Active control of focal length and beam deflection in a metallic nanoslit array lens with multiple sources

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We propose an all-optical method to actively control the transmission of nanoslit arrays for scanning and lensing applications. We show that by utilizing two lateral control slits, the transmitted beam can be actively steered.

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Metal–dielectric interfaces interacting with light sustain surface plasmon polariton (SPP) excitations that can propagate along the interface. Beyond the diffraction-limited value, SPPs can provide extraordinarily enhanced light transmission (EOT) through subwavelength apertures in a metal film [1,2]. Therefore, there is a growing interest in developing plasmonic structures for guiding and manipulating the light propagation at subwavelength scales. One of the features is controlling the shape and direction of the beam emitted through an aperture. Several studies have demonstrated the passive control that is obtained by surrounding the slit with surface corrugations. The corrugation pattern modifies the SPP dispersion, which, in turn, generates a confined beam in the normal [2–5], the off-axis [6,7], or in multiple directions [8]. The corrugation pattern can also be modified to modulate the focal length of the beam [9–11]. Another design approach employs multiple slits separated by nanoslits without any surface corrugation. The nanoslit profile can then be utilized for beam shaping [12]. Theoretical studies of the surface-plasmon–photon interaction on metallic wedge structures provide insight on the SPP-assisted emission properties [13].

Active control of the beam modulation is highly desirable. A recent study proposed embedding Kerr nonlinear medium in the slit array where the nonlinearity, driven by the intensity of the incident beam, induces beam deflection and focusing upon inducing a specific phase retardation at each slit [14]. In this Letter, we propose an all-optical active steering of the transmitted beam through nanoslit arrays.

We consider the typical two-dimensional nanoslit array geometry and introduce two lateral control slits, as shown in Fig. 1(a). We use dimensions typical in nanoslit array studies [6,12,15]. The input and the control fields are characterized by their magnetic field amplitudes H_1 and $H_{2,3}$, respectively. They are chosen to be TM-polarized monochromatic waves at $\lambda = 561$ nm. The corresponding dielectric function of the metal (silver) is $\varepsilon = -11.66 + i0.3771$ [16]. We simulate the beam transmission using a finite-element-method-based software, COMSOL Multiphysics. Figure 1(b) shows the focusing effect when both control signals are at the same intensity. We determine the focal length (f) as the distance where the magnetic field has its maximum amplitude. The beam waist (ω_0), the transverse extension of the beam, is determined at the focal point. Figures 1(c) and 1(d) show the focal length and beam waist, respectively.

When the intensities of the control slits are varied with equal field amplitudes, the focal length and the beam waist are changed, as in Figs. 2(a) and 2(b). The transmitted beam gets more collimated as $H_{2,3}$ are increased up to 0.5 [A/m]. The control is fine when $H_{2,3}$ are much less than H_1 and becomes coarse between 0.3–0.5 [A/m]. When $H_{2,3}$ start to become comparable to H_1, defocusing occurs. This behavior can be described by the usual T junction formed by the outermost slits and the control

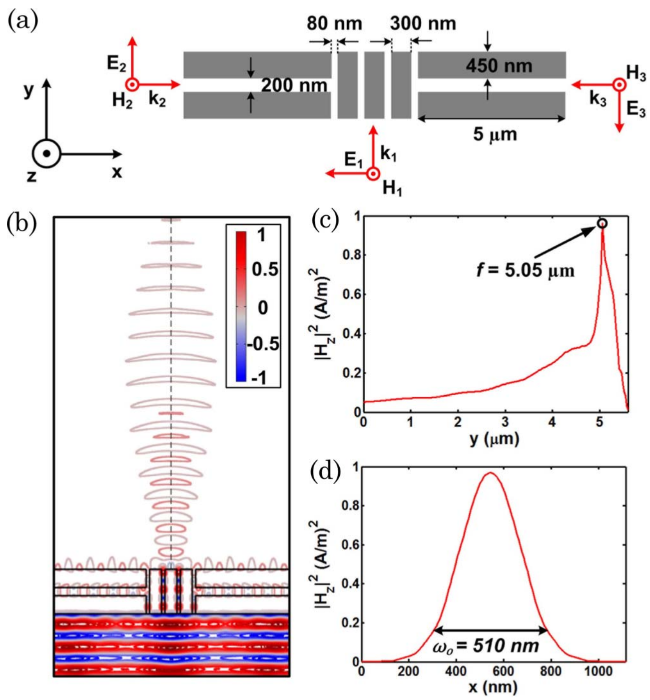

Fig. 1. (Color online) (a) Schematic of the nanoslit lens system with the main input field H_1 and two control sources, H_2 and H_3. (b) Simulation of the system at $H_1 = 1$ [A/m] and $H_2 = H_3 = 0.2$ [A/m]. (c) Focal point f and (d) beam waist ω_0 of the transmitted beam for the system.

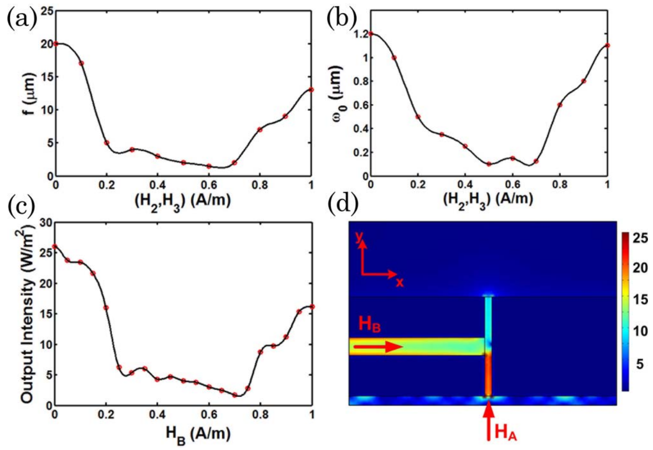

Fig. 2. (Color online) (a) Focal length f and (b) beam waist ω_0 of the transmitted beam as a function of the identical amplitude of the control sources $H_{2,3}$ for $H_1 = 1$ [A/m]. (c) Output intensity of a T junction, depending on the control source H_B when the input is $H_A = 1$ [A/m]. (d) The field intensity (W/m^2) in the T-junction system for $H_A = 1$ [A/m] and $H_B = 0.4$ [A/m].

slits [17–19]. The transmission character of the T junction plotted in Figs. 2(c) and 2(d) shows remarkably the same behavior as Fig. 2(a). In the regime $H_{2,3} \ll H_1$, the control fields have negligible effect on the transmitted field. As they become strong, about half of the input signal, they can effectively close the outermost slits, acting as the T junctions. With the outermost slits being dimmer, the effective aperture of the lens is reduced to the innermost slits. Consequently, both the focal length and the beam waist decrease. When $H_{2,3}$ become comparable to H_1, the outermost slits contribute more and the transmitted beam is diffracted. The increase of directivity and focal length with increasing slit number is a typical nanoslit array behavior [12]. Intensity distributions in the slits are shown in Figs. 3(a) and 3(b), corresponding to the respective cases in which the outermost slits are "on" and "off."

This T-junction picture is accompanied by a SPP contribution, whose role becomes more crucial in the case of angular deflection of the transmitted beam [17–19]. The role played by SPPs is to propagate phase information between the slits and to affect transmission by influencing the interference effects in multiple metallic slit arrays [20–24]. According to these results, we now show that SPP communication of the neighboring slits and the T junctions at the ends can be combined into an all-optical active beam steering mechanism in nanoslit arrays.

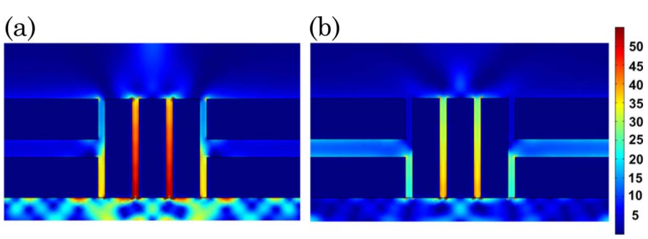

Fig. 3. (Color online) Field intensity (W/m^2) in the nanoslit array for (a) $H_1 = 1.0$, $H_2 = 0$, and $H_3 = 0$ [A/m], and (b) $H_1 = 1.0$, $H_2 = 0.5$, and $H_3 = 0.5$ [A/m].

We consider now the case of unequal field amplitudes applied into the control slits. In Fig. 4, typical simulation results of beam steering are shown. Scanning is accomplished while the beam shape is preserved. Therefore, the f and ω_0 dependency on the control sources limits the continuous beam scan ability.

As for the behavior of the deflection angle with the intensity of the field in the control channel, we consider a practical situation. To make it a single parameter problem, we consider one of the control channels to have no field and the total intensity of the fields in the two control channels to be constant. By simulating these cases, we find the optimum achievement where one channel is empty. The angular deflection is monotonically increasing in an approximately linear fashion up to about half of the main signal. Beyond that point, further increase of the deflection angle is too slow and is almost saturated about the maximum deflection angle of ±14°, as shown in Fig. 5(a). Similarly, the reported focal length and beam waist also are found to be the optimal results. A careful examination of Fig. 5 should reveal that the geometry of the system is also optimized to get the most efficient deflection and focusing effects. The intensity gradient over the slits would be smoother if we use more slits. Then, the influence of the outermost slits would diminish. In addition to the limited number of slits, sacrificing one slit to get deflection may also be considered as an operational boundary that might degrade the transmission efficiency of our proposal. The asymmetric field intensity distribution in Fig. 5(b) is due to the SPP communication between the neighboring slits. This mechanism is explained in Figs. 5(c) and 5(d). The SPPs generated by the control field can excite SPPs on the walls of the neighboring nanoslit waveguide.

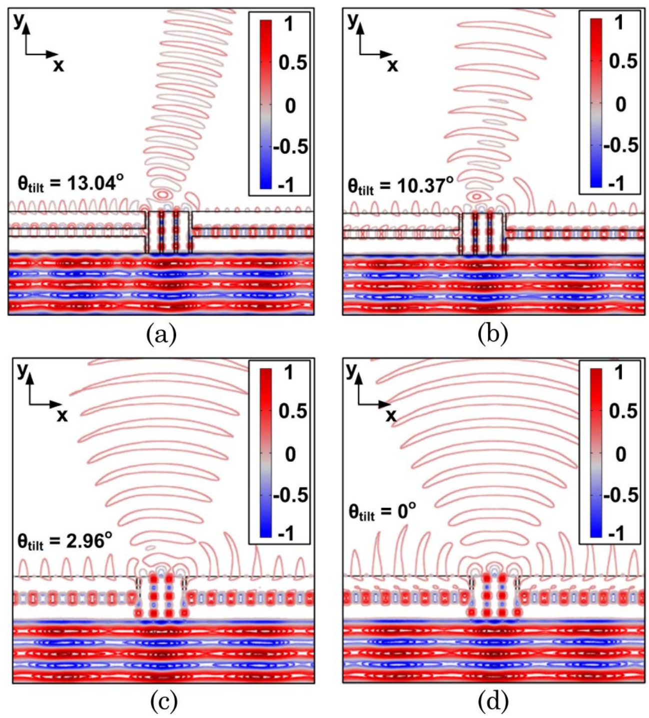

Fig. 4. (Color online) Beam deflection by the nanoslit array lens at fixed $H_1 = 1$ and $H_3 = 0.5$ [A/m] for the value of $H_2 =$ (a) 0, (b) 0.2, (c) 0.4, and (d) 0.5 [A/m].

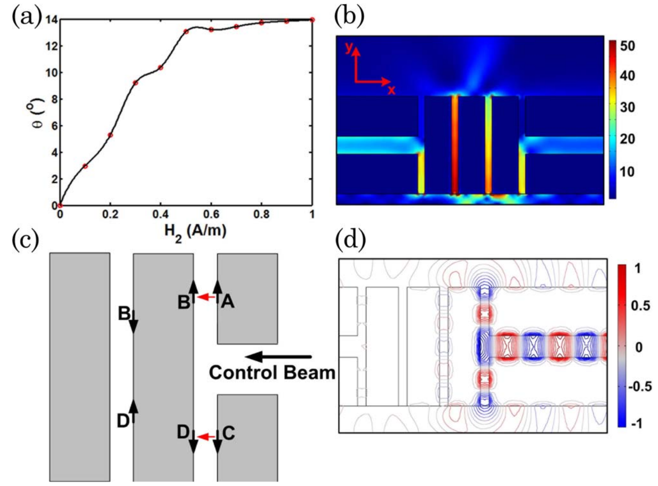

Fig. 5. (Color online) (a) Deflection angle as a function of H_2 at $H_1 = 1$ and $H_3 = 0$ [A/m]. (b) The field intensity (W/m^2) in the nanoslit array for $H_1 = 1.0$, $H_2 = 0.5$, and $H_3 = 0$ [A/m]. (c) Schematic of the nanoslit system under one control source. (d) Simulation of the system at $H_3 = 1$ [A/m] and $H_1 = H_2 = 0$ [A/m].

Because of the losses on the metallic surfaces, the SPP-induced electromagnetic field in the neighboring nanoslit is less intense relative to the outermost slit. There exist counterpropagating SPPs on the walls due to the T-junction geometry. The incoming signal interferes with the effective intensity grating in the nanoslit by the counterpropagating SPPs. Variations of the intensities in the nanoslits result in the required intensity gradient for the beam deflection.

In conclusion, we propose a technique that allows for all-optical beam steering and focusing for nanoslit arrays. The method utilizes two lateral control channels to form T junctions at the ends of the nanoslit array. T junctions and SPP-mediated phase communication between the neighboring slits allow for engineering the required intensity gradients for beam steering and focusing.

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