Tunable directional beaming assisted by asymmetrical SPP excitation in a subwavelength metallic double slit

Xiaowei Li (李晓炜)[1,2*], Qiaofeng Tan (谭峭峰)[1], Benfeng Bai (白本锋)[1,2,3], and Guofan Jin (金国藩)[1]

[1]*State Key Laboratory of Precision Measurement Technology and Instruments, Tsinghua University, Beijing 100084, China*

[2]*Tsinghua-Foxconn Nanotechnology Research Center, Tsinghua University, Beijing 100084, China*

[3]*Department of Physics and Mathematics, University of Eastern Finland, FI-80101 Joensuu, Finland*

[*]*Corresponding author: li-xw06@mails.tsinghua.edu.cn*

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We present a design for tunable directional beaming through a subwavelength metallic double slit surrounded by dielectric surface-relief gratings. On-axis and off-axis beaming can be switched by controlling the incident angle to asymmetrically excite surface plasmon polaritons (SPPs) that are subsequently coupled out to propagating beams by the two gratings on the left and the right sides of the double slit. Furthermore, the division of optical power into two off-axis beaming directions can be tuned smoothly by varying the incident angle while keeping the total power almost unchanged. The mechanism of this effect is analyzed theoretically and verified using rigorous numerical simulations.

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Light emerging from a subwavelength slit or aperture is normally diffracted into all directions. Recently, the directional beaming effect from a subwavelength metallic slit due to the resonant interactions between surface plasmon polaritons (SPPs) and the surrounding grating structures has stimulated much interest due to its possibility to steer and confine emitted light beams in a small spatial range of angle[1,2], which has potential applications in laser beam shaping[3−4], optical interconnection[5], secure communication, optical data storage, and optical imaging, among other areas. Considerable prior research related to optical on-axis and off-axis directional beaming has been conducted[6−13], with the mechanism applied to mid-infrared[3,10], THz wavebands[4], acoustic wave[9], and photonic crystals[12]. However, little work has been done on tunable directional beaming (i.e., modulating the beaming angle or power distribution by controlling signals), although tunable beaming with the use of permittivity-modulating material has been proposed before[8]. Hence, it is of great significance to realize tunably control of the directional beaming, which is highly desirable in various applications.

Previously, various plasmonic devices have been used to exploit the angular-modulation of the incident light[14−16]. For example, Kim *et al.* designed an unidirectional SPP launcher consisting of a single slit with its width comparable to or larger than the incident wavelength[15]. However, such a wide slit has a low SPP excitation efficiency because most of the light illuminating the slit would be directly transmitted through the slit rather than coupling into SPPs[17]. Recently, we demonstrated efficient directional excitation of SPPs on a metal film through a subwavelength double nanoslit[16]. The SPPs can be directed into two opposite propagating directions with a predetermined splitting ratio by varying the incident angle. Such dynamic tunability of SPPs can be used to realize some useful applications. In this letter, a simple and effective design for tunable directional beaming through a metallic double slit surrounded by dielectric surface-relief gratings is proposed. On-axis and off-axis beaming can be switched by controlling the incident angle to asymmetrically excite SPPs that are subsequently coupled out to propagating beams by the two gratings at the left and the right sides of the double slit. Furthermore, the division of optical power into two off-axis beaming directions can be smoothly tuned by varying the incident angle while maintaining the total power almost unchanged.

The schematic of the proposed structure is depicted in Fig. 1. Two 100-nm-wide subwavelength slits spaced by d between their slit centers are perforated into a 300-nm-thick silver film deposited onto a glass substrate with a refractive index of $n_{\mathrm{s}} = 1.5$. p_{R} and p_{L} are off set distances on the right and the left sides. And d_{R} and d_{L} are the grating periods corresponding to the left and the right sides, respectively. When the TM polarized light with wavelength $\lambda_0 = 532$ nm impinges on the double slits from the back side at an incident angle θ, the scattered light from each slit may gain an additional wave vector along the metal film surface, allowing a portion of the incident light to excite SPPs on the silver-air interface. The left and the right dielectric gratings attached to the silver surface are designed to resonantly diffract the SPPs that have been generated by the double slit to propagating modes in the far field. The gratings have rectangular profiles, with thickness h of 40 nm and filling factor of 0.5, and are made of a material with refractive index of 2.0.

To effectively couple SPPs to radiation modes, the grating should be able to couple incident light to SPPs under the same resonance condition[8,9,18]. Therefore, we first inspect an infinite grating, as shown in the inset of Fig. 2(b), by calculating its reflectivity spectra with respect to the change of period and incident angle θ_{inc} using the Fourier Modal Method[19], as shown in Fig. 2(a). Since low reflectance indicates a strong coupling of incident light to SPPs on the metal surface, we can infer

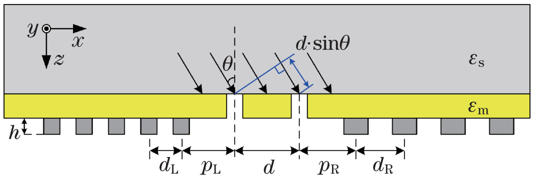

Fig. 1. Schematic of the structure for tunable directional beaming.

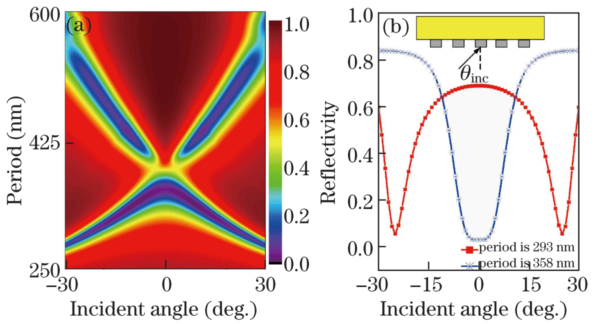

Fig. 2. (a) Reflectivity of an infinite dielectric grating with respect to the change of period and incident angle; (b) angular reflectivity spectra of the grating with a period of 293 or 358 nm.

that the SPPs can be coupled to the far field in this case. Therefore, by choosing the grating period as 358 and 293 nm, as shown in Fig. 2(b), we can realize on-axis (0°) and off-axis (±25°) beaming, respectively.

Then let us consider a double-slit structure without dielectric gratings. In a normal incidence, the equal strength of SPPs can be excited toward the left and the right sides of the slits as a result of symmetry. The phases of the excited SPPs from the two slits can be modulated by, for example, adjusting the widths of the slits or the refractive indices of the materials filling the slits[20] or by changing the incident angle, which we will consider in this letter. At an oblique incident angle θ, the phase difference between the SPP waves excited by the two slits on the air-silver interface can be written as

$$\varphi_{\mathrm{R}} - \varphi_{\mathrm{L}} = \frac{2\pi}{\lambda_0} n_s d \sin\theta, \tag{1}$$

where φ_{L} and φ_{R} represent the initial phases of SPPs excited by the left and the right slits, respectively. By introducing this asymmetry, the left and the right SPPs with different relative phases can be controlled to interfere constructively with one side and destructively with the other side, thereby realizing the directional excitation of SPPs. For example, if we want to excite SPPs only to the left side, the following phase matching conditions should be satisfied:

$$\varphi_{\mathrm{L}} - (\varphi_{\mathrm{R}} + k_{\mathrm{SPP}} d) = 2n\pi, \tag{2}$$

$$\varphi_{\mathrm{R}} - (\varphi_{\mathrm{L}} + k_{\mathrm{SPP}} d) = (2m+1)\pi, \tag{3}$$

where k_{SPP} is the wave number of SPPs propagating the air-silver interface and m and n are arbitrary integers. k_{SPP} and the associated SPP wavelength λ_{SPP} are obtained by

$$k_{\mathrm{SPP}} = \frac{2\pi}{\lambda_{\mathrm{SPP}}} = \frac{2\pi}{\lambda_0}\sqrt{\frac{\varepsilon_{\mathrm{m}}\varepsilon_{\mathrm{d}}}{\varepsilon_{\mathrm{m}}+\varepsilon_{\mathrm{d}}}}, \tag{4}$$

where $\varepsilon_{\mathrm{d}} = 1$ and $\varepsilon_{\mathrm{m}} = -9.14+0.805\mathrm{i}$[21] are the dielectric constants of air and silver, respectively. The SPP wavelength λ_{SPP} is calculated as 502 nm. Therefore, by substituting Eqs. (1) and (4) into Eqs. (2) and (3), we can obtain the double-slit distance $d = 376$ nm and $\theta = 14°$ by choosing $n = -1$ and $m = -1$. Similarly, the SPPs can also be excited unidirectionally to the right side, with $d = 376$ nm and $\theta = -14°$. Rigorous numerical simulations (using the Finite-Element Method software COMSOL Multiphysics) of the field distributions shown in Figs. 3(a1) and (a2) verify the unidirectional excitation of SPPs under these circumstances. Note that, for the double-slit structure, some of the SPPs excited by one slit may propagate toward the other slit along the silver-substrate interface and then contribute to the SPPs generated by this slit on the silver-air interface. This cross-coupling can be broken, for example, by placing a blocking chip between the two slits[22]. However, the blocking chips themselves also act as scatters for exciting SPPs, which would give rise to the noise of the device. Actually, in the practical fabrication of the device, there is usually an adhesion layer (such as Ti or Cr) between the silver film and the substrate[16], which can reduce the SPP cross-coupling between the two nanoslits on the silver-substrate interface.

Now if dielectric gratings are attached to the left and the right sides of the slits, then the SPPs can couple to a far field via the gratings, and directional beaming can be achieved. To demonstrate the tunability of the directional beaming, the left and the right dielectric gratings are designed to couple SPPs for beaming on-axis (0°) and off-axis (−25°), which should have periods of $d_{\mathrm{L}} = 358$ nm and $d_{\mathrm{R}} = 293$ nm, respectively, by referring to Fig. 2(b). Note that, due to the phase-matching condition,

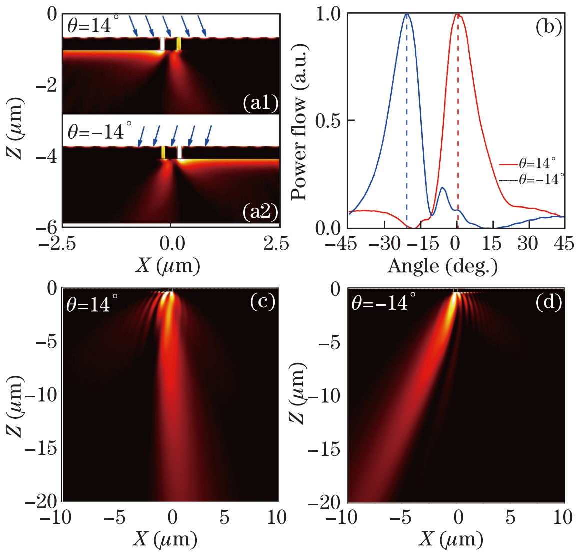

Fig. 3. (a1) and (a2) Simulated time-averaged power flow distribution in the double-slit structure without the dielectric gratings under incident angles of ±14°; (b) cross-section profiles of the power-flow distributions in the circle at $r = -10$ μm with a double slit at the center for (c) and (d); (c) and (d) simulated time-averaged power flow distribution in the double-slit structure with $d_{\mathrm{L}} = 358$ nm and $d_{\mathrm{R}} = 293$ nm under incident angles of ±14°.

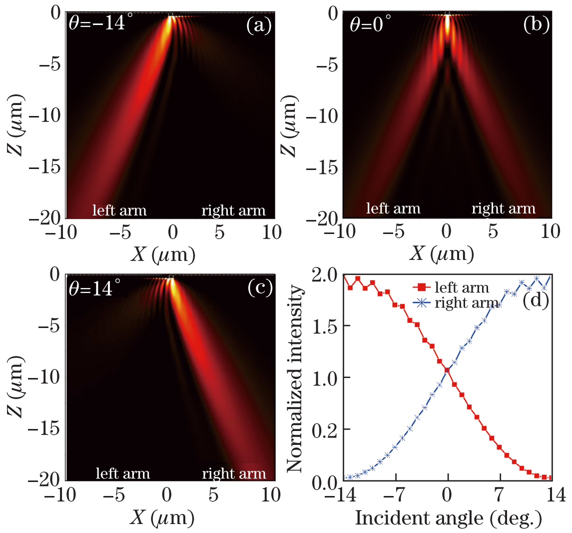

Fig. 4. Time-averaged power-flow distributions of directional beaming generated by the double slit surrounded by dielectric gratings at the incident angles of (a) –14°, (b) 0°, and (c) 14°; (d) variation of intensities in the left and the right beaming arms by changing the incident angle. Both the left and the right dielectric grating periods are 293 nm.

the right propagating SPPs only couple with the beaming direction of –25°. The offset distances $p_{\rm L}$ and $p_{\rm R}$, which influence the fine quality of the beaming, are set to 300 and 200 nm, respectively, according to numerical optimization. The simulated field distribution of the beaming effect under incident angles ±14° are shown in Figs. 3(c) and (d), whose cross-section profiles in the circle at $r= -10$ μm with the double slit at the center are also given in Fig. 3(b). The beaming angle is then extracted as that between the z axis and a line connecting the maximum intensity point at the $r = -10$ μm plane and the coordinate origin. The results indicate that, at +14° (–14°), all SPPs are propagating toward the left (right) side, thereby triggering the left (right) grating to beaming in the on-axis (off-axis) direction. The extracted on-axis and off-axis beaming angles are 0.3° and –20.5°, respectively, which approximately agree with our prediction.

By employing the same principle, it is also possible to split the optical power into two beaming directions. For example, in order to couple the SPPs to ±25° beaming directions, we design the left and the right dielectric gratings with the same period $d_{\rm L} = d_{\rm R} = 293$ nm. The offset distances $p_{\rm L}$ and $p_{\rm R}$ are both set at 200 nm. The simulated time-averaged power flow distribution with respect to the change of incident angle is calculated, where the screenshot for incident angles at –14°, 0°, and 14° are presented in Figs. 4(a)–(c). Obviously, the tunable power division in the two beaming directions can be realized. As shown in Fig. 4(d), by varying the incident angle, one can smoothly tune the power distribution into two beaming branches while keeping the total power almost unchanged.

In conclusion, we propose and theoretically demonstrate a tunable directional beaming structure consisting of double slits surrounded by dielectric surface-relief gratings. By optimizing the structure parameters, both on-axis and off-axis beaming can be switched by controlling the incident angle. The optical power allocation in the two beaming branches can also be smoothly tuned using this technique. The same principle can be extended to device designs in other asymmetrical SPP excitation schemes and other wavelength ranges, such as mid-infrared and THz, which may open the way to make it feasible to tune plasmonic devices based on the directional beaming effect.

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