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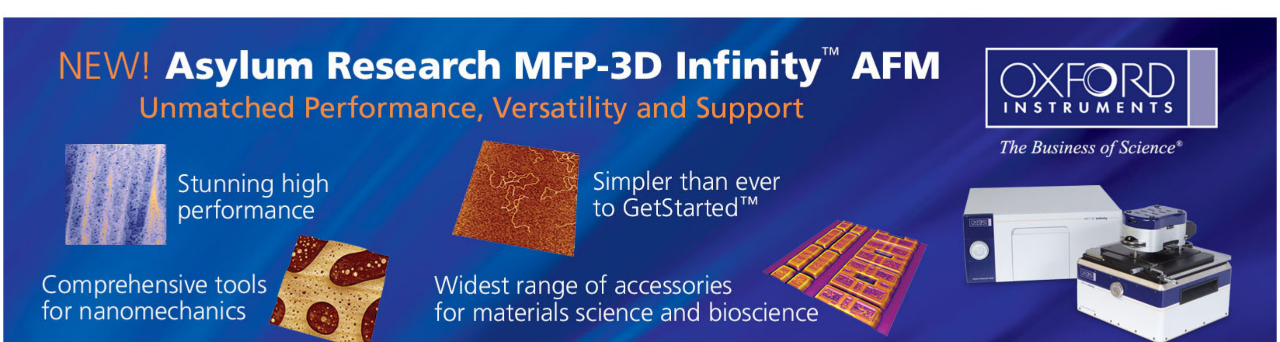

Direct measurement of versatile surface plasmon polaritons excited by split polarization

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We report on the concept, generation, and observation of versatile excited surface plasmon polariton (SPP) patterns via focused split polarization. Unlike the conventional subwavelength features such as holes array, grating, or other protrusion to satisfy the phase matching condition for SPP excitation, we utilized a structured focus to form either counterpropagating interference or a multiple casting plasmonic pattern by means of the arrangement of split polarization and corresponding focus position. The characteristics of the near-field SPP image are in close agreement with the finite-difference time-domain calculation and confirm its feasibility associated with SPP excitations in many areas. © *2011 American Institute of Physics*. [doi:10.1063/1.3552673]

Surface plasmon polaritons (SPPs) are a kind of electromagnetic wave existing at a metal-dielectric interface which is able to propagate up to a few micrometers.[1] Its energy is confined strongly at the interface whose amplitude decays exponentially from the interface into neighboring media. Such an evanescent feature is a prerequisite for applying SPPs on plasmonic based photonic devices. Many spatially arranged subwavelength features were proposed to manipulate the field distribution and the propagation direction of SPPs, such as holes array, grating, or periodic structures.[2–4] The purpose of those delicate structures aims to diffract the incident light into a higher-order wavevector and satisfy the phase matching condition for supporting the existence of SPPs.[1,5–8] Although the prior studies made a huge progress and success, the delicate design in subwavelength scale unavoidably increases the complexity of fabrication, and the lack of the flexibility hinders the application.

As opposed to near-field engineering, the far-field approach provides a direct route to launch SPPs upon a structure free surface. The original concept of the far-field approach comes from Kretschmann and Raether's configuration.[9] Then, Kano *et al.* replace the prism coupler with an objective lens for universal angular spectra of the wavevectors.[10] The use of an objective lens leads not only to a tight focus, but also the freedom to alter SPP distributions. Based on this configuration, various SPP patterns were reported by introducing different states of polarization, such as radial polarization and cogwheel-like structured light.[11–15] However, until now, the generation of SPPs was manipulated by full aperture illumination only. Also, the field distributions of generated SPPs were symmetrical and have an identical shape to the longitudinal component of the focused spot. Excited SPPs with asymmetrical field distribution and corresponding experimental results have not been adequately reported or discussed.

In this study, we adapt a far-field scheme to generate versatile interferometric SPP patterns directly upon a structure free substrate. We split the entrance pupil and allocate different polarizations to different sectors, the so-called spatially inhomogeneous polarization (SIP), to synthesize the three-dimensional field components at focus, thus exciting versatile SPP field distributions. A variety of excited SPPs with different interferometric distributions were demonstrated. The experimental results of scanning near-field optical microscopy (SNOM) show a close agreement with simulation results via finite-difference time-domain (FDTD) method.

The optical configuration is based on the collinear inverted microscopy (Olympus IX81) with an immersion objective lens (Olympus PlanApo-N 60×/1.45 oil), having a half divergence angle of 75.16°, which is well beyond the SPP resonant angle of $\theta_{SP} \sim \pm 45°$ ($\lambda_0 = 632.8$ nm). A multilayer structure [glass ($\varepsilon = 2.28$)/1 nm Ti ($\varepsilon = -5.82 + 12.96i$)/40 nm Au ($\varepsilon = -9.8 + 1.96i$)/air ($\varepsilon = 1$)] is attached to the objective lens with matching oil (n=1.516), as shown in Fig. 1(a). Then, a SIP beam was directed into the objective lens to excite SPPs at the Au/air interface. A SNOM with a 50 nm bared fiber tip was performed to record the near-field image in the experiments. As reference, the

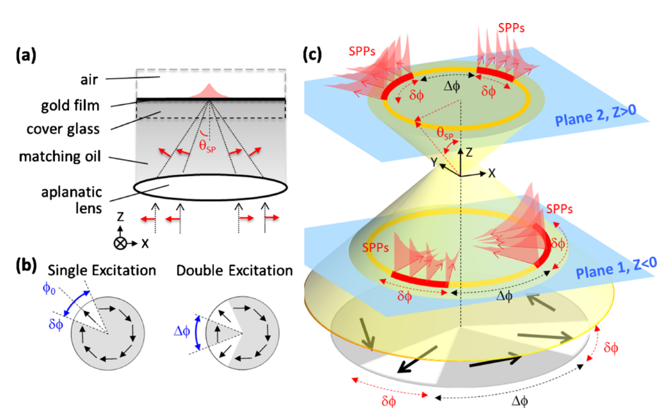

FIG. 1. (Color online) Schematics of the experiment for SPP manipulation. (a) Collinear inverted microscopy in conjunction with an immersion objective lens and multilayer structure glass/Ti/Au/Air. (b) Split polarization with three parameters: $\delta\phi$, ϕ_0, and $\Delta\phi$, respectively. (c) Excitation mechanism of a double excitation scheme and propagation behavior of SPPs associated with different observation planes.

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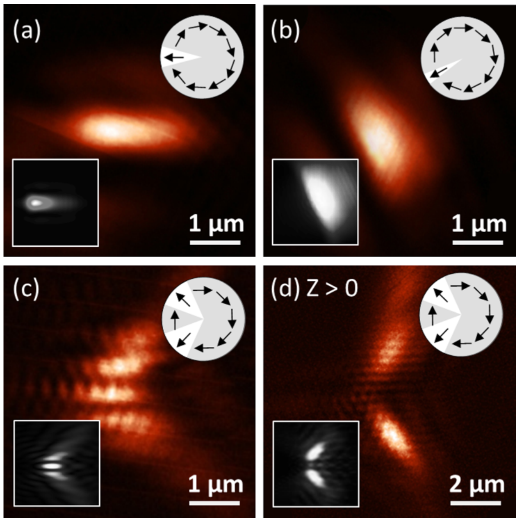

FIG. 2. (Color online) SPP field distributions imaged by SNOM under different excitation schemes: (a) single excitation, $\delta\phi=45°$, on focus; (b) single excitation, $\delta\phi=15°$, on focus; (c) double excitation, $\delta\phi=45°$, $\Delta\phi=45°$, on focus; and (d) double excitation, $\delta\phi=45°$, $\Delta\phi=45°$, defocus $Z>0$, where insets represent FDTD maps.

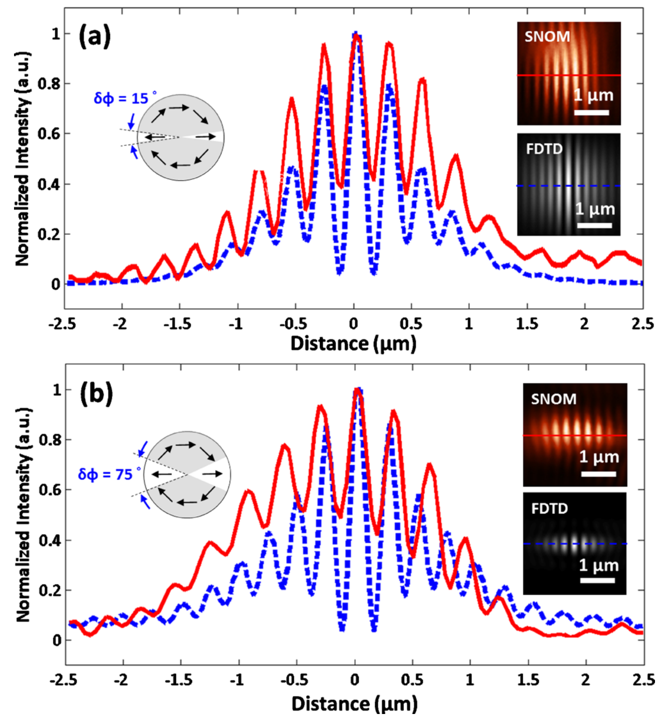

FIG. 3. (Color online) Cross-sectional cut of interference in the case of double excitation scheme with different ratios of the opposite TM sector along the x-axis: (a) $\delta\phi=15°$ and (b) $\delta\phi=75°$, where the period of fringe pattern is increased due to more oblique component of k_y wavevector in the case of $\delta\phi=75°$.

FDTD method in conjunction with vector diffraction theory was adapted to calculate the field distribution of excited SPPs.

The polarization distribution of illumination beams is shown in Fig. 1(b). It is mainly governed by three parameters $\delta\phi$, ϕ_0, and $\Delta\phi$, respectively, where $\delta\phi$ is the arclength of TM-polarized sector, ϕ_0 is the center location of a TM-polarized sector, and $\Delta\phi$ is the arclength between two adjacent arc centers. Each TM-polarized sector emulates an ensemble of SPP dipoles, whose function is similar to the array of holes.[2,3] The interval between each TM-polarized sector was inserted by an orthogonal TE-polarized component, which is used to prevent the occurrence of SPPs at a certain area. Without loss of generality, the TM/TE combination can be extended to various polarization combinations subject to different specific purposes.

The excited SPPs propagate either toward or away from the optical axis depending on the position of air/metal interface. A geometric configuration of a double excitation illustrates the behavior of excited SPPs in the vicinity of the focus, as depicted in Fig. 1(c). An incident light cone with a half divergence angle θ_{SP} hits plane 1 ($Z<0$) and then emerges from plane 2 ($Z>0$) as the rays passing through the focus. The upper and lower cones individually constitute a cross-sectional annular (yellow annular) which indicates the potentially originated location of excited SPPs. At plane 1, the lower converging light cone, which contains a pair of TM portions, excites SPPs on a pair of arcs ($\delta\phi$, red arcs). Then, two groups of excited SPPs would overlap each other and form a strong self-interference pattern. Whereas upper diverging light cone hits the air/metal interface, two groups of excited SPPs independently propagate outward and result in directional patterns.

We conducted a series of polarization distributions to verify the proposed far-field scheme. Figure 2 shows the field distributions of excited SPPs imaged by SNOM. The insets depict the FDTD calculation. In the case of a single excitation on the focus [Figs. 2(a) and 2(b)], the arc center of TM-polarized sector, ϕ_0, determines the propagating direction of excited SPPs. The spread area of excited SPPs is directly governed by the occupied ratio of TM-polarized sector ($\delta\phi$) which exhibits a reciprocal dependence between each other. Figures 2(c) and 2(d) show the function of defocus subject to a double excitation scheme. As two TM portions were kept in phase and focused, two groups of plasmonic waves not only lead to a constructive interference at the center, but also form an additional pair of outer edges. The angular interval of the outer edges is controlled by the size of the sandwiched TE-polarized sector ($\Delta\phi$). When the air/metal interface moves above the focus ($Z>0$), double-excited SPPs go back to the propagating mode. The entire excited SPPs would propagate away from the center and no interference pattern would be observed. As a consequence, the results of double excitation is similar to the work done by Bouhelier *et al.*[11]

Besides the manipulation of SPP patterns, the proposed scheme enables scientists to create interference patterns with a wide range of linewidths and periods. Figure 3 shows the field distribution of excited SPPs by a double excitation scheme with different ratios of the opposite TM sectors along the x-axis. The measured period ($\Lambda_{r\text{-SPP}}$) of SPP interfering fringes along the x-axis increased from $\Lambda_{r\text{-SPP}}=275$ nm to 316 nm as we increased the TM ratio from $\delta\phi=15°$ to 75°. The experimental results closely agree with FDTD results, where $\Lambda_{r\text{-SPP}}=273$ nm at $\delta\phi=15°$ and 312 nm at $\delta\phi=75°$. It is noted that the period of the interference pattern extends horizontally. This is because the spatial period of interference is governed by $\Lambda_{r\text{-SPP}}^2=\Lambda_{x\text{-SPP}}^2+\Lambda_{y\text{-SPP}}^2$, where obliquely propagating SPPs provide an additional k_y wavevector in the horizontal direction. Once a TM-polarized sector occupies the entire entrance pupil, the profile of excited SPPs will be identical to a radial-polarization-generated Airy

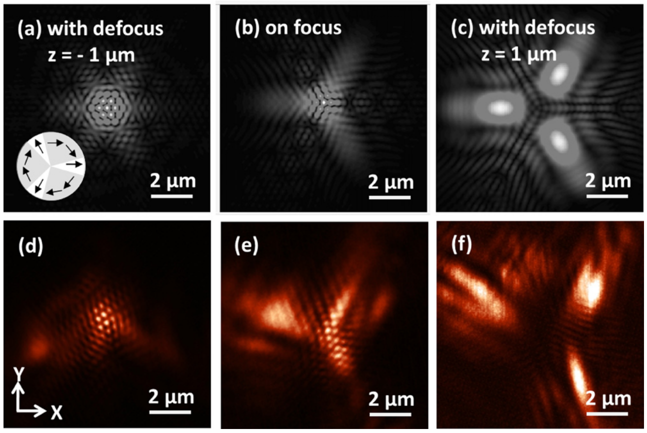

FIG. 4. (Color online) Simulated intensity distribution of SPPs under triple excitation scheme when the observation plane scanned through the focus with (a) defocus Z=−1 μm, (b) on focus, and (c) defocus Z=1 μm. (d)–(f) represent the corresponding near-field images.

disk.[12–14] Such properties ensure that the modulation of the TM/TE ratio controls not only the envelope of the SPP localization but also the fringe pattern.

Finally, we demonstrate a gradual change of SPP distribution from a hexagonal arranged dot array to three independent propagating SPPs. The illumination beam was designed to have threefold TM-polarized sectors with equal arc distance $\delta\phi=45°$, as shown in Fig. 4. At $Z<0$, three bands of in-phase plasmon waves propagated toward the center and yielded a 150-nm-radius dot array profiled by a 300-nm-period hexagonal shape. The dot sizes and separation distances were governed by the standing plasmonic wave; the results were close to the half SPP effective wavelength ($\lambda_{SPP}=2\pi/\mathrm{Re}[k_0(\varepsilon_1\varepsilon_2/\varepsilon_1+\varepsilon_2)^{1/2}]=598$ nm). The separation distance between subwavelength holes can be manipulated by tuning the ratio of TM-/TE-polarized sectors. At $Z>0$, three bands of unmodulated plasmonic waves would lead to three plasmonic fans propagating outward. In combination with the split engineering, other asymmetric SPP patterns can be achieved by introducing designated phase modulation at the entrance pupil.

In conclusion, we proposed a far-field scheme for the generation of asymmetric SPPs upon the structure free metal surface. Based on the split polarization as well as the defocus technique, the proposed scheme provides a similar function of generating and allocating SPP dipoles in the near-field approach. It also provides an irreplaceable flexibility for real-time control by replacing a current polarization converter with a spatial light modulator. The proposed method will certainly has a promising impact on carrying out various SPP excitations for lithographic applications, plasmonic waveguides, and biophotonic devices due to its simplicity and versatility.

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[1]W. L. Barnes, A. Dereux, and T. W. Ebbesen, Nature (London) **424**, 824 (2003).
[2]L. L. Yin, V. K. Vlasko-Vlasov, J. Pearson, J. M. Hiller, J. Hua, U. Welp, D. E. Brown, and C. W. Kimball, Nano Lett. **5**, 1399 (2005).
[3]W. Nomura, M. Ohtsu, and T. Yatsui, Appl. Phys. Lett. **86**, 181108 (2005).
[4]Z. W. Liu, J. M. Steele, H. Lee, and X. Zhang, Appl. Phys. Lett. **88**, 171108 (2006).
[5]H. L. Offerhaus, B. van den Bergen, M. Escalante, F. B. Segerink, J. P. Korterik, and N. F. van Hulst, Nano Lett. **5**, 2144 (2005).
[6]A. Drezet, A. L. Stepanov, H. Ditlbacher, A. Hohenau, B. Steinberger, F. R. Aussenegg, A. Leitner, and J. R. Krenn, Appl. Phys. Lett. **86**, 074104 (2005).
[7]C. L. Zhao, J. Y. Wang, X. F. Wu, and J. S. Zhang, Appl. Phys. Lett. **94**, 111105 (2009).
[8]Y. Xiong, Z. W. Liu, and X. Zhang, Appl. Phys. Lett. **94**, 203108 (2009).
[9]E. Kretschmann and H. Raether, Z. Naturforsch. A **23**, 2135 (1968).
[10]H. Kano, S. Mizuguchi, and S. Kawata, J. Opt. Soc. Am. B **15**, 1381 (1998).
[11]A. Bouhelier, F. Ignatovich, A. Bruyant, C. Huang, G. C. D. Francs, J. C. Weeber, A. Dereux, G. P. Wiederrecht, and L. Novotny, Opt. Lett. **32**, 2535 (2007).
[12]B. H. Jia, X. S. Gan, and M. Gu, Opt. Express **13**, 6821 (2005).
[13]Q. Zhan, Opt. Lett. **31**, 1726 (2006).
[14]W. Chen and Q. Zhan, Opt. Lett. **34**, 722 (2009).
[15]Z. J. Hu, P. S. Tan, S. W. Zhu, and X. C. Yuan, Opt. Express **18**, 10864 (2010).