to the wave function. For example, the application of the angular momentum operator to a wave function with phase profile of $\exp(jm\phi)$ gives $m\hbar$. The spin angular momentum per photon is given by taking the spin operator Sto the polarization state. The spin operator is defined as S = $|R\rangle\langle R| - |L\rangle\langle L|$, where $|R\rangle$ and $|L\rangle$ denote the right- and lefthanded polarization states, respectively. For example, the right- and left-handed circular polarizations results in $S_R =$ $\langle R|S|R \rangle = 1$ and $S_L = \langle L|S|L \rangle = -1$, respectively. By multiplying the Dirac's constant \hbar to the expectation value of the spin operator, we obtain the spin angular momentum per photon. Note that, due to the orthogonality between $|R\rangle$ and $|L\rangle$, the radial polarization $|p\rangle = [\exp(-j\phi)|R\rangle + \exp(j\phi)|L\rangle]/$ $2^{1/2}$ leads to $S_p = \langle p | S | p \rangle = 0$. The PVL plays a role of converting the spin angular momentum of excitation beam to the orbit angular momentum of SP.^{37,38} The contributions of +1, 0, and -1 in Figure 4 are ascribed to the orbit angular

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momenta converted from the spin angular momenta of $|R\rangle$, $|p\rangle$, and $|L\rangle$, respectively. The PVL with the geometric vortex topological charge *m* gives rise to the orbit angular momentum per photon, $m\hbar$, of SP vortex. Thus the total orbit angular momentum per photon of the SP vortex is given by the sum of two aforementioned contributions, i.e., $\hbar = (m + 1)\hbar$, $m\hbar$, and $(m - 1)\hbar$ for $|R\rangle$, $|p\rangle$, and $|L\rangle$, respectively. This algebraic rule can be used for the dynamic switching of SP vortex with the change of polarization state of excitation beam.

One interesting feature of the algebraic rule of SP vortex switching is that the single hot spot can be generated by the PVL with the geometric vortex topological charge of $m = \pm 1$ and the left- and right-handed circular polarization beams, respectively, which results in l = 0. In contrast to the high order Bessel function of the first kind J_l (l = 1, 2, 3, ...), which has zero at the center, the zeroth order Bessel function J_0 has its maximum at the center. Thus, if the SP angular spectrum is presented by J_0 , it should have a single hot spot at the center. There has been considerable interest in generating a subwavelength hot spot by using the plasmonic lens configurations.^{10–12,16,17} The plasmonic lens can be used to form a hot spot at its center by illuminating the radial polarization beam.¹² However, it is difficult to achieve highly accurate alignment between the center of the radial polarizer and the center of the plasmonic lens, especially when the diameter of the plasmonic lens is on the order of micrometers. Another approach for making the single hot spot is to illuminate an asymmetric plasmonic lens with a linear polarization beam.¹¹ However, this method also suffers from relatively low coupling efficiency of SP waves because the SP excitation efficiency of the parts on the curved slit that is not perpendicular to the linear polarization direction is not perfect. In order to compare the results of three approaches mentioned above, we present in Figure 5 the SP field intensity distributions calculated by the RCWA. Parts a, b, and c of Figure 5 correspond to the SP field intensity distributions of the plasmonic lens with the radial polarization beam, the asymmetric plasmonc lens with the linear polarization beam, and the PVL with the vortex topological charge of m = +1 with the left-handed circular polarization beam, respectively. It is observed that all methods produce a single hot spot at the center of the respective structures. However it should be noted that the combination of the PVL with the geometric vortex topological charge |m| = 1 and the counterdirectional circular polarization beam has advantages in its implementation, compared to the other methods in refs¹¹ and¹² since it requires neither the radial polarization nor the highly accurate alignment, without degradation of the hot spot profile.

In conclusion, a novel method for synthesis and switching of surface plasmon vortices with arbitrary topological charges, various dark spot size, and strong angular momentum using the plasmonic vortex lens structure is proposed. The plasmonic vortex lens with circular polarization excitation beam is advan-



FIGURE 5. Near-field intensity distributions showing the single hot spot at the center of the structure, by use of (a) the plasmonic lens illuminated by the radial polarization, (b) the asymmetric plasmonic lens illuminated by the linear polarization, and (c) the PVL with m = +1 illuminated by the left-handed circular polarization beam, respectively. The white arrows in (a)–(c) denote the directions of the polarization.

tageous for forming a single surface plasmon hot spot as well. We believe that the SP vortices having such remarkable properties may become a core element for the manipulation and control of electromagnetic field on a subwavelength scale and will be extensively used for various applications such as nanoscale microscopy, optical data storage, and quantum computing as well as particle manipulation.

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Supporting Information Available. Additional information on orbital angular momentum of the surface plasmon vortex fields. This material is available free of charge via the Internet at http://pubs.acs.org.

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