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Broadband Brewster transmission through 2D metallic gratings

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Recently, we have introduced a mechanism to achieve ultrabroadband light funnelling and total transmission through 1D narrow metallic gratings at a specific incidence angle, the so-called plasmonic Brewster angle. This phenomenon is based on impedance matching between the guided modes supported by ultranarrow linear slits and transverse-magnetic waves at oblique incidence. In this paper, we demonstrate that such phenomenon, representing the equivalent of Brewster transmission for plasmonic screens, can also occur in 2D metallic gratings of various structural forms and shapes, and that it may be made insensitive to the azimuthal, or polarization, angle φ. This finding may have relevant implications to realize large funneling, absorption and squeezing of light in perforated metallic screens.
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I. INTRODUCTION

Extraordinary optical transmission (EOT) through optically thick metal screens perforated with narrow slits or apertures has attracted tremendous attention in the last few years, due to its great potential in optical sensing, imaging and energy concentration.[1–3] It has been demonstrated that light transmission through otherwise opaque screens can be dramatically enhanced when specific resonances are excited and that the ratio of transmitted versus impinging energy on the apertures may be significantly larger than unity, especially for smaller apertures and larger periods. This anomalous phenomenon is usually based on the excitation of surface plasmon resonances (SPRs) and Fabry-Perot (FP) resonances on the metal film or other resonant mechanisms associated with the periodicity of the corrugations.[4]

Even if EOT has been proposed for optical devices, such as light-emitting diodes, selective polarization filters and energy concentrators, one serious drawback that may hinder its potential application is associated with the inherently narrow bandwidth of operation. To circumvent this issue, we have recently introduced a dual funneling mechanism through 1-D slits, inherently nonresonant, which results in total transmission over ultrabroad bandwidths at certain incidence angles.[5] This transmission mechanism through corrugated metallic screens is the equivalent of the broadband Brewster transmission effect for dielectric etalons, providing zero reflection for transverse-magnetic (TM) incident polarization. We have theoretically demonstrated that total transmission based on this effect may occur over a very broad bandwidth without necessarily relying on SPRs, but rather simply based on impedance matching. It is rather surprising that impedance matching may be achieved for a mostly opaque screen; nevertheless, this effect can be explained by considering that at oblique TM incidence the portion of electric field tangential to the surface of the screen may be made small enough to compensate the small average impedance of a plasmonic screen with small apertures. The phenomenon depends very weakly on the frequency of operation or on the screen thickness: in fact the same concept may be applied to a single interface,[6] of great interest for energy concentration and harvesting. It is however sensitive to the incidence angle, similar to Brewster transmission at a dielectric interface and, even if we have flexibility in tuning the transmission angle, it cannot be operated at normal incidence. Similar theoretical results were reported in Ref. 7, and later experimentally verified at infrared frequencies,[8] Our group has also reported a recent experimental verification of these concepts at microwaves[9] and has extended these concepts to acoustic waves.[10] Related works have proposed broadband funneling of light using tapered slits[11] and broadband reflectivity at the "plasmonic critical angle,"[12] based on a related concept.

All these theoretical and experimental findings were so far limited to 1D metallic gratings for a specific polarization angle, since they all relied on the modal properties of plasmonic slits with infinite lateral width. In this work, we explore and demonstrate that such anomalous funneling phenomenon may be extended to various 2D optical gratings with large independence on the polarization angle and on the plane of incidence. This finding makes the application of these concepts even more exciting, as this broadband funneling phenomenon does not necessarily need to be limited to one incident plane of polarization and to 1-D geometries. We show in fact that the plasmonic Brewster transmission is largely insensitive to the azimuthal angle φ (hereafter referred to as the polarization angle) for TM incident waves. These results may be particularly stimulating to realize broadband absorbers, energy concentrators and linear polarizers, as speculated for the 1-D geometry in Ref. 5.

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II. BROADBAND EXTRAORDINARY OPTICAL TRANSMISSION THOUGH 2D METALLIC GRATINGS

Several experimental works have investigated TE and TM transmission through 2D metallic gratings.[13,14] In Ref. 13, transmission was measured only at normal incidence, while in Ref. 14 its angular dependence was investigated. EOT was observed due to the excitation of resonant modes along the aperture length, which may be coupled to spoof surface plasmon modes. However, no earlier works have explored the possibility of broadband Brewster transmission through 2D gratings.

The original concept that we proposed in Refs. 5 and 6 to realize Brewster transmission for optical gratings was based on a simple transmission-line model, which relies on the modal properties of infinitely wide metal-dielectric-metal slits periodically carved in a plasmonic screen. One of the drawbacks of this geometry is that it works only on one plane of polarization: our model was based on oblique TM waves with electric field orthogonal to the slits, as shown in the sketch of Fig. 1(a) with $\varphi = 0$. The corresponding contour plot [Fig. 1(b)] shows the angular transmission spectrum for a silver screen of thickness $l = 400\,\mathrm{nm}$, slit width $w = 12\,\mathrm{nm}$, and period $d = 68\,\mathrm{nm}$ in this polarization plane. The transmission is computed by full-wave simulations based on the finite integration technique.[15] The refractive index of Ag is fitted using realistic experimental data with material loss and frequency dispersion taken into account.[16] Consistent with our results in Refs. 5 and 6, a distinctive vertical band arises at the plasmonic Brewster angle ϑ_B, in very good agreement with the analytical formula derived in Ref. 5 and indicated by the dashed line in the plot

$$\cos\vartheta_{\mathrm{B}} = (\beta_s w)/(k_0 d), \tag{1}$$

with β_s being the guided wave number in the plasmonic slits and k_0 being the vacuum wave number. This equation is derived based on impedance matching between the obliquely incident TM wave and the plasmonic mode supported inside the slit. In Fig. 1(c), we now rotate the plane of polarization by an angle $\varphi = 45°$, as sketched in the figure. It is evident in the corresponding transmission spectra (Fig. 1(d)) that Brewster transmission is largely affected by the polarization plane, due to the large anisotropy of the interface.

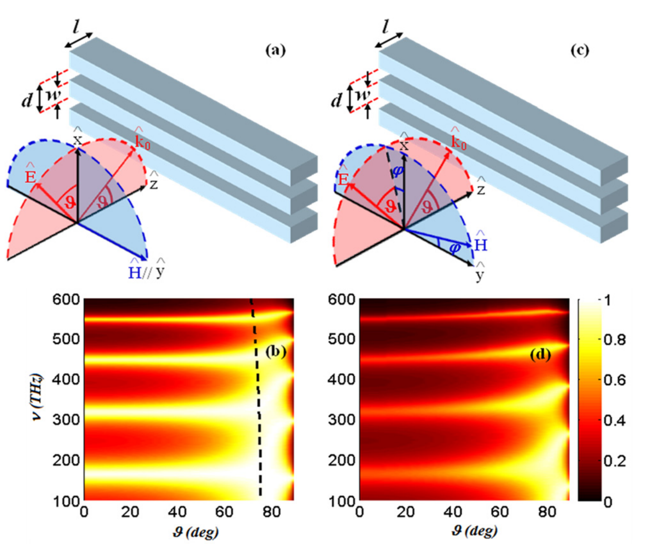

FIG. 1. (a), (c) Schematic sketch of the 1-D grating and the excitation conditions. The grating structure in this scenario is similar to Fig. 1 in Ref. 5. (b) Angular transmission spectra for a 1D grating with $l = 400\,\mathrm{nm}$ (thickness), $w = 12\,\mathrm{nm}$ (slit aperture) and $d = 68\,\mathrm{nm}$ (period) for $\varphi = 0°$. (d) Same as in (b) for $\varphi = 45°$.

We may speculate that a way to overcome this issue is to realize two orthogonal sets of slits. Provided that the coupling between neighboring slits is negligible and that their period is smaller than the wavelength of operation, any incident TM wave, independent of the polarization angle, may couple into the orthogonal mesh and tunnel at the Brewster condition. In fact, we may always decompose the impinging TM wave into orthogonal waves with magnetic field parallel to the two crossed sets of slits and, due to their subwavelength widths, we may expect that the two polarizations are weakly coupled to each other.

The corresponding geometry becomes effectively a 2D grating of rods with rectangular cross section $d_x \times d_y$, as shown in Fig. 2(a). It is noticed that the proposed structure may resemble conventional plasmonic frequency selective surface (FSS) structures.[17] However, our structure is much thicker than an FSS and it operates in a dual scenario, supporting ultrabroadband transmission (with no frequency selectivity) at a specific angle of incidence.

Our structure is illuminated by a TM plane wave with arbitrary incidence angle ϑ and polarization angle φ. The calculated transmission spectra for impinging TM waves as a function of frequency and incidence angle ϑ for $\varphi = 0$ are shown in the left panels of Fig. 3, namely 3(a), 3(c), and 3(e). We consider here $l = 400\,\mathrm{nm}$, $d_x = d_y = 100\,\mathrm{nm}$ and various slits widths w_x and w_y, as indicated in each panel. Similar to the 1D case, the fundamental physical mechanisms behind the transmission spectra are retained. For example, at normal incidence ($\vartheta = 0$), typical EOT peaks based on the FP resonance mechanism are observed in all panels. Such resonances are shifted to lower frequencies when considering narrower slits, since the guided wavelength in the slits is reduced due to plasmonic effects.[18] These resonances produce horizontal transmission bands in Fig. 3, weakly affected by the incidence angle but inherently limited in frequency.

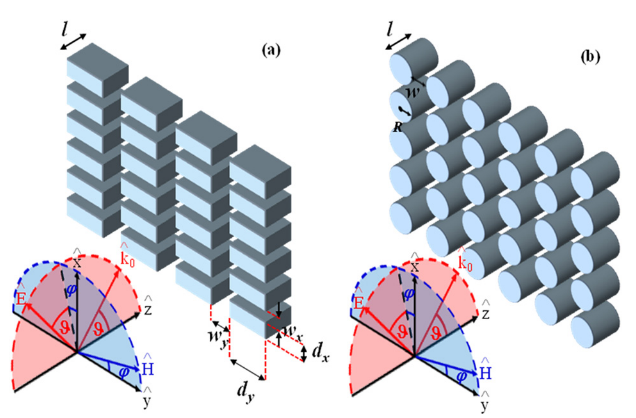

FIG. 2. (a) Geometry of a 2D metallic grating made of rods of height l and rectangular cross section $d_x \times d_y$. (b) Same as in (a) for rods of circular cross section with radius R.

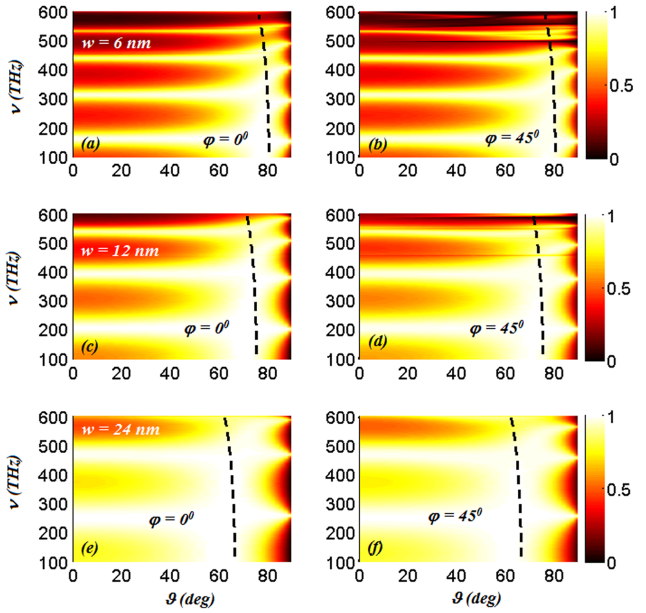

FIG. 3. Angular transmission spectra for the structure shown in Fig. 2(a) with thickness $l = 400$ nm and channel widths $d_x = d_y = 100$ nm with various slit widths ($w_x = w_y = w$) for different polarization incidence planes. The dashed lines indicate the predicted dispersion of the plasmonic Brewster angle, given by Eq. (1).

For narrower slits, the bandwidth is reduced because of the higher Q factor of these resonances and the correspondingly larger stored reactive energy in the slits. In contrast, at a specific incidence angle [$\vartheta_B = 69.4°$ for the grating with slit width $w_x = w_y = 12$ nm], an anomalous Brewster transmission mechanism is achieved, which produces total transmission through the slits independent of the frequency of operation, appearing as a vertical band [dashed lines correspond to the predicted Brewster angle using Eq. (1)] in all panels. Narrower slits produce a shift in the Brewster angle ϑ_B. Evidently, for electric field polarized along one of the slit axes ($\varphi = 0°$ or $90°$), the performance of the 2D grating is with very good approximation analogous to the one of the corresponding 1D setups. This implies that the orthogonal slits are uncoupled, and therefore the array may be excited in the two orthogonal planes as if it were a 1-D geometry.

In the right panels of Fig. 3, namely 3(b), 3(d), and 3(f), we consider the case with $\varphi = 45°$, for which both sets of orthogonal slits are equally excited. This is the worst-case scenario for our geometry, a case in which coupling may become important and affect the Brewster tunneling. It is obvious by comparing the left and right panels that the transmission spectra are practically identical, confirming that such array of square rods produces Brewster transmission and light squeezing independent on the polarization plane of TM incident waves. These results may be also interpreted as the Brewster transmission through an effective metamaterial having a large relative refractive index, as the effective geometry turns out to be similar to the one proposed in Ref. 19 for different purposes. A more rigorous homogenization model, as the one introduced in Refs. 5 and 6 may be extended to this 2-D geometry to take into account effects of spatial dispersion in the metamaterial parameters, which are expected to be strong.[20]

Since the two orthogonal slits are uncoupled, we may also consider the case of different slit widths $w_x \neq w_y$ and different channel widths $d_x \neq d_y$, which, according to Eq. (1), may provide different Brewster transmission angles for different polarization planes of incidence. This is due to the fact that the effective slit width and period in the two orthogonal directions provides a different tunneling angle, following Eq. (1). This may be particularly interesting to direct the impinging power towards different angles, depending on the impinging polarization plane. We verify this effect in Fig. 4, where we consider the case $d_x = d_y = 100$ nm, $w_x = 6$ nm, and $w_y = 12$ nm. It is seen that the two orthogonal polarizations tunnel at different angles $\vartheta_B = 80°$ for $\varphi = 0°$ and $\vartheta_B = 75°$ for $\varphi = 90°$ and with different angular beamwidths. In the case of oblique polarization ($\varphi = 45°$, middle panel), the transmission is worsened in this configuration, due to the large anisotropy of the transmission mechanism for the two orthogonal polarizations. In this scenario, Brewster transmission is severely reduced, in particular at larger frequencies. This is different from the array of square rods considered in the previous figure, which provided robust Brewster tunneling for any incidence plane.

Since we have verified that anomalous light funneling may be obtained in dense arrays of rectangular rods forming orthogonal meshes of plasmonic slits, it may be interesting to verify whether the same anomalous Brewster transmission can appear also for different shapes of 2D metallic gratings. In Fig. 5, we examine a 2-D grating composed of circular cylindrical rods, whose geometry is shown in Fig. 2(b). The structure has thickness $l = 400$ nm, rod radius $R = 50$ nm, and various spacing widths w, as indicated in each figure. In the left panels, Figs. 5(a) and 5(b), we examine the case of polarization orthogonal to one of the lattice axis ($\varphi = 0°$). Also in this scenario, for which it is difficult to visualize uncoupled slits, the electromagnetic response is consistent with the rectangular grating, and ultrabroadband light squeezing is achieved at the Brewster angle. Again, at normal incidence typical EOT resonances based on the FP resonance mechanism are visible in all panels. They result in the horizontal transmission bands clearly seen in all panels, with narrow bandwidths of operation. The bandwidth becomes narrower when the spacing width is smaller, as expected. At the Brewster condition [$(\vartheta_B, w) = (75.7°, 6\,\text{nm})$ and $(\vartheta_B, w) = (71.2°, 12\,\text{nm})$], total transmission independent on the frequency of

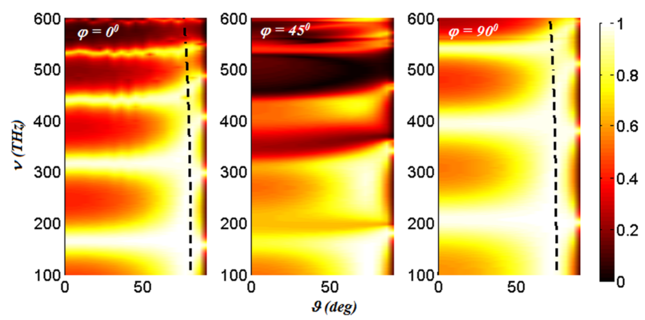

FIG. 4. Angular transmission spectra for the structure depicted in Fig. 2(a) with thickness $l = 400$ nm and channel widths $d_x = d_y = 100$ nm with slit widths $w_x = 6$ nm, $w_y = 12$ nm for different polarization incidence planes. The dashed lines indicate the predicted dispersion of the plasmonic Brewster angle, given by Eq. (1) using the width value w_x for panel (a) and w_y for panel (c).

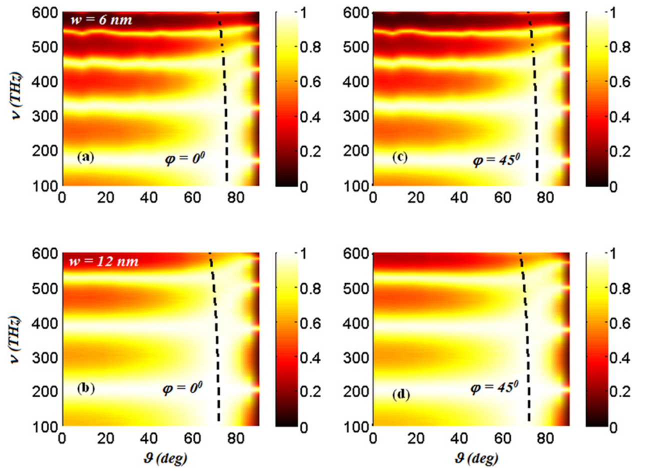

FIG. 5. Angular transmission spectra for the structure depicted in Fig. 2(b) with $l = 400$ nm and cylinder radius $R = 50$ nm with various spacing widths w at different azimuthal angles. The dashed lines indicate the predicted dispersion of the plasmonic Brewster angle, given by Eq. (1) with $w_{eff} = 11.5$ nm for panels (a) and (c) and $w_{eff} = 16.5$ nm for panels (b) and (d).

operation is obtained, which is visible as a vertical transmission band (dashed lines) in all panels. By matching our results with the predicted Brewster transmission in Eq. (1) we find that the effective width in the two cases is $w_{\mathrm{eff}} = 11.5$ nm and $w_{\mathrm{eff}} = 16.5$ nm, respectively, corresponding to the dashed lines in the figure. As expected, the effective widths represent an average spacing between neighboring rods.

Figures 5(c) and 5(d) show analogous results for incident electric field at $\varphi = 45°$ compared to the lattice axes, again the worst-case excitation. It is seen that the different polarization plane does not affect the angular transmission spectra, ensuring that similar phenomena may be obtained also with other 2D gratings. Again, transverse anisotropy may ensure broadband transmission independent of the incidence plane.

The response highlighted here may inspire angle-insensitive polarizers, absorbers, and energy harvesting devices, as it may provide an efficient way to trap incident light with TM polarization over ultrabroad bandwidths and wide angles, independent on the polarization plane and possible presence of absorption in the channels. Recently, broadband absorption enhancement has been demonstrated with 2D plasmonic gratings coupled to thin-film solar cells.[21,22] These concepts are based on combining multiple resonances to broaden the bandwidth of operation. Here, we instead suggest using 2D gratings to concentrate light using simple impedance matching, without any sort of resonance, implying even broader bandwidths. These results may provide larger conversion efficiencies than what currently available in energy-harvesting devices, in particular when optimized designs are considered.

III. CONCLUSIONS

In this paper, we have shown that anomalous Brewster transmission may be supported by 2D metallic gratings over ultrabroad bandwidths. We have shown that this phenomenon may be made completely insensitive on the polarization angle and incidence plane for impinging TM polarized waves, but selective to the incidence angle. This may provide interesting venues for low-loss energy concentration and harvesting devices and for polarization detection.

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