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Photon harvesting by evanescent waves outcoming from very narrow grooves

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We investigate the mechanisms involved in the focusing of the optical energy in very narrow metallic grooves. This focusing drives the total absorption of a gold surface structured on a tiny part of its area (less than 3%). The key phenomenon is unveiled thanks to the decomposition of the electromagnetic field into its propagative and evanescent parts. We unambiguously show that the focusing is not due to plasmonic waves flowing toward the grooves, but rather to the magneto-electric interference of the incident wave with the evanescent field, this field being mainly due to the resonant wave escaping from the groove.

Experimental discovering that nanometric holes drilled in a metallic sheet can transmit much more light than expected [1] was the beginning of a huge interest on plasmonics for the matter of both harvesting and concentration of photons [2]. The problem to couple all the power of an incident wave with an absorber or an emitter, i.e. to make perfect antenna, is of great importance [3–5]. Up to now, the energy funneling of an incoming light beam at the nanometric scale is engineered by use of surface plasmons to propagate energy toward the target in a two-step process [6–9]: conversion of the incident energy to a plasmonic wave, and then scattering of this wave into the target. In the specific case of metallic slit gratings, this approach is reinforced by the fact that the normally incident energy flux is bended at the interface and propagates along the metallic surface toward the slits [10].

This elegant two-step process, if correct, could greatly simplify the design of light harvesting structures. However, the assumption that plasmonic waves carry their own energy requires to neglect interference terms in the Poynting vector. And yet, such situations can be found, where interference terms between the magnetic field of one wave and the electric field of a second wave play a crucial role to drive energy flux. For instance, the key point of the tunnel effect through a thin layer of low index medium sandwiched between two high index media (frustrated total internal reflection) lays in the interference between the evanescent field E_1, H_1 escaping from the first interface and the evanescent field E_2, H_2 reflected on the second interface: the Poynting vector is null in the direction perpendicular to the interface for both waves taken independently, but their magneto-electric interference $E_1 \times H_2 + E_2 \times H_1$ gives the tunneling energy flux [11]. Similarly, in the domain of light scattering by small metallic particles (Mie theory) [12], magneto-electric interferences play a crucial role. Bohren [13] and Paul [14] have shown how Poynting-vector streamlines are bended toward a particle or a molecule, thus clearly illustrating the origin of their optical cross section.

Recently, Miyazaki made use of the magneto-electric

interferences [15] to explain energy concentration in the back-closed version of his nanosheet plasmon cavity [16]. These previous works compute the incident energy flux from the interference of the incident wave and the total scattered field, however they do not separate the propagative and evanescent parts of this field. In this letter, by studying the funneling of infrared light in very narrow grooves etched in a gold surface, we unambiguously identify the leading mechanism as *the magneto-electric interference of the incident wave with the evanescent field escaping from the grooves*.

Let's consider a system similar to the one studied by Le Perchec *et al.* [17] with a much smaller aperture ratio w/d , in the infrared region where metal has much less losses. Figure 1 (a) shows the grating made of grooves etched in a plane gold surface (period $d = 2000$ nm, width $w = 56$ nm, height $h = 640$ nm). The infrared light ($\lambda =$

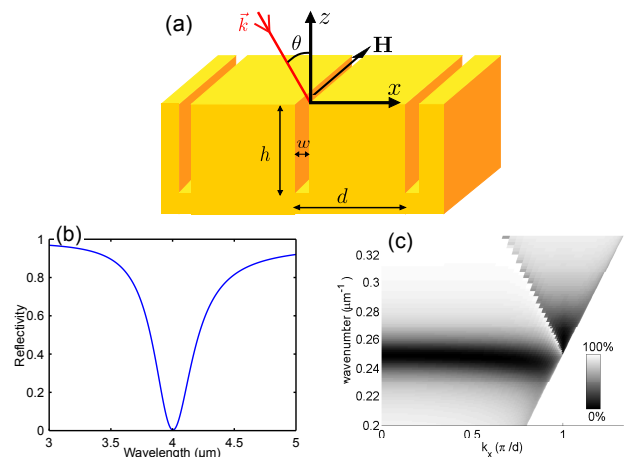


FIG. 1. (a) Geometry of the grating of slits with a periodicity of d , w and h are the slit width and height. (b) Grating optimized to have a resonance of the reflectivity $R = 0$ at a wavelength $\lambda = 4000$ nm. Its geometric parameters are $w = 56$ nm, $h = 640$ nm and $d = 2000$ nm. (c) Reflectivity diagram on a scale of gray. The resonance is almost independent of the angle of incidence θ .

3000 nm to 5000 nm) is TM-polarized and incident with an angle θ . The grating is subwavelength, so there is only one order diffracted in the air corresponding to the specular reflection. The dielectric function of gold is computed from the Drude model $\varepsilon(\lambda) = 1 - [(\lambda_p/\lambda + i\gamma)\lambda_p/\lambda]^{-1}$ which matches well the experimental data in the considered wavelength range for $\lambda_p = 161$ nm, $\gamma = 0.0085$ [18]. The electromagnetic analysis of this structure is done using a B-spline modal method [19], which allows for a fast and exact computation of Maxwell equations. The reflectivity of the grating is plotted in Fig. 1 (b). Although the grating is structured on a tiny portion of its surface (less than 3%), it exhibits a resonance with a total absorption at $\lambda = 4000$ nm at normal incidence. As shown on Fig. 1 (c), the absorption remains high even for large incidence angles.

We consider the electromagnetic field in the air, and we split it into three terms. The magnetic field writes:

$$H_{total} = H_i + H_r + H_e, \quad (1)$$

where H_i is the incoming wave, H_r is the reflected wave, and H_e is the sum of the diffracted evanescent waves. Similar definitions stand for the electric field components. In the following of this letter, $E \times H$ stands for the mean time average value of the vectorial product and is practically computed from complex amplitudes as $\frac{1}{2}\Re(E \times H^*)$. Thanks to the decomposition of Eq. (1), the Poynting vector writes as the sum of five terms:

$$S = S_i + S_{ei} + S_r + S_{er} + S_e, \quad (2)$$

with

$$\begin{aligned} S_i &= E_i \times H_i \\ S_{ei} &= E_e \times H_i + E_i \times H_e \\ S_r &= E_r \times H_r \\ S_{er} &= E_e \times H_r + E_r \times H_e \\ S_e &= E_e \times H_e. \end{aligned}$$

The missing term $E_i \times H_r + E_r \times H_i$ is null since the propagation wavevector is real. The terms S_i and S_r are respectively the incident and the reflected fluxes of the plane wave. The term S_e corresponds to the energy carried by the evanescent waves. The term S_{ei} corresponds to the magneto-electric interference between the evanescent and the incident fields. It is easy to prove that the five terms of equation (2) are flux conservative (null divergence) thus each of them can be considered as an independent energy flux vector in the air. In order to simplify the discussion, we consider an optimized device at the resonance wavelength. So we have no reflected wave, the fields H_r and E_r are null and the Poynting vector writes as

$$S = S_i + S_{ei} + S_e.$$

The Poynting-vector streamlines for S_i , S_{ei} and S are plotted at two angles of incidence in Fig. (2) so that the flux of energy between two lines is constant.

At normal incidence, as expected for a propagative plane wave in air, the lines for incident flux S_i are equidistant and in the propagation direction. The lines of magneto-electric interference S_{ei} are coming from the surface and are converging on the groove. On the metallic surface, they compensate for the flux of the incident

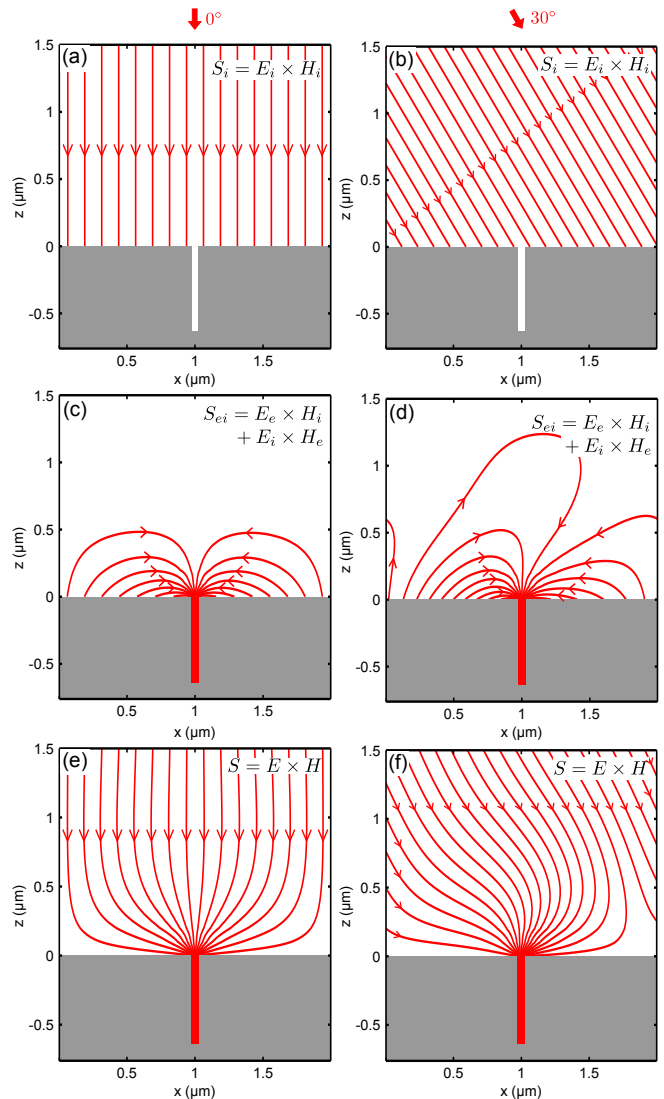


FIG. 2. Poynting-vector streamlines in one period of the slit grating for two angles of incidence $\theta = 0^\circ$ (left column) and $\theta = 30^\circ$ (right column) at $\lambda = 4000$ nm. Streamlines of the incident wave are shown on (a) and (b). Streamlines of the interference between the incident wave and the evanescent field are shown on (c) and (d). The energy flux of the evanescent waves is negligible in this structure for $\theta = 0^\circ$; refer to Fig. 3 (a) for an illustration at $\theta = 30^\circ$. Streamlines of the total Poynting vector are shown on (e) and (f). In both cases, the incident energy is funneled inside the slit where it is fully absorbed inside the metal.

plane wave and focalize it inside the groove. Drawing lines perpendicularly to Poynting streamlines on Fig. 2 (c), and taking in account that the predominant term in S_{ei} is $E_e \times H_i$, one can deduce that the evanescent wave shape is quasi-cylindrical [21, 22]. The evanescent flux S_e (not shown) carries an energy 1000 times weaker and does not play an active role in the focusing for this structure at normal incidence. On Fig. 2 (e), the total flux of energy S is shown to funnel to the groove in the near-field region ($z \lesssim 500$ nm). Eventually all the incident flux is dissipated, mostly inside the groove.

For an incidence of 30° , the magneto-electric interference S_{ei} is still funneling the energy towards the slits (Fig. 2 (d)). But it does no more compensate for the incident flux which lines are equidistant. Indeed, on Fig. 2 (d), there are more lines going out from the metal surface on the left (10 lines) than on the right (6 lines). Nonetheless, Fig. 2 (f) shows that the incident energy gets focalized into the groove despite this asymmetry. In fact, at oblique incidence, the evanescent field carries an energy flux S_e which is no more negligible, as shown in Fig. 3: the energy is redirected from the right side of the groove to the left side. This redistribution of the energy compensates for the dissymmetry of S_{ei} which appears in Fig. 2 (d). In conclusion S_e plays no role on the focusing but on the redistribution of energy. By the way, this invalidates the hypothetical role of plasmonic waves, which are evanescent waves, on the focusing mechanism.

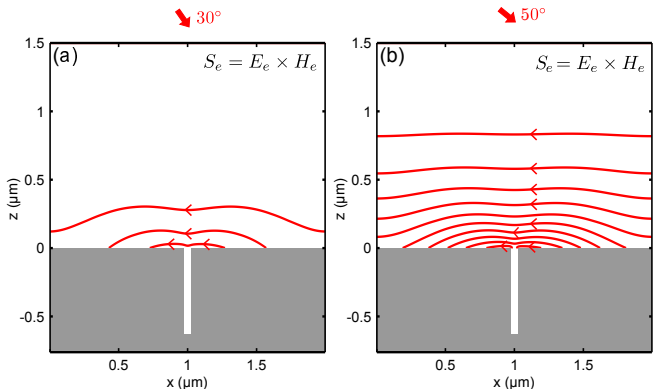


FIG. 3. Poynting-vector streamlines of the evanescent field for two angles of incidence (a) 30° and (b) 50° at $\lambda = 4000$ nm. S_e does not play a role of focusing but redistributes the energy in the grating.

Now, we aim at describing the origin of the evanescent field. The subwavelength grating behaves as a Fabry-Perot resonator. We consider the isolated single interface in two configurations: one where the incident field is a unit-amplitude plane wave in air; the other where the incident field is a wave coming from the bottom of the groove, and is unit-amplitude at the interface [20]. In the first case (Fig. 4 (a)) the reflected wave has an amplitude ρ_1 and an evanescent field η_1 . Due to the

low aperture ratio w/d , one gets $|\rho_1| \lesssim 1$ and $|\eta_1| \ll 1$. In the second case (Fig. 4 (b)) the transmitted wave (which corresponds to the reflected wave here above) has an amplitude τ_2 and the evanescent field in the air writes η_2 . If a unit-amplitude wave is defined as taking the value $H_y = 1$ at the center of a groove entrance, then Fig. 5 shows that evanescent amplitudes η_1 and η_2 are nearly equals. Due to the low aperture ratio w/d , one gets $|\tau_2| \ll 1$.

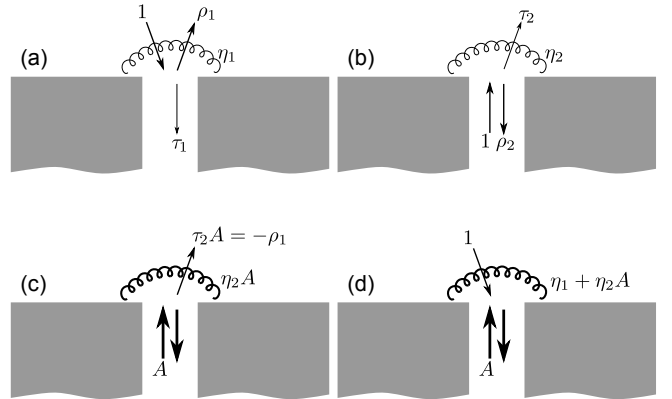


FIG. 4. Isolated single interface analysis of the metallic grating optimized to absorb all the incident light. (a) Unit plane wave from air: ρ_1 is the amplitude of the reflected plane wave, η_1 is the vector of evanescent field amplitudes. (b) Unit modal wave from bottom of grooves: τ_2 is the amplitude of the plane wave escaping in the air, η_2 is the vector of evanescent field amplitudes. (c) Same as (b), but with the modal wave having the amplitude A . (d) Superposition of (a) and (c), showing the field amplitudes in the grating excited by a unit plane wave: the reflectivity is null and the evanescent field is dominated by the term escaping from the resonator.

At the resonance, the wave coming from the bottom of the groove has an amplitude $A = -\tau_2^{-1}\rho_1$ so that all the amplitudes at stake in Fig. 4 (b) are multiplied by the factor A , which leads to Fig. 4 (c). The response of the grating excited by a unit-amplitude plane wave at resonance is thus given by the superposition of amplitudes of Fig. 4 (a) and (c), shown on Fig. 4 (d). This leads to the expected null-amplitude reflected wave. Besides, the resulting evanescent field writes $\eta_1 + \eta_2 A \simeq \eta_2 A$ because $|\eta_1| \simeq |\eta_2|$ and $A \gg 1$ (e.g., for the grating described on Fig. 1 and studied on Fig. 5, one computes $|A| \simeq 11$). In summary, the wave built inside the grooves escapes in the air as both a propagating plane wave and an evanescent field. The propagating plane wave interferes destructively with the directly reflected wave leading to the null reflection, and the evanescent field interferes with the incoming plane wave to focus the energy into the groove. The two effects are of course not independent: we have no reflection because the energy is nearly fully collected in the groove.

At last, we want to highlight that the key role played by the magneto-electric interference of propagative waves

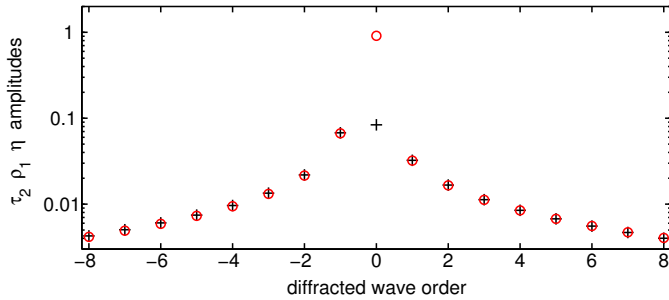


FIG. 5. Amplitudes of the first 17 diffracted waves in air by the isolated interface. Red circles: amplitudes for an unit plane wave in air, which is incident with an angle of 30° on the grating described on Fig. 1. Black crosses: amplitudes for an unit plane wave incident from the grooves, with a relative phase corresponding to the previous incident wave. The diffracted wave order 0 is the only one which is propagative. All the other ones are evanescent and correspond to the vectors $|\eta_1|$ (red circles) and $|\eta_2|$ (black crosses). If the unit waves are defined as having magnetic field equal to 1 in the center of a groove's entrance, $|\eta_1|$ and $|\eta_2|$ are nearly equals. The values $|\rho_1|$ and $|\tau_2|$ correspond respectively to the red circle and the black cross at diffracted order 0. The ratio $|\rho_1/\tau_2|$ is about 11.

with the evanescent field in the funneling mechanism is not limited to resonant structures. Let's thus consider the non-resonant case of a grating made of infinitely deep grooves, i.e. the simple isolated interface illustrated on Fig. 4(a), with a reflected wave of amplitude ρ_1 . For an incidence angle of 30° , one gets $|\rho_1|^2 = 0.83$: about 17% of the incident energy enters the grooves. This value is much larger than the aperture ratio $w/d = 2.8\%$, thus there appears to be funneling. Now, if we compare to the situation of Fig. 4(d), the evanescent field of Fig. 4(a) is lowered by a factor $|\eta_1 + \eta_2 A|/|\eta_1| \simeq |A| \simeq 11$. One thus computes that the interference of the incident wave with the evanescent field gives a funneling of about $1/|A| \simeq 9\%$. The missing 8% stem from the interference of the evanescent field with the reflected wave ρ_1 , which paradoxically contributes to the energy focusing inside the grooves. The key of the paradox lays here: first the main contribution for the interference is $E_e \times H_r$ ($E_r \times H_e$ is much smaller, at least at the interface level); second, the magnetic field H_r has the sign of H_i due to the metallic reflection.

As a conclusion, we have unveiled the funneling mechanism of incident light in very narrow grooves etched in metallic gratings. It originates from the magneto-electric interference between the incident wave and the evanescent field, in both resonant and non resonant situations. In the resonant case, the evanescent field originating from a groove grating can lead to the full harvesting of incident photons for a broad range of incidences, and their collection in a vanishing-size aperture. This approach

opens a new route for the conception of electromagnetic resonant antennas, based on the tailoring of the escaping evanescent field.

Eventually, we have shown that evanescent waves propagating along the interface jump over the grooves, and do not guide the energy into them. This clearly demonstrates that the funneling is not mediated by plasmon waves at the surface. However, evanescent waves play a role in the redistribution of the energy across the grating.

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