Strong three-dimensional field localization and enhancement on deep sinusoidal gratings with two-dimensional periodicity

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The study of total light absorption due to excitation of localized surface plasmons on deep metallic crossed gratings having a sinusoidal profile with a two-dimensional periodicity shows a very strong increase in the electric field intensity, reaching 800 times the incident intensity. The region with high intensity is strongly localized at the groove top and is characterized by a volume much smaller than the diffraction limit, both in transverse direction along the grating plane, and in longitudinal direction when going away from the grating surface. The field enhancement and its localization are much more pronounced than in shallow gratings.

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Excitation of plasmon-type surface waves (PSW) on metallic gratings has been discovered experimentally by Wood more than 110 years ago [1]. The anomalous diffraction was not immediately related to surface waves, although Wood and Rayleigh made hints toward the resonant nature of this phenomenon [2]. Fano was the first to give an explanation linked with surface waves [3], although at that time they were not known as linked to the plasma of free electrons in metals.

The study of diffraction anomalies in gratings led to numerous applications mainly because of two phenomena. First, the excitation of PSW can lead to total absorption of incident light [4] that plays an important role in photovoltaics. Second, this absorption is accompanied by strong enhancement of the electromagnetic field, localized close to the grating surface. The field enhancement that accompanies the resonant PSW excitation is of high interest to improve a broad range of applications that directly rely on the light-matter interaction at the nanoscale. This involves fluorescence spectroscopy [5,6], label-free biosensing [7], solid-state lighting [8], surface-enhanced Raman scattering [9–11], and nonlinear optical effects [12,13]. A specific effect of coherent thermal radiation has been demonstrated due to PSW [14].

Following the experimental work of Ebbesen *et al.* [15], the problem of PSW in lamellar metallic gratings and hole arrays has been the subject of extensive theoretical, numerical, and experimental work. It has been demonstrated that deep corrugations can support new kinds of plasmon modes created by the coupling between the groove cavity resonances and the plasmon surface wave [16–19]. Specific studies have also been shown that surface plasmons in deep and narrow Gaussian grooves exhibit very flat dispersion curves [20]. A totally different situation is observed when considering deep and narrow Gaussian ridges [21].

As for any grating profile, if the grating period permits coupling with the outgoing radiated wave (the condition is the same as for the possibility to excite a PSW with an incident wave using the grating periodicity), the radiation losses of the PSW increase with the increase of the groove depth. Above some critical groove depths, the PSW can no longer propagate along the surface, and cavity modes inside the grooves appear. At a given value of the groove depth (approximately half-wavelength), the cavity mode can be almost completely “hidden” inside the groove, and the boundary conditions are satisfied to insure a new surface plasmon mode [17,22–26] that is characterized by field enhancement localized on the top of the grooves. The analysis of the maps of the electromagnetic field of previously known grating profiles shows that the field enhancement is localized in strips along the top of the metallic bumps. However, the effective volume with an enhanced electric field is large in this case. In order to reduce the region with enhanced field, we propose the use of a crossed grating having two-dimensional (2D) periodicity.

In this Letter, we show that deep metallic crossed gratings having a sinusoidal profile with a 2D periodicity enable concentrating the electric field in a volume of subwavelength dimensions along the three directions of space. This region is strongly localized at the groove top and is characterized by a high local intensity. As for shallow grooves, the excitation of this new mode is accompanied by light absorption (Fig. 1). One of the main differences between the PSW on shallow and deep gratings is that whereas for shallow gratings, the field enhancement appears all over the grating profile, in the case of deep grooves, it is localized on the top of the grooves because of the existence of a cavity resonance inside the grooves that separates the field at the top from the field at the bottom.

For our purposes we have chosen gold as grating material, because aluminum is rapidly covered with aluminum oxide several tens of nanometers thick, which will separate the metal surface from the cladding, and the region of field enhancement would be inside the oxide. The grating profile has a sinusoidal form in each direction along the surface, having the same period d and the same groove depth:

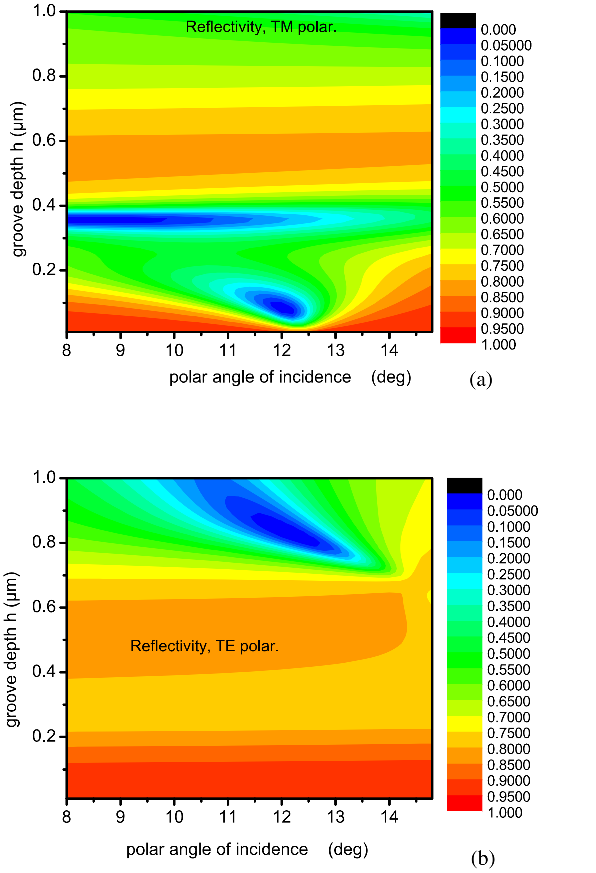

Fig. 1. Reflectivity of a crossed sinusoidal grating as a function of polar incident angle and the groove depth for the two fundamental incident polarizations.

$$f(x,y) = \frac{h}{4}[\sin(Kx) + \sin(Ky)], \tag{1}$$

where $K = 2\pi/d$, and h is the total groove depth. Thus, along each of the x and y axis the groove depth is only half of the total, whereas the groove depth is equal to h along the cell diagonals. The simulations are made using a rigorous differential theory of gratings based on a curvilinear transformation of the coordinate system, known as C-method, proposed first by Chandezon *et al.* [27] and improved later by using the factorization rule proposed by Li and Chandezon [28]. Details of the method are available online in a recent review on grating theories [29].

Figure 1 represents the reflectivity of the grating having a period $d = 500$ nm as a function of incident polar angle θ (measured from the grating normal inside the plane of incidence) and the groove depth h. The azimuthal angle φ (between the plane of incidence and the x axis) is kept null, the wavelength is equal to 632.8 nm and the incident electric field is perpendicular to the plane of incidence (we continue to call this TE polarization) or lies inside it (polarization TM). The wavelength, period, and the angle(s) of incident are chosen to preserve a single (0th) reflected order in the cladding, assumed as air.

A small region of strong absorption for shallow grooves is presented for TM polarization, and it is characterized by a strong angular dependence, due to the

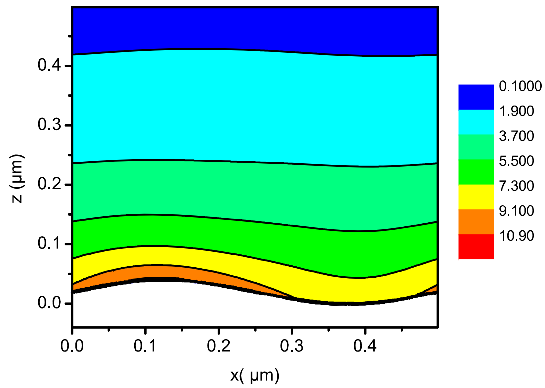

Fig. 2. Map of the modulus of the diffracted electric field inside one grating cell along the profile in x-direction at $y = d/4$. Incident electric field is normalized to 1, $h = 0.08$ μm, $\theta = 12°$.

grating equation, because the surface plasmons on shallow gratings are not localized in real space (and thus it is strongly localized in the inverse space). This can be observed in Fig. 2, with field amplitude varying less than 30% (from 8 to 10.8 at $y = d/4$). The decrease of the field amplitude along the vertical direction is determined by the rate of decrease of the PSW field when going away from the metal surface, and will be discussed further on.

The second interesting region in Fig. 1(a) appears close to $h = 0.35$ μm, and it is much more extended angularly than the anomaly for $h = 0.08$ μm. As observed in

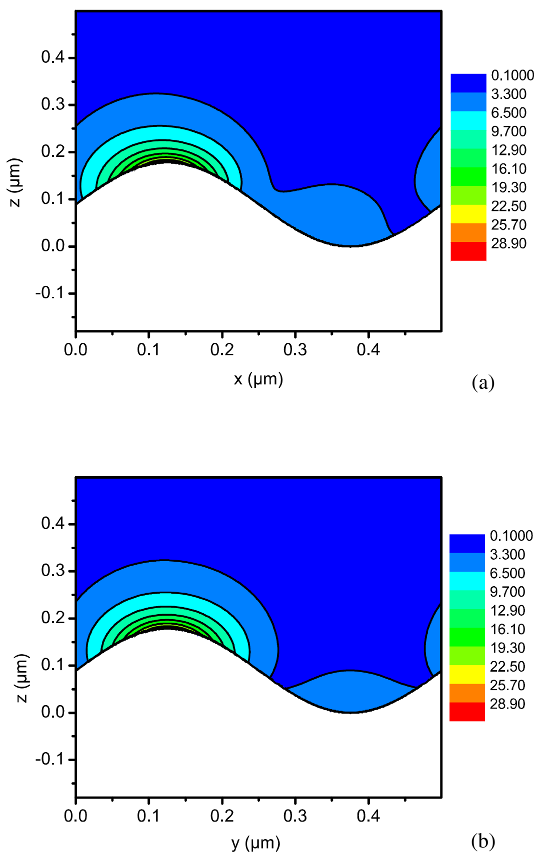

Fig. 3. Map of the modulus of the diffracted electric field for deep grooves with $h = 0.3575$ μm and $\theta = 8.25°$. $\lambda = 0.6328$ and TM polarization. (a) x-z cut and (b) y-z cut.

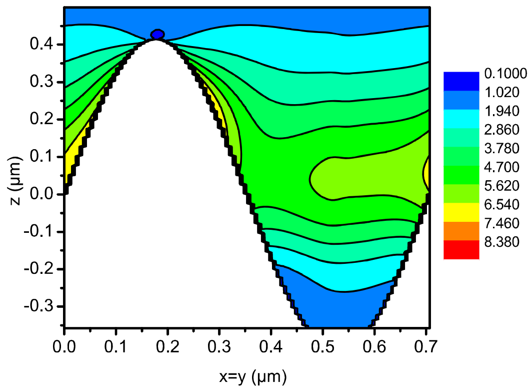

Fig. 4. Map of the modulus of the diffracted electric field for deep grooves with $h = 0.83$ μm and $\theta = 12.2°$. $\lambda = 0.6328$ μm and TE polarization, diagonal-z cut.

Fig. 3, the electric field is strongly localized at the groove top. In the lateral direction, the electric field amplitude decreases ten-fold from its maximum value within a length of 1/5 of the wavelength of light. In the vertical direction the decrease is even more rapid.

As the intensity is the square of the amplitude, the region with strong field enhancement of the intensity is even smaller. The ten-fold decrease in intensity from its maximum at the groove top occurs at a distance of ± 85 nm in direction parallel to the grating plane and within 55 nm in the vertical direction.

If we go back to Fig. 1(b), a region of strong light absorption is obtained in TE polarization for very deep grooves. This effect is accompanied by relatively lower field enhancement, but found inside the grooves (Fig. 4), which appears more like a cavity resonance. This type of field map was obtained in [26] for deep metallic sinusoidal one-dimensional grating in TE polarization with the plane of incidence perpendicular to the grooves.

The stronger localization of the field on deep gratings means that its Fourier spectrum has to contain strong higher harmonics, when compared to the shallow grooves. Figure 5 shows that the Fourier spectrum of the z-component of the electric field in the resonant case for deep gratings is much richer than for shallow grooves. The same is valid for the other electric field components, not shown here, because the z-component is predominant. Let us remember that the only diffraction order that propagates in the cladding is order (0,0); all other orders are evanescent. In the case of shallow grooves, the PSW is represented mainly by a single diffraction order $(-1, 0)$ that propagates in $-x$ direction, whereas for deep grooves there is no predominant diffraction order, which confirms the localized character of this PSW mode.

High-order diffraction modes decrease faster in the cladding than the lower orders. For instance, the second diffraction orders $(0, \pm 2)$, $((\pm 2, 0)$, and $(\pm 1, \pm 1)$ decrease approximately twice as fast as the first ones. Hence, the stronger high-diffraction orders in the deep grooves lead to stronger localization and faster decrease along the vertical direction, as compared to shallow grooves (Fig. 6).

To conclude, we demonstrate the existence of a new kind of diffraction anomaly in deep bi-dimensional metallic gratings of sinusoidal profile. The excitation of this new mode is revealed by incident light absorption and concentration of the electric field on top of the grooves in a volume of sub-wavelength dimensions along the three directions of space with a high local intensity. These features are explained by stronger high-diffraction orders as compared to shallow sinusoidal gratings.

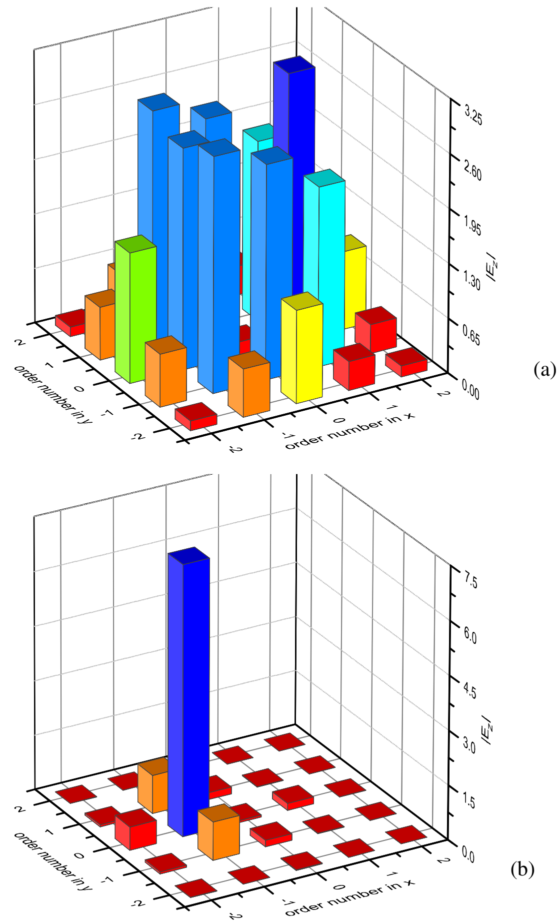

Fig. 5. Fourier decomposition of the vertical component of the electric field vector for deep (a) and shallow (b) grooves.

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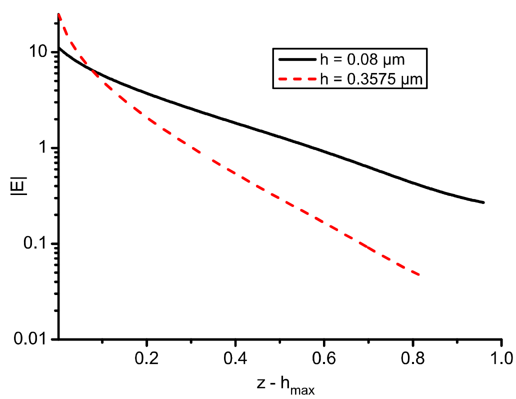

Fig. 6. Decrease of the electric field amplitude with the distance from the groove top for shallow and deep grooves.

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