Efficient unidirectional ridge excitation of surface plasmons

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Abstract: Using leakage-radiation microscopy, we characterize the efficiency of unidirectional surface-plasmon excitation with periodic (800 nm) arrays of 130-nm-high and 330-nm-wide gold ridges on a thin gold film illuminated with a focused (5-μm-wide) laser beam. We demonstrate that, at the resonant wavelength of 816 nm, the excitation efficiency of > 0.4 can be obtained with ≥ 5 ridges by adjusting the beam position. Conducting numerical simulations, we account for the experimental results and calculate the electric-field enhancement achieved near the gold surface.

OCIS codes: (240.6680) Surface plasmons; (230.1950) Diffraction gratings; (230.3120) Integrated optics devices; (250.5403) Plasmonics.

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Plasmonics being concerned with manipulation of surface plasmon-polaritons (SPPs) using nanofabricated metal structures has attracted much attention due to potential applications in nanosensing and nanophotonics [1–4]. Both applications require high miniaturization of components involved, with the issue of efficient SPP excitation becoming increasingly important. Traditional Kretschmann and Otto configurations are known to be able to convert almost all incident light power into SPPs [5]. However, these techniques require (infinite) plane wave and thereby are not readily compatible with the demand for miniaturization. We have recently showed the possibility to efficiently convert a focused laser beam (at normal incidence) into an SPP beam (i.e., a laterally confined SPP wave possessing small divergence) using periodic set of metal ridges on top of a metal surface [6]. Using 50-nm-high and 280-nm-wide gold ridges we have achieved the SPP excitation efficiency (defined as the power ratio between an SPP beam propagating in a given direction and an incident laser beam) of ~ 0.2 at the wavelength of ~ 800 nm, which we believe is the best result obtained so far. We have also shown via numerical simulations that one can dramatically increase this efficiency by propitiously choosing the ridge dimensions found for this configuration to be ~ 130 nm in height and ~ 350 nm in width. In this letter we report on fabrication and investigation of ridge SPP couplers with optimized parameters [6].

The configuration for SPP excitation exploited in this work is essentially the same as that described in our previous paper [6] and was first introduced by Ditlbacher *et al* [7]. Straight 130-nm-high and 330-nm-wide gold ridges (of nominally rectangular profile) were fabricated using electron-beam lithography on the surface of a 50-nm gold film supported by a quartz substrate. The number of ridges in the configuration under investigation changes from one (single-ridge configuration) to 15 in steps of two with the period being fixed at $\Lambda = 800$ nm [Fig. 1(a)]. We used leakage-radiation microscopy (LRM) to both image the SPP propagation and measure the power of the excited SPP beam [6–8]. The illumination is accomplished by focusing a Gaussian laser beam (tunable wavelength range 700–860 nm) normally to the surface with a 20-fold objective (NA = 0.4) to a spot with a diameter estimated to be $\sim (5 \pm 0.5)\ \mu$m (at the level $1/e^2$ of intensity). The incident beam was linearly polarized in the direction perpendicular to the ridges [which run parallel to the y axis in Fig. 1(b)] resulting in the excitation of two SPP beams propagating in opposite directions, whose intensities strongly depended on the position of the illumination spot relative to the structure [Fig. 1(c)]. Note that unless otherwise stated, the SPP excitation efficiency refers to the SPP beam propagating to the left [i.e., towards negative x coordinates in Fig. 1(b)] from the structure.

The most basic description of SPP launching by periodic set of ridges (period Λ) relies on the momentum conservation: $k_{\mathrm{SPP}} = k_0 \sin\theta + nG$, where k_{SPP} and k_0 denote the wave-vector magnitudes of the excited SPP and incident light, respectively, θ is the angle of light incidence in the plane perpendicular to the ridges, n is an integer, and $G = 2\pi/\Lambda$ is the grating momentum [Fig. 1(b)]. Efficient SPP excitation (in the first grating order) at normal incidence requires thereby that the grating period should be equal to the SPP wavelength: $\Lambda = \lambda_{\mathrm{SPP}}$. In this case, the laser illumination scattered on different ridges generates coherent SPP waves, which interfere constructively with each other increasing the efficiency of SPP excitation. In the experiment, we used a discrete set of the laser (free-space) wavelengths centered at the wavelength of 816 nm

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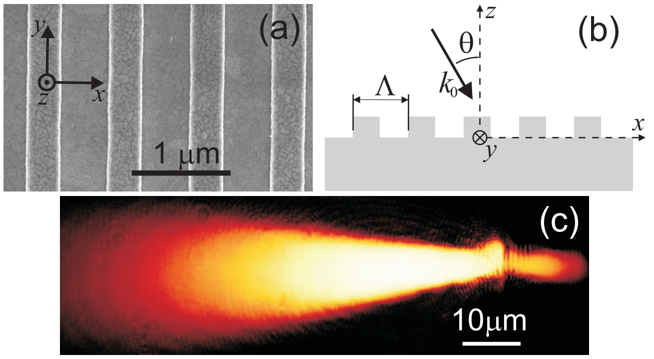

Fig. 1. (a) SEM image of a fragment of the fabricated structure consisting of 130-nm-high and 330-nm-wide ridges. (b) Geometry of the illumination configuration. (c) Typical LRM image of a strong SPP beam excited on the 11-ridge array on its left side. A much weaker SPP beam propagating to the right is also visible.

corresponding to $\lambda_{\mathrm{SPP}} = \Lambda = 800$ nm [5]. For each wavelength and number of ridges, the incident laser beam was laterally adjusted [along x axis in Fig. 1(b)] so as to maximize the excited SPP beam power [Fig. 2(a)]. It is seen that the dependence of the SPP excitation efficiency on the number of ridges exhibits a rapid saturation [Fig. 2(a)], even more rapid than in the case of the 50-nm-high ridges (cf. with Fig. 5(b) in [6]). The highest efficiencies were measured at the free-space wavelength of 816 nm as expected. At this wavelength, the SPP excitation efficiency of 0.45 ± 0.06 was achieved with 11 ridges, reaching the level of > 0.4 already with five of them.

The excitation efficiency is very sensitive to the transverse position of laser beam relative to the grating [6], rendering the (practically) unidirectional SPP excitation [Fig. 1(c)]. We conducted the efficiency measurements while the laser beam was scanned across the 11-ridge array illuminated at the wavelength of 816 nm [Fig. 2(b)]. Taking into account that the array center is positioned at $x = 8$ μm, one can deduce the excitation efficiency, η, for the (unwanted) SPP beam propagating to the right when the left-propagating SPP beam is most efficiently excited. Since the highest efficiency of 0.45 is achieved at $x = 4.6$ μm, the corresponding efficiency for the right-propagating SPP beam should be (under the assumption of symmetric excitation configuration) the same as that for the left-propagating one at $x = 8 + (8 - 4.6) = 11.4$ μm, i.e. $\eta = 0.013$, which is ~ 35 times smaller than 0.45 [Fig. 2(b)]. We think that such an efficient suppression of the right-propagating SPP beam can be due to the second-order Bragg reflection from ridges, which redirects the SPP back into the desirable direction, as well as due to the (reciprocal) out-coupling of the propagating (over many ridges) SPP, which can be rather strong since the in-coupling is efficient.

Using a two-dimensional electromagnetic Green's tensor approach, we calculated [6] the corresponding dependence of SPP excitation for the nominal structure parameters [Fig. 2(b)]. There is a good agreement between the experimental and simulated dependencies in their shape, albeit the simulated SPP excitation is more unidirectional than that observed in the experiment, ensuring ~ 140 times more efficient SPP excitation to the left than that to the right. The latter is believed to be due to perfect geometry used in the numerical simulations, featuring identical ridges with exactly the same separation, whereas fluctuations in the geometrical parameters are to be expected only in the experiment. There is also a discrepancy in the maximum value of efficiency, which does not fall into the interval determined by measurement errors. This difference can be explained by deviations in the ridge parameters (in ridge shape and sizes) of

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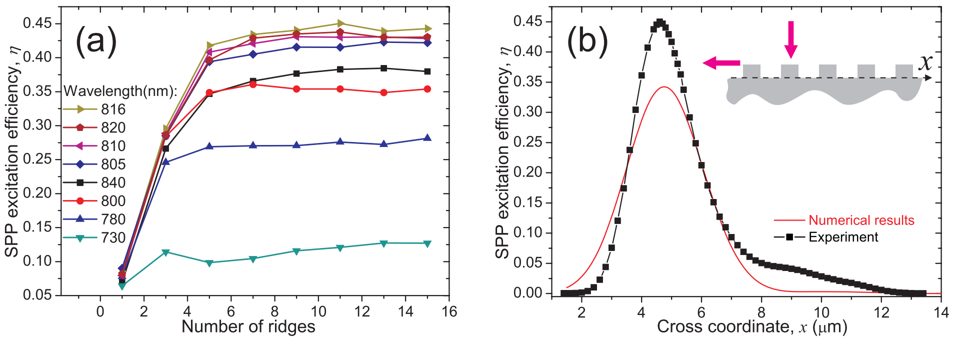

Fig. 2. (a) The maximum efficiency of SPP excitation obtained experimentally for different laser wavelengths as a function of number of ridges. The lines connecting the points are only to guide an eye. (b) Experimental and numerical results for the SPP excitation efficiency versus the position of a laser beam scanned across the 11-ridge array extending from $x = 4$ μm to $x = 12$ μm. Error bars both in (a) and (b) are omitted for clarity of presentation. The error of measurements is estimated to be ∼ 13%.

the fabricated structure from the nominal values. It is also known [9] that the dielectric constant of gold within ridges may be different from that reported in literature [10, 11].

Having realized such a high efficiency of (local) SPP excitation, we anticipated to also achieve the field enhancement near the gold surface with respect to the field of the incident laser beam. Continuing our simulations of the 11-ridge array, we calculated the electric-field amplitude (normalized to the amplitude of the incident laser beam) distribution near the surface for the maximum SPP excitation (Fig. 3). Unidirectional excitation of the left propagating SPP is clearly displayed in this distribution showing also that the electric field is indeed enhanced by ∼1.5–1.9 times on the left side of the array due to the SPP excitation. One should keep in mind that, upon direct illumination of a smooth metal surface, the field at the surface is rather small due to the reflectivity being close to -1. In this respect, the obtained field enhancement is quite an achievement and very promising for sensing applications, since the enhanced (propagating) field covers a large surface area [Fig. 1(c)] thus allowing the interrogation of a considerable amount of a test substance.

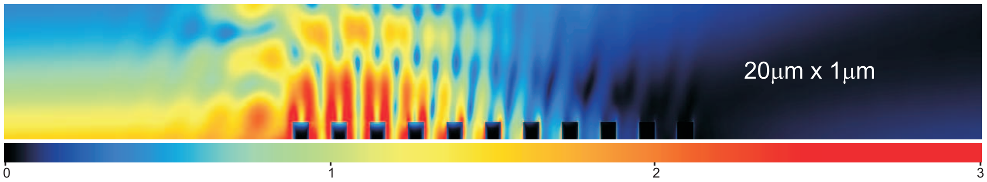

Fig. 3. Numerical results for electric-field amplitude distribution near the 11-ridge array illuminated under the optimal conditions for SPP excitation. The field values are normalized to the amplitude of the incident field.

For the purpose of achieving *local* field enhancement (within a well-defined surface area) one can employ focusing of the excited SPP beam, for example by a parabolic chain of nanoparticles [12] creating thereby an even stronger electric field. Alternatively, the excited beam can be shaped from the very beginning as a converging one [13, 14] by using a circularly curved ridge array (Fig. 4). Apparently, for such an array to produce a tightly focused spot, it should be entirely covered with an incident laser beam exciting the converging SPP beam. This requires an increased laser-beam diameter, which leads to a decreased SPP excitation efficiency partially because of the incident field polarization no longer being strictly perpendicular to the ridges. In this case, we measured the efficiency to be $\eta = 0.06 \pm 0.01$ for the array with an internal radius of curvature $R = 28.8\ \mu$m. Comparing the lateral sizes of the focused SPP beam [$\sim 1.7\ \mu$m, Fig. 4(b)] and the divergent one [$\sim 12\ \mu$m, Fig. 1(c)] at the same distance ($R \approx 30\ \mu$m) from the excitation place, one can see that the focusing effect is practically balanced with the efficiency decrease with respect to the achieved field enhancement. It is though expected that the optimum parameters for curved and straight ridge arrays might be quite different. Reducing the array's radius of curvature helps to decrease SPP propagation loss [Fig. 4(c,d)], but somewhat decreases the efficiency of excitation because of the smaller array area. This can provide some flexibility in designing of structures for practical applications. Note that curved ridge arrays can also be found useful for efficient coupling of a SPP beam into waveguiding structures.

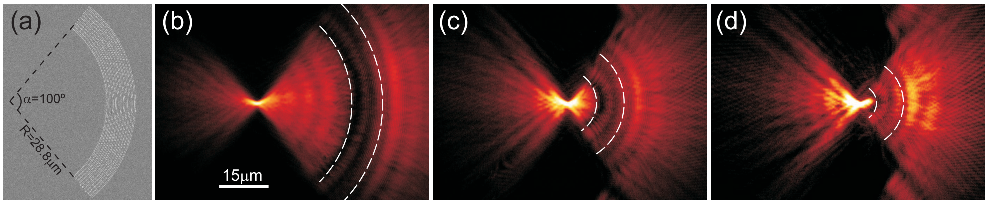

Fig. 4. (a) SEM image of a circularly curved 11-ridge array. (b–d) LRM images of SPP excitation and focusing at the laser wavelength of 816 nm. An approximate position of the arrays is shown with the dashed curves. Internal radii of curvature of the arrays are (b) 28.8 μm, (c) 9.6 μm, and (d) 4.8 μm.

In summary, we demonstrated an efficient unidirectional SPP excitation with a focused laser beam achieving the SPP excitation efficiency of 0.45 ± 0.06 at the resonant wavelength of 816 nm. We conducted numerical simulations accounting for the experimental results and estimated the field enhancement obtained near the gold surface due to the SPP excitation. Finally, we demonstrated curved ridge SPP couplers that tightly focus SPPs upon excitation. The presented approach to generation of enhanced electric fields may be an alternative to localized plasmons for achieving enhanced fluorescence and Raman scattering [15].

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