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Tunable-Focusing of Surface Plasmon Polaritons With a Slightly Irregular Line of Nanofootprints

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Abstract: Tunable surface plasmon polariton launchers are highly demanded in various applications of nanophotonics for achieving controllable plasmonic signals coupling and multiplexing. Here, a tunable-focusing device with simplified structure is suggested. It consists of an array of nanofootprints. This device allows us polarization-controlled tunable plasmonic directing and focusing on the two-dimensional metallic surface. The simulation and experimental results indicate that the focal position of the excited plasmon field can be flexibly tuned between two distinct positions just by manipulating the incident polarization state. Hence, this nanofootprints structure can serve effectively as controllable plasmonic routers and demultiplexers. It also has promising application prospects in many other fields of optics.

Index Terms: Plasmonics, near field microscopy, subwavelength structures, plasmonics, nanostructures

1. Introduction
Surface plasmon polariton (SPP) is a form of electromagnetic surface wave that propagates along a metal-dielectric interface [1], [2]. Its tight spatial confinement and high information processing speed have made it a very tempting option for realizing ultra-high-density photonic integration and led to its advances in optical information technology recently [3]. For this purpose, tunable-focusing is highly required for achieving controllable SPP signals coupling and multiplexing. Several schemes that tuning the location of plasmonic focus by adjusting the incident angle [4], the wavelength [5], [6], or/and the polarization [7]–[11] of the excitation beam have been proposed.

In this work, the tunable-focusing device was further simplified to a set of metallic nano-footprints and its nanostructures were designed to modulate the SPPs wavefront. It enables polarization-controlled tunable plasmonic directing and focusing on the two-dimensional metallic surface and allows coupling light with different polarizations into distinct positions. Hence, this nano-footprints structure can serve as controllable plasmonic routers and demultiplexers. As a proof-of-concept, a nano-footprints structure, functioning as a polarization based diplexer is designed. It is intended to be able to separate circularly polarized light of different handedness and concentrate the excited SPP
wave into well-separated positions. The focused field distributions which were excited by incident light with different polarization states were investigated, both theoretically and experimentally.

2. Method

The SPPs properties are highly dependent on the nano-structure and composition of the interface. This allows manipulating light at the nanoscale to achieve desired functions. In this research, a line of nano-slots with spatially-tuned rotation angle distribution was arranged to realize polarization-controlled tunable plasmonic focusing. The designed nano-footprints structure is illustrated in Fig. 1.

The two focusing positions are set to (2 μm, −3 μm) and (3 μm, 2 μm) for left-handed circularly polarized (LCP) and right-handed circularly polarized (RCP) light, respectively. The coordinate positions and rotation angles of each slot were carefully designed to regulate the optical path and the initial phase.

The phase of SPP generated by a specified slot depends on the polarization of incident light. The purpose of the nano-footprints design is to form different SPP phase profiles for LCP and RCP light. And then the phase can be separate into uniform and non-uniform ones.

The expected initial phases for each slot with LCP and RCP incidence are defined as $\Phi_L(n)$ and $\Phi_R(n)$, respectively. To achieve polarization-controlled phase modulation, they can be decomposed into the distance-dependent one ($\varphi_d$), which is determined by the relative position of the slot to the focal point and independent on the polarization state of the incident light, and the angle-determined one ($\varphi_a$), which is has its initial phase affected by the handedness of the circularly polarized incident light.

$$\begin{align*}
\Phi_L(n) &= \varphi_d(n) + \varphi_a(n) \\
\Phi_R(n) &= \varphi_d(n) - \varphi_a(n)
\end{align*}$$

Considering the effective wavelength of the SPP, the relationship between $\varphi_d$ and $D$ can be written as,

$$\varphi_d(n) = (\Phi_L(n) + \Phi_R(n))/2 = 2\pi \frac{D(n)}{\lambda_{SPP}}$$

Since the phases of SPP wavefronts excited by LCP and RCP light can be described as, $\Phi = \pm[\theta + \pi/2 - \pi \cdot H(\theta)] + \pi/2$. $\theta \in [-\pi/2, 0) \cup (0, \pi/2]$ [12], where the plus and minus signs correspond to the cases of LCP and RCP respectively, which is ‘+’ for LCP incidence and ‘−’ for RCP incidence, and $H(\theta) = \begin{cases} 1 & (\theta > 0) \\ 0 & (\theta < 0) \end{cases}$, is the unit step function. Hence, $\varphi_a$ is determined as follows,

$$\varphi_a(n) = (\Phi_L(n) - \Phi_R(n))/2 = \begin{cases} \theta + \pi/2, & \theta \in [-\pi/2, 0) \\ \theta - \pi/2, & \theta \in (0, \pi/2] \end{cases}$$
The Finite-Difference Time-Domain (FDTD) method was adopted to investigate numerically the performance and the surface-plasmon-related optical properties of the nano-footprints. A circularly polarized plane wave with the wavelength of 632.8 nm was used as the excitation light. It was normally incident from the bottom to the array of crooked nano-footprints. The structure consisted of a column of rectangular slots. The adjacent slots are separated by 0.3 \( \mu \text{m} \) in the y direction, making the total length of the pattern to be about 12 \( \mu \text{m} \). On the one hand, the separation of slots in the y-direction should be larger than the length of each slot to avoid overlapping of adjacent nano-slots. On the other hand, the separation should be kept less than the operating wavelength. Because when the separation is much larger than the wavelength, more beams may be produced owing to the in-plane diffraction which is undesirable [12]. The length and width of each slot is 250 nm and 100 nm, respectively. The slots with the same size but varying coordinate positions and rotation angles were carved through a 0.12 \( \mu \text{m} \) thick gold film. They performed as plasmonic launchers to couple the incident light into the propagating SPP waves and phase modulators to regulate the SPP phase to converge toward different focuses. The slots are located a few micrometers away from the foci in the x direction. The permittivity of gold at the wavelength of 632.8 nm is obtained by fitting the experimental data from the handbook [13] with the Lorentz–Drude model.

3. Results and Discussions

The local field distribution in the vicinity of the probe tip was simulated with the three-dimensional FDTD (FDTD Solutions, Lumerical, Canada). Perfectly-matched-layers boundary conditions were utilized for all boundaries for all the simulations presented below. Within the simulation region, non-uniform FDTD mesh method was used and the minimum grid size was set to be 0.5 nm. A circularly polarized plane wave was normally incident from the glass side on the structure. The distribution of the electric field intensity \( |E|^2 \) of the SPP wave in the xy-plane located 2 nm above the gold film is calculated and presented in Fig. 3(c) and (d). It demonstrates that the incident beams with different handedness polarizations are directed to their desired focal positions (indicated by the intersection of two dashed lines) specified in the design. For the incident light with left-handed circular polarization the plasmon field on the gold surface is focused into a solid spot at the lower-right position, while for light with right-handed circular polarization, the field is focused at the upper-right position. It suggests that the directional SPP focusing can be achieved. And the position of the concentrated plasmon field can be flexibly and dynamically tuned by adjusting the wave plate in an optical system to control the polarization state of incident light.

The designed tunable-focusing device was fabricated by focused ion beam milling (Fig. 2(a) shows the scanning electron microscope image) and the confined optical field distribution on its surface was directly measured to verify the theoretical calculation. The measurement scheme is illustrated in Fig. 2(b). The nano-footprints structure was illuminated from the base side by a circularly polarized red laser with the wavelength of 632.8 nm. It coupled the incident light into propagation SPP waves. And the SPP waves travelled along the air-metal interface and interfered. Under different handedness of circularly polarized illumination, the optical field intensity distributions right above the gold surface were mapped by a transmission-mode aperture scanning near-field optical microscopy (SNOM) (NTEGRA Spectra, NT-MDT, Russia). The experimental and simulation results are presented correspondingly in Fig. 3. It demonstrates that the nano-footprints device is capable of realizing its desired functionalities. Nevertheless, if we go get a closer look, we may still find some differences between the experimental and theoretical results (e.g., the position of the detected focusing spot deviates slightly from the calculated one). This might be caused by some realistic factors, such as the fabrication errors of the nano-structures and the deviation from the sample surface normal from the optical axis of the incident beam.

4. Conclusion

In summary, we have proposed a tunable-focusing device with simplified structure. It is composed of an array of nano-footprints, i.e., a slightly irregular line of tilting nano-slots on a gold film. It can
Fig. 2. (a) The scanning electron microscopy image of the fabricated nano-footprints structure and (b) measurement scheme of the plasmon field on the surface.

Fig. 3. Calculate electric field distributions (xy plane, \( z = 2 \text{ nm}, 14 \times 14 \mu \text{m} \)) with (a) (c) LCP and (b) (d) RCP illumination. (a) (b) phase distributions, and (c) (d) intensity distributions. And experimental results of the plasmon field intensity distribution on the surface with (e) LCP and (f) RCP illumination. The intersection of the dashed lines indicates the desired focal position.
achieve polarization-controlled tunable plasmonic directing and focusing on the two-dimensional metallic surface. In this work, simulations using FDTD and experiments using SNOM were conducted for detecting the performance and optical properties of this tunable-focusing device. The plasmon fields concentrating on gold surface under LCP and RCP illumination were presented. Despite negligible differences, the results are in good agreement with the desired ones. It shows that the incident beams with different handedness polarizations are directed to their desired focal positions specified in the design. This commits the effectiveness and simplicity of our approach. It indicates that this nano-footprints structure allows coupling light with different polarizations into well-separated positions. The focal position of the excited plasmon field can be flexibly tuned between two distinct positions just by manipulating the incident polarization state. Hence, this nano-footprints structure can serve as controllable plasmonic routers and demultiplexers. On the other hand, it can be applied to analyze the incident polarizations effectively by detecting the focal position of the plasmon field. Hence, this method may have promising applications not only in plasmonics but also in many other fields of optics.

References