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2014

Man, Z., Du, L., Min, C., Zhang, Y., Zhang, C., Zhu, S., Paul Urbach, H., & Yuan, X. C. (2014). Dynamic plasmonic beam shaping by vector beams with arbitrary locally linear polarization states. *Applied physics letters*, 105(1), 011110, 1-6.

<https://hdl.handle.net/10356/102504>

<https://doi.org/10.1063/1.4887824>

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Citation: *Applied Physics Letters* **105**, 011110 (2014); doi: 10.1063/1.4887824

View online: <http://dx.doi.org/10.1063/1.4887824>

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Dynamic plasmonic beam shaping by vector beams with arbitrary locally linear polarization states

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(Received 5 April 2014; accepted 12 June 2014; published online 8 July 2014)

Vector beams, which have space-variant state of polarization (SOP) comparing with scalar beams with spatially homogeneous SOP, are used to manipulate surface plasmon polarizations (SPPs). We find that the excitation, orientation, and distribution of the focused SPPs excited in a high numerical aperture microscopic configuration highly depend on the space-variant polarization of the incident vector beam. When it comes to vector beam with axial symmetry, multi-foci of SPPs with the same size and uniform intensity can be obtained, and the number of foci is depending on the polarization order n . Those properties can be of great value in biological sensor and plasmonic tweezers applications. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4887824>]

Surface plasmon polaritons (SPPs) are electromagnetic evanescent waves bound to a metal/dielectric interface. Their properties of strong resonance and enhancement of electromagnetic field make the SPPs attractive in various applications including sensing,^{1,2} optoelectronics,³ super-resolution imaging,⁴ and negative refraction.⁵ Thus, excitation and manipulation of SPPs have attracted significant interest and many novel setups for the generation of SPPs have been proposed so far, such as Kretschmann-Raether⁶ and Otto configurations,⁷ gratings and defects.^{8–10} Recently, the method of SPPs excitation based on a high numerical aperture (NA) microscope has drawn an increasing attention due to the highly dynamic and structureless features.^{11–15} For example, a tightly focused radially polarized (RP) beam can excite a sharp SPPs peak on a flat metal film,¹² which has a sub-diffraction limit spot size, and thus is well suited for super-resolved imaging¹⁶ and bio-sensing.^{1,2} Moreover, in our recent work, this sharp SPPs field has proved to own unique capabilities in trapping metallic particles.¹⁷ While an azimuthally polarized (AP) beam is unable to excite SPPs due to the polarization mismatch.¹³ In recent years, apart from the well-known RP and AP beams, a lot of other vector beams with various space-variant state of polarization (SOP) have been reported,^{18–25} for instance, vector beams with cylindrical,^{18–20} elliptical,²¹ and bipolar symmetries²² of linear polarization. The geometric configuration of linear polarizations as an additional degree of freedom should be considered in terms of SPPs manipulation, and consequently, produces more novel phenomena with great potentials to new applications.

In this Letter, we explore the excitation and manipulation of a focused SPPs field by modulating the polarization mode of incident vector beams. Based on the vectorial diffraction theory, we first build an analytical model for calculating the three-dimensional electric fields of SPPs excited by vector beams with arbitrary locally linear SOP. The cylindrical vector beams with various orders are taken as examples to verify the validity of our analytical model. The theoretical and experimental results reveal that the polarization mode of the incident beam plays an important role in determining the excitation, orientation, and distribution of SPPs. When it comes to the higher order cylindrical vector beams, multi-foci of SPPs with same size and uniform intensity can be obtained. The number of focus is tunable by changing the polarization order n . These unique near-field features of SPPs should have great potential in applications like biological sensor and plasmonic tweezers.

Figure 1 illustrates the configuration for SPPs excitation, which is a three layer system composing of a thin metal film [with thickness of d and relative permittivity of ϵ_2] sandwiched

FIG. 1. Optical setup for SPPs excitation by means of an oil-immersion objective lens with a high NA.

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between air [$\epsilon_3 = 1$] and glass substrate [$\epsilon_1 = 1.516^2$]. An oil-immersion objective lens with large NA focuses the incident beam onto the dielectric-metal interface located at the focal plane to excite ring-shaped SPPs in the resonance angle. Then the ring-shaped SPPs act as secondary circular source propagating on the metal film inward to the center, and finally form a standing wave pattern after constructive interference. Thus, the Gouy phase may have little effect on the SPPs here.²⁶ An immersion oil is used between the objective lens and glass substrate to match the refractive index.

Mathematically, a locally linearly polarized beam can be expressed as^{18,19,22,25}

$$\mathbf{E} = A_0 \cdot [\cos \delta(r, \varphi) \hat{\mathbf{e}}_x + \sin \delta(r, \varphi) \hat{\mathbf{e}}_y], \quad (1)$$

where A_0 is the amplitude, δ is a function of r and φ determining the polarization mode, r and φ are the polar radius and azimuthal angle, and $\hat{\mathbf{e}}_x$ and $\hat{\mathbf{e}}_y$ are the unit vectors along x and y axes, respectively.

The electric field of SPPs excited on a metal film in a microscopic configuration can be calculated with the Richards-Wolf vector diffraction theory²⁷ when an incident beam describes by Eq. (1) are focused by a high NA lens. The field components of SPPs in the air above the metal film can be derived as

$$E_r^{SPP}(r_s, \varphi_s, z_s) = \frac{-iB}{\pi} \int_0^{2\pi} \int_0^\alpha \sin \theta P(\theta) A(\theta) \exp \left\{ i \left[r_s k_1 \sin \theta \cos(\varphi - \varphi_s) + z_s \sqrt{k_3^2 - k_1^2 \sin^2 \theta} \right] \right\} \\ \times [\sin(\delta - \varphi) \sin(\varphi_s - \varphi) + \cos(\delta - \varphi) \cos \theta \cos(\varphi - \varphi_s)] t_p^r(\theta) d\varphi d\theta, \quad (2)$$

$$E_\varphi^{SPP}(r_s, \varphi_s, z_s) = \frac{-iB}{\pi} \int_0^{2\pi} \int_0^\alpha \sin \theta P(\theta) A(\theta) \exp \left\{ i \left[r_s k_1 \sin \theta \cos(\varphi - \varphi_s) + z_s \sqrt{k_3^2 - k_1^2 \sin^2 \theta} \right] \right\} \\ \times [\sin(\delta - \varphi) \cos(\varphi - \varphi_s) + \cos(\delta - \varphi) \cos \theta \sin(\varphi - \varphi_s)] t_s(\theta) d\varphi d\theta, \quad (3)$$

$$E_z^{SPP}(r_s, \varphi_s, z_s) = \frac{-iB}{\pi} \int_0^{2\pi} \int_0^\alpha \sin \theta P(\theta) A(\theta) \exp \left\{ i \left[r_s k_1 \sin \theta \cos(\varphi - \varphi_s) + z_s \sqrt{k_3^2 - k_1^2 \sin^2 \theta} \right] \right\} \\ \times [-\cos(\delta - \varphi) \sin \theta] t_p^z(\theta) d\varphi d\theta. \quad (4)$$

Here, B is a constant, α is the maximum allowed incident angle of the objective lens, $P(\theta)$ is the pupil function, $A(\theta)$ is the apodization factor of the focusing lens, and t_p^r , t_s , and t_p^z are the transmission efficiencies of E_r , E_φ , and E_z components through the metal film (Fig. 1) at incident angle of θ , respectively. The transmission efficiencies can be derived as follows:

$$t_p^r = \frac{\sqrt{\epsilon_3 - \epsilon_1} \sin^2 \theta}{\cos \theta} \times \frac{t_p^{12} t_p^{23} \exp(ik_{2z}d)}{1 - r_p^{12} r_p^{23} \exp(i2k_{2z}d)}, \quad (5)$$

$$t_s = \frac{t_s^{12} t_s^{23} \exp(ik_{2z}d)}{1 - r_s^{12} r_s^{23} \exp(i2k_{2z}d)}, \quad (6)$$

$$t_p^z = \frac{\sqrt{\epsilon_1}}{\sqrt{\epsilon_3}} \times \frac{t_p^{12} t_p^{23} \exp(ik_{2z}d)}{1 - r_p^{12} r_p^{23} \exp(i2k_{2z}d)}, \quad (7)$$

in which t_s^{ij} and t_p^{ij} are the Fresnel transmission coefficients for s - and p -polarization at the ij interface, and r_s^{ij} , r_p^{ij} the corresponding reflection coefficients, k_{2z} denotes the z -component of wave vector within the metal film, and d is the metal film thickness, respectively.

To verify the above analytical model, we take vector beams with different polarization orders as examples, studying the excited SPPs field both theoretically and experimentally.

For vector beam with polarization order n [n is integer], the function δ in Eq. (1) can be expressed as $\delta = n\varphi$, and the relative SOP of those beams can be characterized in the higher-order Poincaré sphere.^{28,29} We first explore the two fundamental cases when $n = \pm 1$. The experimental setup for generating the two vector beams and exciting SPPs is presented in Fig. 2. For $\delta = +\varphi$, it is the well-known RP beam, which is achieved

FIG. 2. Experimental setup for SPPs excitation by the tightly focused two polarization modes in terms of $\delta = +\varphi$ and $\delta = -\varphi$. The insets of (a) and (b) show the polarization vector for $\delta = +\varphi$ and $\delta = -\varphi$, respectively.

by passing a 532 nm linearly polarized beam sequentially through a quarter-wave plate to convert it to circular polarization, a spiral phase plate for phase compensation, an azimuthal-type analyzer for filtering out the radial components, and a polarization rotator consisting of two half-wave plates for the AP/RP interconversion.³⁰ While for $\delta = -\varphi$, the beam has axial symmetric polarization state and can be realized by simply adding another half-wave plate after the polarization rotator with its fast axis along the horizontal axis. The polarization vector distributions of the above two vector beams are shown with insets (a) and (b) in Fig. 2, respectively, where the polarization singularity appears at the beam center in both cases. The two generated polarization modes are subsequently tightly focused by an oil-immersion objective lens [Olympus 100 $\times$, NA=1.25] onto the glass-silver [with thickness $d=48$ nm and the relative permittivity $\epsilon_2 = -10.2 + 0.8238i$] interface to excite SPPs. For such a case, the surface plasmon resonance angle is calculated to be about 43.82°. If the NA of the objective lens is given as 1.25, then the maximum incident angle on the silver film extends to 55.54°, satisfying the SPPs excitation angle at a broad wavelength range. A CCD camera placed at the back focal plane of the objective lens is used to record the reflected laser beam.

Figures 3(a) and 3(b) show the captured reflected intensity distributions for the above two beams, respectively. Both of them present dark arcs at the same angular region that corresponds to the coupling of the local beam to the SPPs, and hence verify the excitation of SPPs. However, they also exhibit difference from each other. For $\delta = +\varphi$, it is a full dark ring, demonstrating the excitation of SPPs from all directions. While for $\delta = -\varphi$, no dark arcs exist at the four diagonal directions where AP components locate, due to the fact that a focused AP beam is TE polarized^{31–34} without the functionality for SPPs excitation.

The SPPs fields excited by the above two polarization modes are demonstrated in Fig. 4. In Figs. 4(a)–4(f), we show the calculated SPPs intensity on the silver film according to Eqs. (2)–(4). For both cases, the longitudinal component [E_z] is much stronger and dominates the total field. However, their near-field patterns are much different: For $\delta = +\varphi$, a sharp bright spot is formed at the center because of the constructive interference of the longitudinal field component (Figs. 4(a) and 4(d)), while it is donut-shaped with very weak intensity (Fig. 4(c)) for the radial component; for $\delta = -\varphi$, the pattern is dark at the center, which is surrounded by four identical bright spots for all of the transverse, longitudinal, and total intensity distributions. Such different

FIG. 3. Intensity distribution for (a) $\delta = +\varphi$ and (b) $\delta = -\varphi$ captured by CCD camera at the back focal plane of the high NA oil-immersion objective lens. The dark arcs correspond to the SPPs excitation.

FIG. 4. Intensity distributions for $\delta = +\varphi$ [the left column] and $\delta = -\varphi$ [the right column] on the silver film. (a) and (b) Calculated total intensity distribution. (c) and (e) Calculated intensity of the in-plane component. (d) and (f) Calculated intensity of the out-of-plane component. (g) and (h) Experimentally measured intensity distribution. All the intensities are normalized to the maximum of each mode, and the area of each contour map is $2.4 \mu\text{m} \times 2.4 \mu\text{m}$.

performances of the two cases are based on the properties of incident polarization mode. For $\delta = +\varphi$, the incident beam is purely radially polarized and circularly symmetric [indicated by the black arrows in inset of Fig. 2(a)]. As a result, SPPs are excited at the full dark ring position (Fig. 3(a)) in-phase for the dominated E_z and propagate towards the center to form a sharp bright spot after constructive interference, which agree well with previous report.¹² In contrast, for $\delta = -\varphi$, the vector beam is fully radially polarized only at four axis directions and present oppositely directed polarization vectors [some arrows are inward and others are outward, as shown in inset of Fig. 2(b)]. Thus, the SPPs are only excited at the four dark arcs (Fig. 3(b)) corresponding to the RP component positions, and have a phase difference of π for the dominated E_z between the adjacent excitation arcs due to the oppositely directed polarization arrows, giving rise to a dark point at the center after destructive interference of SPPs.

Figures 4(g) and 4(h) give the experimentally measured near-field SPPs field intensity distribution with a new method in Ref. 35, which is especially sensitive to the out-of-plane component [E_z]. Thus, we can see those experimental results are in excellent agreement with theoretical longitudinal component distributions (Figs. 4(d) and 4(f)), proving that our analytical model is able to give a correct prediction. More importantly, the experimental results reveal the capability of polarization mode as an additional optical degree of freedom

FIG. 5. Polarization distributions [black arrows] of the incident polarization mode with $n = -3, -2, 2$, and 3 [the first row] and the corresponding total intensity distributions of the SPPs field on the silver film [the second row].

in determining the excitation, orientation, and distribution of the focused SPPs, thus has great potential in manipulating SPPs.

Besides the above two fundamental cases, we further consider the higher order polarization modes [$\delta = n\varphi$]. Figure 5 shows four cases of high order vector beams when $n = -3, -2, 2$, and 3 together with their corresponding SPPs intensity distributions. Obviously, multifocal SPPs pattern with the number of main spots given by $2|n - 1|$ is obtained, due to the similar reasons as the case of $n = -1$ (Fig. 4(b)). For instant, the main spots for the case of $n = 3$ are four, same to that of $n = -1$. Therefore, we can easily control the number of hot spots of SPPs by simply choosing the desired incident polarization mode, which could contribute to trap desired number of particles in plasmonic tweezers.¹⁷

To summarize, we have introduced space-variant locally linear SOP of the incident vector beam to manipulate SPPs excited in a high NA microscopic configuration. Based on the vector diffraction theory, we build an analytical model for the three-dimensional electric field of SPPs excited by the vector beams. Furthermore, we experimentally validate that our analytical model gives correct predictions for the SPPs excited by vector beams with two different polarization orders. When it comes to the vector beams with higher order axial symmetry, we found multifoci of SPPs with the same size and uniform intensity can be obtained, the number of which is controllable depending on the polarization order n . In addition, the mechanisms and reasons for that excellent performance are also explained. Most importantly, our analytical model can be applied to investigate the behaviors of vector beams with arbitrary locally linear SOP in terms of SPPs excitation, such as vector beams with elliptical symmetry,²¹ bipolar symmetry,²² and parabolic symmetry,²⁵ yielding more novel phenomena with great potentials to new applications.

This work was partially supported by the National Nature Science Foundation of China under Grant Nos. 61036013, 61138003, 11204141, and 61377052 the Tianjin Municipal Science and Technology Commission under Grant Nos. 11JCZDJC15200 and 12JCYBJC31000, and the

Specialized Research Fund for the Doctoral Program of Higher Education under Grant No. 20120031120034.

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