Steering plasmon beam from a point source

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We extend the phase modulation method by in-plane diffractions from plane wave incidence to point source of surface plasmon polariton (SPP). A well-defined SPP focus is successfully realized from a point source under the diffraction by a carefully designed nanohole array, which is easy to layout in the future integrated optical circuits. With this method, the SPP Airy beam and finite plane wave are demonstrated as well, proving a general applicability of this modulation method. The proposed method and realized functions are expected of benefits for the future integration optics.

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The surface plasmon polariton (SPP) has sparked great research enthusiasm due to its unique property of confinement of electromagnetic (EM) field on metal surface, which is of potential usage for routing EM wave at subwavelength scale [1]. Plenty of achievements in tailoring SPPs in planar dimension have been reported in the recent decade, such as Bragg mirrors [2], demultiplexer [3], and focusing [4]. However, most of these functions rely on either the coupling process or SPP plane wave incidence (near plane wave front). A probable part of future integrated photonic circuits would be such a device that SPPs are generated by the source from one port, then manipulated and injected to another port (i.e., the SPPs source in a possible photonic circuit is probably a quantum dot or from a narrow waveguide [5]). In this consideration, these SPP sources cannot be regarded as plane wave as expected in previous works for its nonzero NA. Instead, it is more appropriate to take them as a point source. In this Letter, we propose a phase modulation method to tailor the SPP propagations from a point source, by which plasmonic focusing, Airy beam, and finite SPP plane wave are well demonstrated by the in-plane diffractions.

In our recent works, a novel phase modulation method for propagating SPP plane waves by diffractions from nonperiodic nanoarray was introduced, where the equivalent phase has an extra 2π change when the incident surface wave passes through a unit row of array with the local lattice parameter (b) gradually changed in the wave propagation direction [6,7]. As a result, the local diffraction angle (α) is defined by the local lattice b as shown in Fig. 1(a). The corresponding phase evolution of the diffracted SPPs can be written as $\varphi(x) = \varphi_0 + k_{\mathrm{spp}}x - 2n\pi$. Here, φ_0 is the initial phase of the incident wave and n is the sequence number of the lattices along the propagation direction. The validity of this method has been proved in the generation of Airy plasmon [6] and broadband focusing [7] from the plane SPP wave incidences. In fact, this diffraction method is still valid for the waves from a point source by the principle of first-order diffraction, as shown in Fig. 1(b), that is, an extra 2π phase change when the incident surface wave passes through a unit row of the nanoarray with the local lattice parameter changes gradually. However, the initial propagation phase difference of the neighbor units is $\Delta\varphi = k_{\mathrm{spp}} b \sin\theta$, which is different from that of plane wave incidence. So that, the phase difference of the neighbor lattice points is $\Delta\varphi = k_{\mathrm{spp}} b \sin\theta - 2n\pi$, where θ is incident wave direction with respect to z axis, as in Fig. 1(b). What's more, the incident direction (θ) of the point source varies at different positions as

$$\sin\theta_n = \frac{x_0 - l_n}{\sqrt{(x_0 - l_n)^2 + z_0^2}} = \frac{x_0 - \sum_n b_n}{\sqrt{\left(x_0 - \sum_n b_n\right)^2 + z_0^2}}, \quad (1)$$

in which (x_0, z_0) is the location of the point source, b_n is the distance between the nth and $(n-1)$th units, and l_n is the position of the nth unit in x axis. Then we can get the phase evolution of the point source along the nanoarray as

$$\varphi_n = \sum_n \Delta\varphi_n = \sum_n k_{\mathrm{spp}} b_n \frac{x_0 - \sum_n b_n}{\sqrt{\left(x_0 - \sum_n b_n\right)^2 + z_0^2}} - 2n\pi. \quad (2)$$

First, we would demonstrate the focusing of SPPs from one point source (O_1) to another point (O_2) in the z axis by a well-designed nanoarray, as schematically shown in Fig. 2(a), which indicates the possibility of routing SPPs from one port to another. At the beginning, the

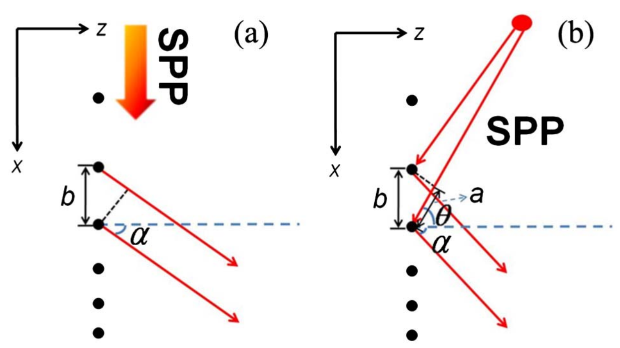

Fig. 1. (Color online) Schematics of diffraction principle of SPPs for (a) plane wave incidence and (b) point source incidence.

horizontal positions (z_m) of the units of nanoarray along the z axis ($x = 0$) were defined by the method of the plane wave case as we mentioned before [7]. Hereafter, O_2 was set as the source of the "plane wave" and O_1 is the target foci. It is easy to get that all the diffracted waves of the nanoarray from the source O_1 will have the same phase (or phase difference of $2m\pi$) when they propagate through O_2 by the principle of reciprocity. Then we calculated the position of every unit of every line with z-axis location of z_m by solving $\varphi_n = \Psi(x)$, where φ_n is the phase of point source as illustrated above and $\Psi(x) = -k_{\text{spp}}x^2/2(f_0 - z_m)$ is the phase evolution with focal length of $(f_0 - z_m)$, in which f_0 is the designed focal length and z_m is the horizontal position of the line defined before. So that all the diffracted SPP waves by the nanoarray would have the same phase with respect to their directions to the focus O_2, which are originally generated from the point source O_1.

In experiments, we fabricated the well-designed nanohole array with hole diameter of 240 nm by the focused ion beam (Strata FIB 201, FEI Company) on a 60 nm thick silver film sputtered on a SiO_2 substrate. Figure 2(b) shows the scanning electron microscopy (SEM) image of the fabricated sample, where the nanoarrays are designed centered of $z = -5$ μm in z-coordinate (as partially shown in the inset image) and designed focal length is $f_0 = 30$ μm. A series of concentric circle grooves with the inner circle radius of 3 μm and the incremental of 610 nm is designed locating at ($z_0 = 0$ μm, $x_0 = -25$ μm) to launch SPP from an incident laser beam, which works as the SPP point source [as its leakage radiation microscope (LRM) image shown in the inset of Fig. 2(c)]. The depths of all structures are about 20 nm. The SPP propagations and diffractions were detected by a home-built LRM system with an oil-immersion lens (160×, NA = 1.4) [6–8]. Figure 2(c) is the experimental result with focal length of $f_0 = 30$ μm for an SPP wavelength of $\lambda \sim 610$ nm (from $\lambda_0 = 632.8$ nm of He–Ne laser). A theoretical calculation was also performed using Huygens–Fresnel (HF) integration [9,10] as the result depicted in Fig. 2(d), well reproducing the experimental one. The longitudinal and the transverse profiles of the focal spot are plotted in Fig. 2(e), which is as good as the result of plane wave design [7], demonstrating the realization of SPPs focusing from a point source.

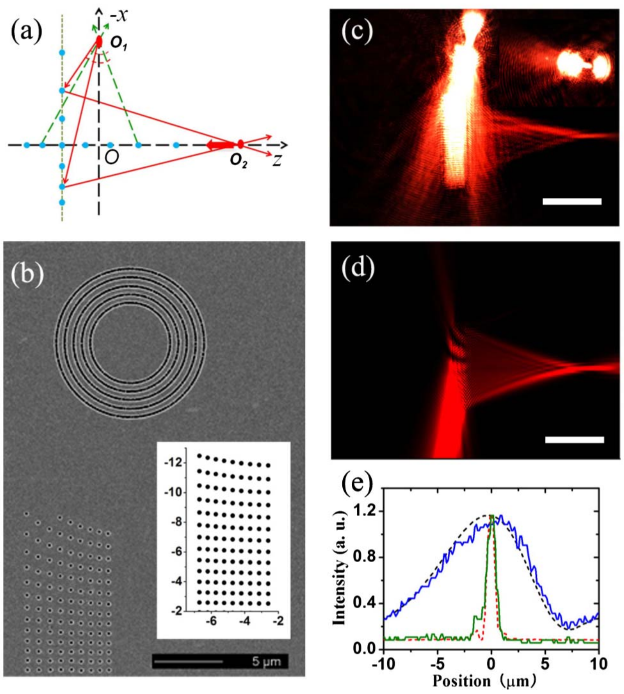

Fig. 2. (Color online) (a) Schematic of SPP focus design from a point source. (b) Top-view SEM image of sample fabricated by FIB. Inset is a part of designed array coordinates, where the array center in z axis is about $z = -5$ μm, and point source locates at ($z_0 = 0$ μm, $x_0 = -25$ μm). (c) Experimental result recorded by LRM and (d) calculated one. Scale bar of 10 μm. (e) Profiles of the focal spot for experiment (solid curve) and calculation (dash curve). The green and red curves are in z direction (longitudinal), and the blue and black ones in x direction (transverse).

Notably, quite distinct from previous SPP focus results with focal spots symmetrically on both sides [4,7], SPP focusing revealed here [Fig. 2(c)] is only for one side as designed shown in Fig. 2(a). It is a unique unidirectional SPP focus design at the manipulation of a regular (rectangular) layout. The focal intensity is higher than the previous one as well [7] due to this unidirectional design, which is of great importance in restraining the power consumption and would be helpful in practical integrations. It also should be mentioned here that our SPP focusing device is based on the diffraction process, which would inevitably lead to some energy loss (e.g., energies passed over the array or scattered out). We may roughly estimate the diffraction efficiency by checking the beam intensities at different places. It would be a little bit low (~10%) as well as the propagating loss is included. Even though, we believe this efficiency can be further improved by enlarging the array area and carefully modifying the diffraction units.

Next, a nondiffractive and self-bending plasmonic Airy beam from a point source is also designed and generated with this method. Plasmonic Airy beam has arrested increasing interests owing to novel properties [6,11,12]. Previous generation methods are based on the coupling process or diffractions from Gaussian SPP beam (near plane wave). Here, in the case of a point source, the nanoarray parameter can also be obtained by solving $\varphi_n = \Psi(x)$, where

$$\psi(x) = -\frac{2}{3}\left(-\frac{x}{x_a}\right)^{3/2} - \frac{\pi}{4},$$

the phase for Airy beam, and $x_a = 1.08$ μm is a scale factor same as that in our previous work [6]. The position of the point source is set at ($z_0 = 5$ μm, $x_0 = -25$ μm). The designed vertical positions are shown in Fig. 3(c) and the horizontal dimension is periodic with $P_z = 520$ nm, which is designed for the matched Bragg condition of the started position ($x = 0$). The calculated result with HF integration and the experimental result recorded by LRM are shown in Figs. 3(a) and 3(b), respectively, which are in very good coincidence. The experimental trajectory of the main lobe is plotted together with the theoretical parabolic curve in Fig. 3(d), which also shows considerable agreement, indicating the outcome of plasmonic Airy beam.

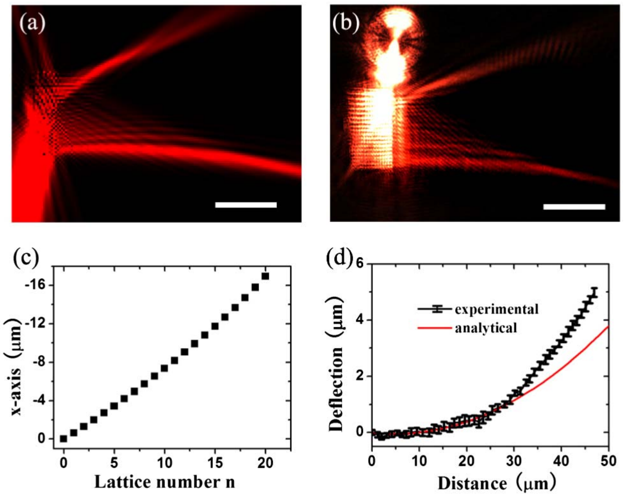

Fig. 3. (Color online) (a) Calculated result of Airy beam design from point source. Inset, the design data of nanopoints positions. (b) Experimental result and inset, the experimental curve of the main beam together with the analytical one. Scale bar of 10 μm.

At last, we would like to demonstrate a finite SPP plane wave generated by above method from an SPP point source. A plane wave is a constant-frequency wave whose wavefronts are infinite parallel planes normal to the phase velocity vector. A finite plane wave with finite parallel wavefronts propagating along the z axis is designed here. The design process is almost the same as the focus design. The first step is to define the horizontal position of the units of the nanoarray as that in the focus design with the principle of reciprocal. Then the vertical positions are calculated with the phase along the x direction preserved for plane wave of $\Psi(x) = 0$ in $\varphi_n = \Psi(x)$. The design data is shown in the inset of Fig. 4(a) for point source at $x_0 = -30$ μm, $z_0 = 0$ μm. The calculated result with HF integration and experimental one are shown in Figs. 4(a) and 4(b), respectively. The intensity of the experimental result decreases along the z direction due to the propagation loss of SPP. In spite of this, both of the results show good realization of finite SPP plane wave.

In conclusion, we successfully extend the phase modulation method of in-plane diffraction from the plane wave incidence to the point source. With this, SPP focus, Airy beam, and a finite plane wave are well demonstrated with a point source, indicating the general applicability of this method. Furthermore, different from our previous bidirectional Airy beam and focusing, all of these designs

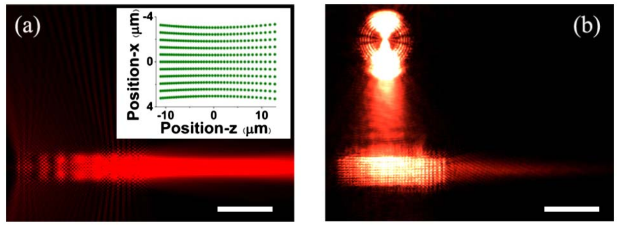

Fig. 4. (Color online) (a) Calculated result of SPP finite plane wave from point source. Inset, the design data of nanopoints positions. (b) Experimental result. Scale bar of 10 μm.

have a common unidirectional property, which is beneficial for the power consumption. Our results indicate this in-plane diffraction method holds a general sense, with which the realized plasmonic functions are expected of promising application for the future beam engineering and integrated optical circuit.

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