Experimental research on the longitudinal field generated by a tightly focused beam*

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The longitudinal optical field is a peculiar physical phenomenon that is always involved with the domain of near-field optics. Due to its extraordinary properties, it has recently attracted increasing attention in research and application. In this work, the longitudinal fields generated by the evanescent illumination of tightly focused, different polarized hollow beams are investigated. The focused light fields are numerically simulated according to vector diffraction theory, and their vector analysis is also carried out. The longitudinal fields on the focal plane are demonstrated experimentally using tip-enhanced scanning near-field microscopy. The simulation and experimental results show that the tightly focused radially polarized beam is suited to generating a stronger and purer longitudinal optical field at the focus.

Keywords: longitudinal optical field, high numerical aperture, focusing beam, polarization

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1. Introduction

The longitudinal optical field (LOF) is often used to refer to an optical field with its electric field vector component along the propagation optical axis of the beam. However, due to the transverse nature of electromagnetic fields in isotropic media, it is not considered realizable to generate a longitudinally polarized field. It was theoretically demonstrated that any illumination with finite size contains LOF components even in vacuum.[1–3] Furthermore, a strong LOF can be created at the tight focus of the incident beam due to the electric field interference at the focal spot.[4] The LOF can be further strengthened by focusing the radially polarized (RP) beam. A particular feature of this field is that it is confined to a small volume in the vicinity of the focus[5] and has hardly any energy flow.[6] Based on this advantage, the LOF is favored in optical trapping,[7] and it is attractive in molecular orientation determination[8] and particle accelerating[9,10] applications. Moreover, theoretical studies show that the longitudinal electric field can effectively excite the localized surface plasmon at the tip apex of a metallic probe, and strongly contribute to the enhancement of the local optical field.[11] When illuminated by the transversal field, the tip apex remains uncharged. So it does not actively contribute to the local field enhancement. While in the situation of LOF illumination, the charge of the metallic tip is driven to the foremost of the tip and forms large surface charge accumulation at the tip apex, which leads to the effective enhancement of the local electric field at the tip apex.[12] It is therefore ideal to utilize an LOF to excite the tip to effectively enhance the local field, especially in tip-enhanced scanning near-field optical microscopy (TE-SNOM),[13,14] because this is the essential and indispensable condition for achieving higher optical signal enhancement and detection sensitivity.

Due to its peculiarities and application prospects, the LOF has been increasingly attracting research attention during the past decades. Hayazawa *et al.*[15] characterized the LOF formed at a tightly focused spot with the TE-SNOM, and demonstrated well that the optical fields at the focuses of linear, pseudoradially and pseudoazimuthally polarized illumination were consistent with the calculated results.[15] However, a comparison of the relative intensities among these particularly polarized focuses was not investigated.

In this paper, the distribution of the optical field at the focus of a tightly focused hollow beam is systematically studied. Firstly, the LOFs generated by tightly focused hollow laser beams with different polarizations are investigated numerically according to vector diffraction theory. The generation of the LOF is analyzed theoretically through the phase distribution simulation of the longitudinal component and vector analysis of the electric component, which have rarely been of concern in previous studies. Then the distributions of the LOF on the focal plane are characterized experimentally utilizing a TE-SNOM. The relative intensities at the focus of different polarized illuminations are detected and compared, since the experimental results are characterized with the same illumination intensity, before being focused by the objective. The differences between the tightly focused RP and linearly polarized (LP) illuminations are discussed based on the theoretical and experimental results. The prospects of the LOF excitation methods are then suggested and described.

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2. LOF generation by a tightly focused beam

The investigated LOFs are generated by tightly focusing the incident LP and RP beams. As figure 1 illustrates, the beam with a planar wavefront propagates along the z axis and is focused by a high-numerical aperture (NA) aplanatic focusing system. The geometrical focus position is set to be the origin of the coordinate system, denoted by o. The distribution of the optical field at the focus can be calculated according to vector diffraction theory.[16,17] The distributions of the tightly focused LP and RP 532 nm laser beam on the focal plane are calculated and represented, respectively, as shown in Fig. 2. The objective with NA= 1.45 is oil immersed ($n = 1.5$). The entrance pupil corresponds to NA= $1 \sim 1.45$.

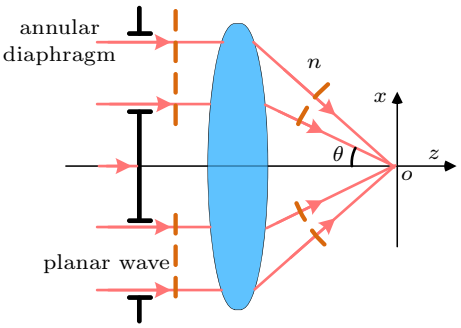


Fig. 1. (color online) The geometrical configuration of focusing a planar wave by a high-NA objective.

2.1. LOF generated with an LP beam

Since LP illumination is an easily accessible and commonly used excitation source, for comparison the generation of an LOF with an LP beam is discussed first. For the focusing of the LP incident beam with the polarization direction along the x axis, the E_x, E_y, and E_z components of the optical field vector near the focal region can be represented as[6,16,17]

$$E_x = -\frac{\mathrm{i}A}{\pi}\int_0^{2\pi}\int_{\alpha_0}^{\alpha_1}\cos^{1/2}\theta\sin\theta\left[\cos\theta+(1-\cos\theta)\sin^2\phi\right]\times\exp[\mathrm{i}k(xs_x+ys_y+zs_z)]\,\mathrm{d}\theta\,\mathrm{d}\phi, \quad (1)$$

$$E_y = \frac{\mathrm{i}A}{\pi}\int_0^{2\pi}\int_{\alpha_0}^{\alpha_1}\cos^{1/2}\theta\sin\theta(1-\cos\theta)\cos\phi\sin\phi\times\exp[\mathrm{i}k(xs_x+ys_y+zs_z)]\,\mathrm{d}\theta\,\mathrm{d}\phi, \quad (2)$$

$$E_z = \frac{\mathrm{i}A}{\pi}\int_0^{2\pi}\int_{\alpha_0}^{\alpha_1}\cos^{1/2}\theta\sin^2\theta\cos\phi\times\exp[\mathrm{i}k(xs_x+ys_y+zs_z)]\,\mathrm{d}\theta\,\mathrm{d}\phi, \quad (3)$$

in which A is a constant related to the amplitude of the incident light, θ is the angle between the ray of refracted light and optical axis, ϕ is the azimuth angle of the refracted ray, and s represents the axial unit vector.

2.2. LOF generated with an RP beam

An RP beam is a kind of cylindrically polarized beam. Its electric field vibration direction is axis-symmetrically distributed. Thus, the focusing of an RP beam is more suited to being formulated in the cylindrical coordinate system. The axial (E_z) and transverse (E_r) components can be represented in the cylindrical coordinate as[6]

$$E_r = A\int_{\alpha_0}^{\alpha_1}\cos^{1/2}\theta\sin(2\theta)l_0(\theta)\mathrm{J}_1(k\rho_s\sin\theta)\times\exp(\mathrm{i}kz_s\cos\theta)\,\mathrm{d}\theta, \quad (4)$$

$$E_z = 2\mathrm{i}A\int_{\alpha_0}^{\alpha_1}\cos^{1/2}\theta\sin^2\theta l_0(\theta)\mathrm{J}_0(k\rho_s\sin\theta)\times\exp(\mathrm{i}kz_s\cos\theta)\,\mathrm{d}\theta, \quad (5)$$

where $\mathrm{J}_n(k\rho_s\sin\theta)$ denotes a Bessel function of the first kind of order n, and l_0 represents the amplitude of the incident field, which is assumed to vary radially but remain cylindrical in symmetry about the optical axis. For the planar incident beam, $l_0 = 1$ within the entrance pupil, and $l_0 = 0$ outside the pupil area.

According to Eqs. (1)–(5), the distributions of the tightly focused hollow beam (with $\lambda = 532$ nm) on the focal plane ($z = 0$) are calculated, and the results are shown in Fig. 2. The α_n parameter, and the limits of the integration of θ, are determined based on the NA $1 \sim 1.45$ of the oil immersed ($n = 1.5$) objective lens. Thus the incident beam is hollow and the incident angle is greater than the critical angle. So the focus is generated only by the interference of total internal reflection (TIR) illumination. This means that the optical field formed at the focus is a non-propagating evanescent field, which is closely confined to the interface or the focal plane. For a tightly focused RP beam, the larger the incident angle of the refracted ray, the smaller the diameter of the focal spot. The hollow beam, in which the ray with a smaller incident angle is blocked, reduces the size of the focal field and increases the proportion of the longitudinal component.

For an LP beam focus, the LOF distribution near the focus presents two symmetric lobes rather than one spot, as shown in Fig. 2(f). It is noticed that there is a π phase difference between the upper and lower half of the phase distribution of the E_z component (Fig. 2(h)), which explains why the z component presents a minimal value in the center and splits into two parts as a result of deconstructive interference. In addition, the field intensity contributes much more to the transverse component but not the longitudinal component at the focus. While for the RP beam focus, the LOF distribution displays a strong circular spot in the center of the focus as a result of constructive interference (Fig. 2(e)). The intuitive explanation is that the optical setup is also of cylindrical symmetry, as indicated in the case of the RP beam. It can efficiently focus all the RP components into the focus spot and form constructive interference. This results in the fact that the field intensity mostly contributes to the LOF at the focus.

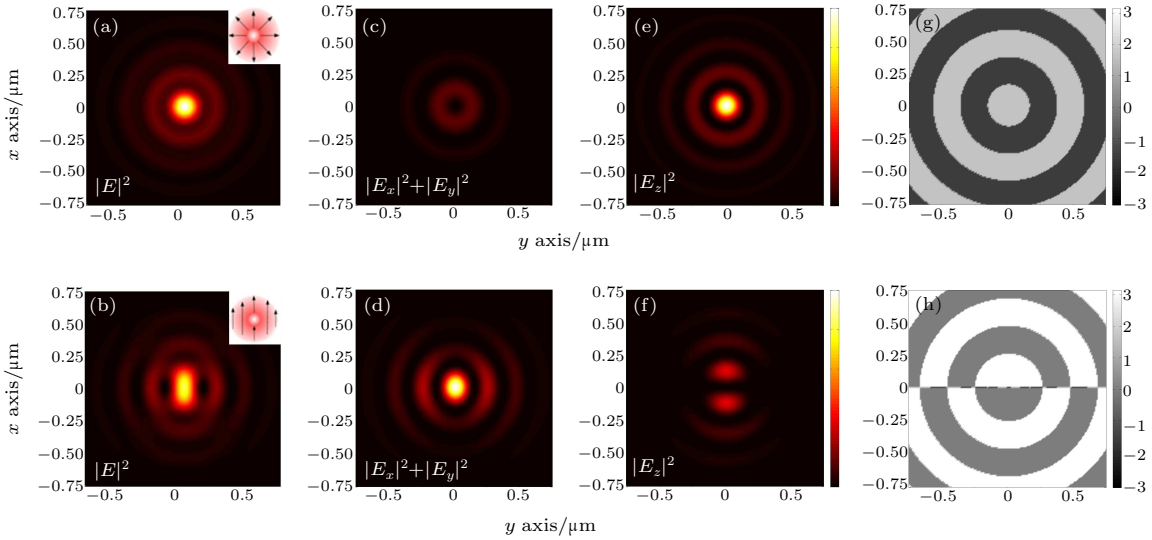


Fig. 2. (color online) Calculated electric field intensity distributions (a)–(f) and longitudinal field phase (g), (h) distributions in the focal plane ($z = 0$). Panels (a), (c), (e), and (g) in the upper row are for the RP beam, and panels (b), (d), (f), and (h) in the lower row are for the LP beam. Panels (a) and (b) represent the total electric field intensity distributions. Panels (c), (d) and (e), (f) correspond to the transverse and longitudinal fields, respectively.

Furthermore, the LOF distributions of the focal field in the x–z plane are calculated and the results are shown in Fig. 3. The focus is at the interface of the lower ($n = 1$) and higher ($n = 1.5$) refractive index (RI) media. Since the beam travels from the higher RI medium to the lower one, and the incident angles are all greater than the critical angle, TIR occurs at the interface of the two media (i.e., the focal plane) and the focus is formed by the interference of the TIR illumination. It is seen from the calculation results that the longitudinal component decays more rapidly with z in the $z > 0$ space. This means that the LOF is a localized and non-propagating field. The size of the longitudinal field volume is about on the order of a half-wavelength. For tightly focused RP illumination, the focal field contains a dominant longitudinal component with its peak on the optical axis. While from the case of LP hollow beam focusing, the longitudinal component is mainly split into two lobes, which are not of cylindrical symmetry, and remains hollow as it propagates and focuses.

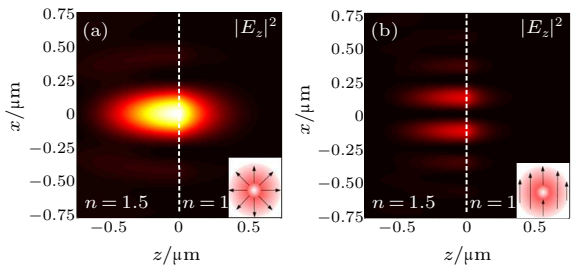


Fig. 3. (color online) Calculated electric field intensities of the LOF distributions in the x–z plane ($y = 0$) illuminated by (a) RP and (b) LP beams, respectively, with the dashed line indicating the interface between the lower and higher index media.

3. Experimental setup

Due to its peculiarities, the LOF has important applications, especially in the excitation of localized field enhancement in TE-SNOM. To characterize the distributions of the LOF on the focal plane of the tightly focused beams and experimentally investigate the comparative intensities of the LOF with different polarized beams, experimental detection is carried out.

According to the theoretical analysis, we perform near-field optical experiments to characterize the focusing properties of LP and RP beams. The RP beam used in this experiment is generated by a liquid crystal device. Owing to the special alignment of the liquid crystal molecules, this device locally rotates the orientation of the linearly polarized incident beam and converts the polarization into a radial state.[18] As is well known, the apertureless probe is sensitive to LOF in near-field optical detection.[19] In our experiment, a transmission-mode TE-SNOM detection system (Fig. 4) is established. A metallic tip attached to an atomic force microscope (AFM) cantilever is utilized as an apertureless probe. In the TE-SNOM, a metal or metal-coated tip acts as a local scatterer in the near-field region of the sample to interact with the localized evanescent field, and partially converts it into a propagating signal. Since the tip strongly responds to the electric field component polarized along the tip axis, it selectively picks up the longitudinal component and scatters the signal into the far-field for detection.[19] Thus, the TE-SNOM is suitable for characterization.

The TE-SNOM experimental system consists of an AFM (NT-MDT, SMENA, Russia) with a gold tip, an inverted microscope (Olympus, IX81, Japan), a photomultiplier tube (PMT) as detector, a controller, and other optical and electronic components. A laser beam (532 nm), after being expanded and collimated, is reflected by a beam splitter and directed into the inverted microscope. The polarization state of

the incident beam is controlled with a half-wave plate and a polarization converter (Arcoptix, Switzerland). The latter can convert an LP beam into an RP beam via appropriate adjustment. The incident beam is tightly focused by a high-NA objective ($60^{\times}$, NA= 1.45, oil immersed) on a cover glass. After approaching the surface of the cover glass, the tip scans over the focal plane of the objective. With the interaction between the tip apex and the LOF near the focal spot, the signal is locally enhanced and scattered into the far-field. The scattered optical signal is collected with the same objective, and then directed to the PMT for detection. By raster scanning in the spatial cross-section plane, the LOF distribution close to the focal spot can be mapped. In this setup, an annular diaphragm is adopted. It is located in the incident path and provides the total internal reflection illumination beyond the critical angle. In this case, an evanescent field is generated at the focal plane. Thus, the tip apex only interacts with the highly confined evanescent field, thereby avoiding the far-field background noise from the body of the tip, and the signal-to-noise ratio of the detection is therefore significantly improved.

In addition, this experimental characterization method also provides the basis and method of aligning the TE-SNOM tip with the strongest LOF intensity position on the focal plane.

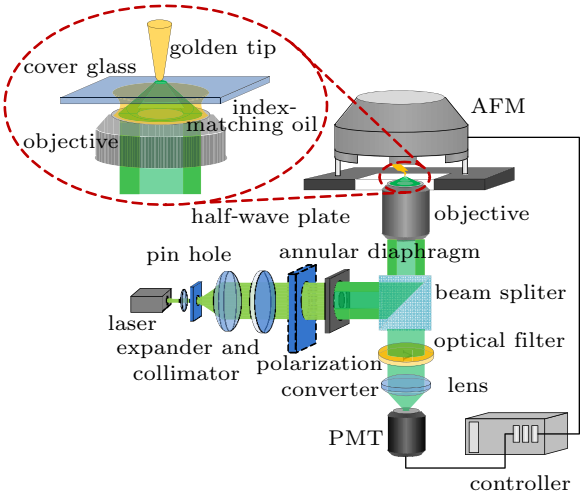


Fig. 4. (color online) Schematic diagram of the detection system.

4. Experimental results and discussion

For comparison, RP and LP illuminations are used separately in the experiment, and the two polarized beams have the same intensity before being incident to the high-NA objective. The characterized field distributions are shown in Figs. 5(b) and 5(d). The experimental results are in accordance with the calculated LOF distributions as shown in Fig. 2. For the RP beam, the LOF distribution shows a bright circular spot in the focus center, while for the LP beam it appears to have two lobes. According to the cross-section Fig. 5(f), the LOF intensity at the focus of the tightly focused RP beam is about three times stronger than that of the LP beam. The research indicates that in order to have a strong longitudinal component at the focus, not only is a high-NA objective required, but an RP beam illumination is also preferred.[20] This is because the RP beam is cylindrically symmetric with respect to the optical axis, so that it matches the symmetric constructive interference condition to form the longitudinal component. Furthermore, the longitudinal components of all the ray bubbles at the focus are in phase and superimposed together, so that a comparatively strong and pure LOF can be generated by a tightly focused RP beam illumination.

To further investigate the generation of LOFs at the tight focus, we perform vector analysis according to vector diffraction theory. At the tight focus of the incident beam, the LOF is formed due to the interference of the electric vector in the z-axis direction. For a tightly focused incident LP beam, the LOF splits into two lobes distributed on the two sides of the center as mentioned above. As illustrated in Fig. 6(b), in the center of the focus the electric components along the z-axis cancel each other out. This results in the null LOF in the focus center, and according to this, when using the LP beam as the TE-SNOM illumination, some groups align the tip apex with one of the two side lobes to obtain relatively good enhancement, but the LOF and hence the enhancement is rather weak. However, for the RP beam, after passing though the high-NA lens, diametrically opposite points on the converging beam have electric vectors that are in the same longitudinal direction but in transverse directions. Hence, in the center of the focus the longitudinal components of the electric field are superimposed constructively while the transversal ones cancel each other out. As demonstrated in Fig. 6(a), the z-axis direction electric component is increased at the focus, while the transversal one is restrained. As a result, with the constructive interference of the longitudinal field and the destructive interference of the transversal field, the LOF generated in the center of the RP beam focus is considerably strong and pure.

According to Novotny *et al.*,[12] the pure longitudinal field offers an ideal method to efficiently concentrate the charges on the apex of the tip. For the TE-SNOM illumination, the optical field can most effectively interact with the tip and be enhanced, and the far-field background noise generated by the transversal field is then reduced. In the transmission-mode TE-SNOM setup, the excitation beam is commonly focused by a high-NA objective. When the incident light with an appropriate wavelength and polarization illuminates on the metalized tip, the local electric field and the optical signal can be effectively enhanced, owing to the lightning-rod effect and the excitation of localized surface plasmons. Since the LOF can efficiently interact with the tip-like nano-aperture and enhance the local field, the tightly focused RP beam is effective for the field enhancement and suitable for the excitation. The RP illu-

mination forms a compacted LOF at the focus. By aligning it with the tip apex, the confined electric field at the tip apex can be actively enhanced and the local optical signal can be efficiently increased. Thus, for the cylindrically symmetric converging optical configurations, the RP incident beams which form stronger longitudinal components at the focuses can better enhance the field at the tip apex. This also adapts to the reflection-mode TE-SNOM setups using a parabolic mirror.

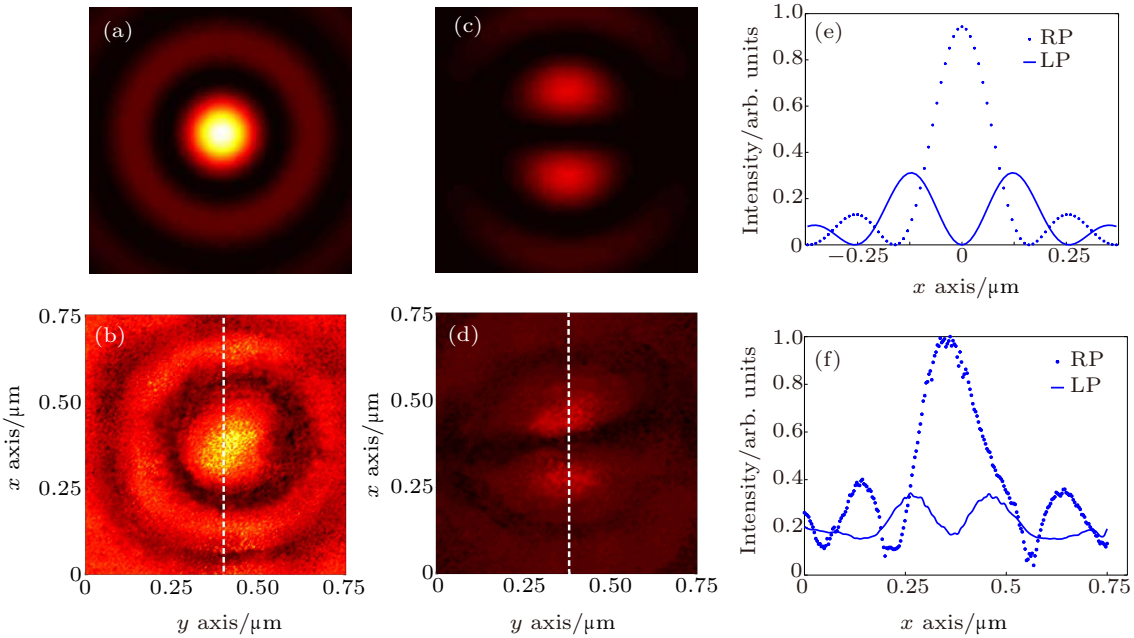


Fig. 5. (color online) Theoretical (a), (c) and experimental (b), (d) results of the LOF distributions in the focal plane under RP ((a), (b)) and LP ((c), (d)) illuminations; and the calculated (e) and detected (f) cross-sections of the focus along the x axis in the center (which is denoted by the white dashed lines). Each area detected experimentally is 0.75 μm × 0.75 μm.

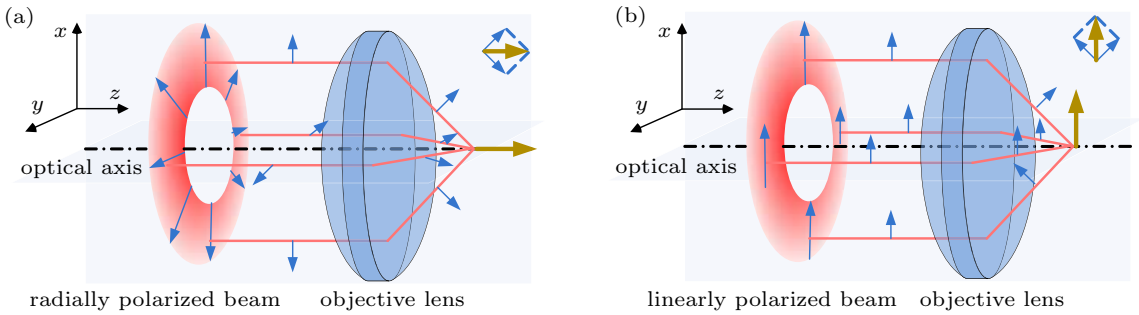


Fig. 6. (color online) Schematic illustrations of the electric field vector combination of (a) RP and (b) LP beams in the center of the focus by a high-NA objective.

5. Conclusion

In this work, the LOFs generated by tightly focused RP and LP beams are numerically and experimentally investigated. For tightly focused RP beams, the LOF forms a small circular spot in the center of the focus, and most of the electric component contributes to the longitudinal field. The generated, comparatively strong and pure LOF is localized in subwavelength volume close to the interface. This shows the excellent focus performance due to the cylindrical symmetry properties, and is suitable for investigating the interaction between light and matter on a nanoscale level. When the longitudinal field interacts with a metalized tip, most charges can converge to the apex of the tip and form large surface charge accumulation on the top, which generates a strong localized enhanced nanoscale field and makes the efficiency of the enhanced field much higher than that of the other optical fields, such as transverse or vortex fields. This will benefit optical imaging with super-resolution, the localized excitation of SPP devices, near-field and nano-spectroscopy (e.g. tip-enhanced Raman spectroscopy), optical trapping and nanoscale manipulation, nano-optical probe processing, nano-optical lithography, and so on. On the other hand, the split two-peak focus formed by the tightly focused LP beam can also be advantageous in optical manipulation, for example, realizing the rotation of optically trapped objects for producing torque.[21,22]

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