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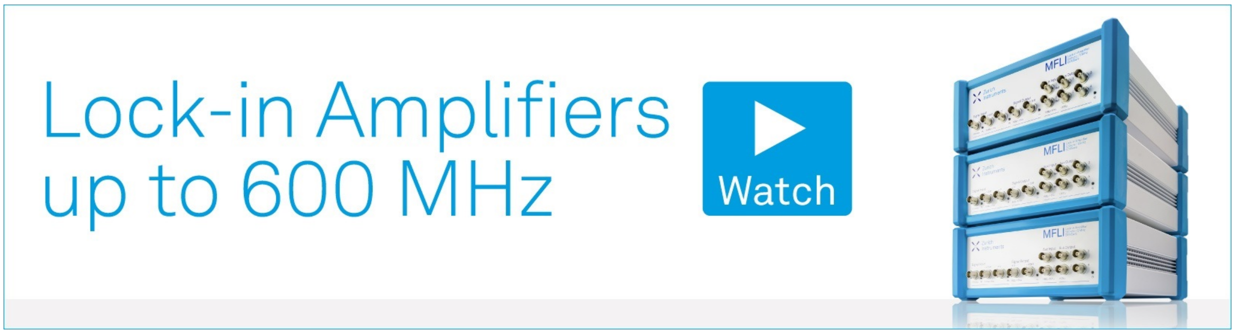

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Frustrated total internal reflection and critical coupling in a thick plasmonic grating with narrow slits

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We demonstrate the possibility of critical coupling through frustrated total internal reflection in a thick plasmonic grating below the first diffraction order. Differently from conventional approaches relying on the excitation of surface plasmon-polaritons, here we exploit the light coupling with the leaky modes supported by the grating. This mechanism entails a wide-angle coupling and effectively access spectral bands that would otherwise be difficult to probe using conventional plasmonic critical coupling techniques, such as the Otto configuration. Our finding may pave the way to efficient plasmonic bio-sensor devices.
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Light coupling with systems, such as waveguides, microcavities, diffraction gratings, and plasmonic materials, plays a fundamental role in many optical devices.[1] This great variety of scenarios notwithstanding, the core physical mechanism of light coupling can be described by a unified theory dealing with the wave interaction with an open resonator.[2] Among the various coupling regimes, a significant role is attributed to the "critical" coupling.[2] In this regime, light is completely absorbed and this occurs when the internal loss rate of the system equals the radiation leakage. Critical coupling is important for many reasons, for example, it allows concentration of light into subwavelength regions, locally boosting linear and nonlinear optical processes, and can be used in bio-sensor devices. In plasmonic systems, perhaps the best known example of critical coupling is represented by the frustrated total internal reflection due to the generation of a surface-plasmon-polariton (SPP)[3] (Otto configuration). This happens when a smooth metal film, for example, silver, is put close enough to the surface of a prism. In this situation, the impinging light, instead of undergoing total internal reflection at the prism-air interface above the critical angle, is completely absorbed by the metal plate. Other examples of critical coupling in plasmonic systems include absorption by the Wood-Rayleigh anomalies in metallic gratings due to coupling of light into an SPP mediated by one of the reciprocal lattice vectors of the grating itself,[4] light absorption in thin metallic gratings, with dense and narrow corrugations, caused by the excitation of quasistatic SPPs along the groves,[5] absorption in a two-dimensional or three-dimensional metallic nanostructure by matching the frequency and field pattern of an incident wave to that of a localized SPP resonance,[6] and resonant absorption in a multiple-port SPP resonator.[7]

In this Letter, we explore a different, yet effective approach, to realize frustrated total internal reflection and critical coupling in a thick plasmonic grating with narrow slits. The physical mechanism behind our approach is not based on the excitation of SPP or the absorption resonances of extremely shallow metallic gratings, but it instead exploits the coupling of the light with the intrinsic leaky modes of the metallic grating beyond the total internal reflection angle.

To provide some physical insights into this phenomenon, we refer to the geometry described in Fig. 1 consisting of a metallic layer of thickness l corrugated by slits of width w and period d in contact with the flat side of a hemicylindrical prism.

We can assume with no loss of generality that the prism is the input medium with refractive index n_{in} and ϑ is the incident angle of the plane, TM-polarized (H-field parallel to the grooves) wave that impinges the grating. The total internal reflection condition is achieved for incident angles beyond the critical angle $\vartheta_c = a\sin(n_{out}/n_{in})$, where $n_{out} < n_{in}$ and n_{out} is the refractive index of the output medium, in our case $n_{in} = 1.52$, $n_{out} = 1$, and $\vartheta_c = 41.13°$. The H-field above and below the metallic grating can be conveniently expanded into a superposition of plane waves as follows:

$$H(x,z) = \begin{cases} e^{i\left(k_x x + \sqrt{n_{in}^2 k_0^2 - k_x^2}\, z\right)} + \sum\limits_m r_m e^{i\left(\alpha_m x - \sqrt{n_{in}^2 k_0^2 - \alpha_m^2}\, z\right)} & z \le 0 \\ \sum\limits_m t_m e^{i\left[\alpha_m x + \sqrt{n_{out}^2 k_0^2 - \alpha_m^2}\,(z-l)\right]} & z \ge l, \end{cases} \tag{1}$$

where $k_0 = 2\pi\nu/c$ is the vacuum wave-vector, ν is the frequency, and $k_x = n_{in} k_0 \sin\vartheta$ is the transverse momentum of the incident wave, t_m (r_m) is the complex transmission (reflection) coefficient of the *m-th* diffracted order, and α_m is the generalized transverse wave-vector: $\alpha_m = k_0 n_{inc} \sin\vartheta + 2m\pi/d$, $m = 0, \pm 1, \pm 2, \ldots$ The transmission and reflection coefficients are calculated using the Fourier modal method (FMM) following the procedure outlined in Ref. 8. In Eq. (1), for simplicity, we have assumed unitary

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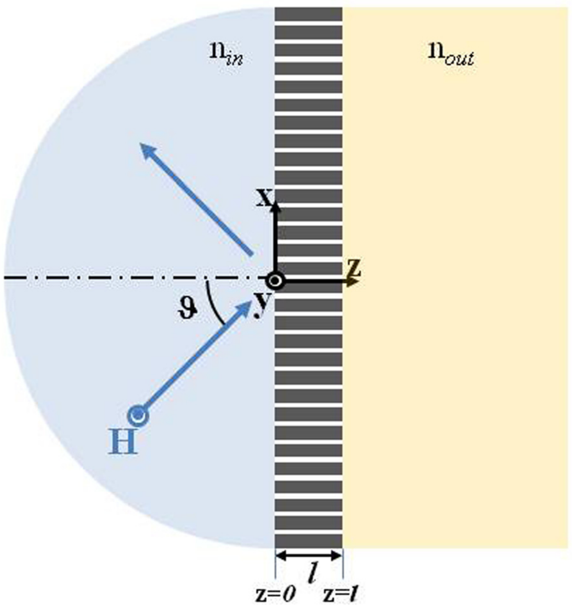

FIG. 1. Geometry under consideration: a plane, monochromatic, TM polarized wave impinges on a metallic grating of thickness l, slit aperture w, and period d in contact with the flat side of a hemi-cylindrical prism.

amplitude of the incident field. Once the field in Eq. (1) is calculated, the electromagnetic problem is formally solved and the reflectance R (reflected power normalized to the incident power), transmittance T and absorption $A = 1 - R - T$ can be calculated. In Figs. 2(a)–2(c), T, R, and A are calculated in the (ν, k_x) plane for a silver grating with period $d = 96\,\text{nm}$, slit aperture $w = 12\,\text{nm}$, and thickness $l = 300\,\text{nm}$. For silver, we have used realistic values of the dispersion of the electric permittivity taken from the book of Palik.[9] The frequency range spans from 100 THz ($\lambda = 3\,\mu\text{m}$) to 600 THz ($\lambda = 0.5\,\mu\text{m}$), so that the incident wavelength is always much greater than the grating periodicity, $\lambda \gg d$, and all the diffracted orders are evanescent except the 0th. The region $0 \le k_x/k_0 \le 1$ (incident angle $0 \le \vartheta \le \vartheta_c$) corresponds to propagative modes where Fabry-Perot-like bands of extraordinary optical transmission are present, as expected.[10]

The region $1 \le k_x/k_0 \le n_{in}$ (incident angle $\vartheta_c \le \vartheta \le 90°$) corresponds instead to the total internal reflection regime, in this case the transmittance drops to zero, as one may expect, but the reflectance is not always unitary, on the contrary, coherent bands of absorption are clearly visible. Note that in our configuration the light coupling with the SPP at the glass/silver interface ($z = 0$) is ruled out because of the transverse momentum mismatch between the incident wave and the SPP. The momentum mismatch cannot be compensated by any of the reciprocal lattice vectors of the grating due to the condition $\lambda \gg d$. The light coupling with the air/silver SPP at $z = l$ would, in principle, be possible, but it is practically excluded due to the large thickness of the grating. Those absorption bands correspond to light coupling with leaky modes supported by the metallic grating. To confirm this conjecture, we have plotted in Fig. 2 the dispersion (dashed line) of the generalized guided modes of the system calculated by finding the local maxima of the coupling strength (CS), defined as $\text{CS} = \sum_m |t_m|^2$, in the (ν, k_x) plane.

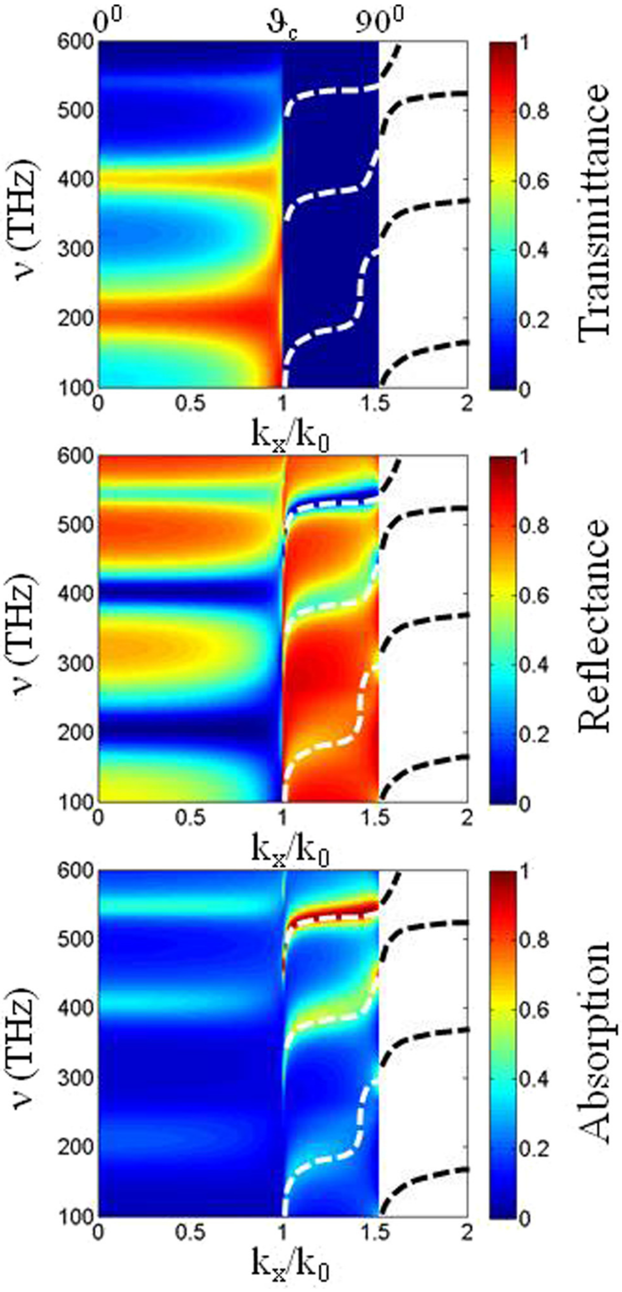

FIG. 2. T, R, A in the (ν, k_x) plane. The dashed curves represent the dispersion of the leaky/guided modes. The structure's parameters are $d = 96\,\text{nm}$, $w = 12\,\text{nm}$, and $l = 300\,\text{nm}$.

It is well known that for a non-absorbing, planar system, subject to transverse k_x momentum conservation, the guided modes correspond to poles of CS along the $\text{Re}k_x$-axis.[11] If we look for generalized guided modes to include also leaky modes, then the poles of the CS migrate into the complex $(\text{Re}k_x, \text{Im}k_x)$ plane, but, still, the maxima of the coupling strength along the $\text{Re}k_x$ axis give a very good approximation of the dispersion associated with these generalized guided modes. In fact, in our case, we find that the maxima of the coupling strength follow almost perfectly the bands of coherent absorption confirming that those bands are generated by critical coupling of light with the leaky modes of the metal grating. For the sake of completeness, we have also extended the calculation of the guided mode dispersion into the region

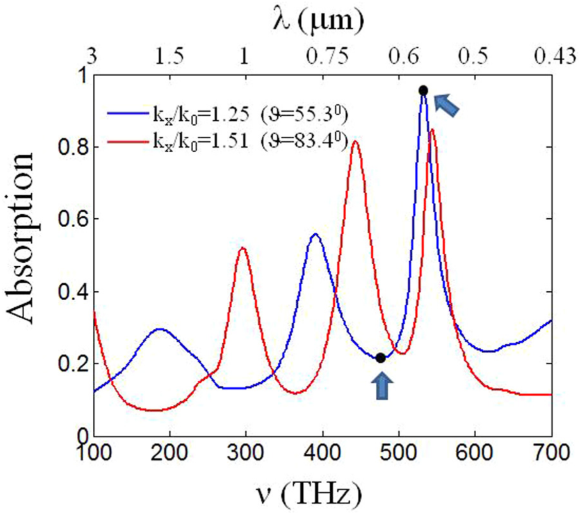

FIG. 3. Absorption vs. frequency for two incident conditions above the critical angle.

beyond the cone of light ($k_x/k_0 \geq n_{in}$) where true guided modes (non-leaking) can be found, although, obviously, this region is not accessible in our configuration. In Fig. 3, we show the absorption calculated along $k_x/k_0 = 1.25$ ($\vartheta = 55.3°$) and at grazing incidence $k_x/k_0 = 1.51$ ($\vartheta = 83.4°$). The resonances have the general tendency to increase their absorption peak at higher frequencies, this is an expected phenomenon due to the reduced metal conductivity leading to a better field penetration and consequent increment of the ohmic losses.

The two arrows in Fig. 3 on the $\vartheta = 55.3°$ curve indicate the spectral position where we calculate the local dissipation due to Ohmic losses and the H-field localization (shown in Fig. 4). These two cases correspond, respectively, to resonant reflection with minimum absorption, 4(a) and 4(b), and resonant absorption ($A \cong 1$), 4(c) and 4(d). The local Ohmic losses are calculated as $\mathrm{Im}(\varepsilon)|E|^2$,[12] where ε is the metal permittivity. Notice that the intensity of the field inside the slits as well as the Ohmic losses along the slit walls are much more pronounced in the case of the resonant absorption than in the case of resonant reflection, as one may expect. The case in Figs. 4(c) and 4(d) with strong field localization inside the slits and the enhanced ohmic losses epitomizes the critical coupling condition.

In Fig. 5, we show the absorption in the (l,k_x) plane, respectively, at 600 THz ($\lambda = 0.5$ μm), 500 THz ($\lambda = 0.6$ μm), and 400 THz ($\lambda = 0.75$ μm). The figures show that, in the total internal reflection region, complete absorption, i.e., critical coupling ($A = 1$), over several bands is feasible through a careful choice of the grating's thickness.

Finally, in Fig. 6, we provide a comparison between the critical coupling that can be achieved by the classical Otto configuration, i.e., using a smooth metal film, through the excitation of a SPP at the air/metal interface and the one that can be achieved using the leaky modes of the metallic grating. The absorption has been calculated in both cases at a fixed frequency (500 THz) by varying the incident angle and the air gap between the prism and the metallic structure.

We note that critical coupling in the grating case is achieved for a wide range of incident angles from the critical angle up to grazing incidence. On the contrary, the critical coupling achieved through the Otto configuration is much more sensitive to the incident angle and becomes effective just for a narrow angular range close to the critical angle. The situation becomes even more exacerbated at lower frequency, i.e., near IR, where the angular range for the critical coupling becomes extremely narrow and squeezed close to the critical angle.

In conclusion, we have demonstrated that it is possible to achieve frustrated total internal reflection in a thick metallic grating with narrow slits by exploiting the light coupling with the intrinsic leaky modes of the grating. The physical mechanism highlighted here offers much more flexibility in terms of the allowed bands for critical coupling than typical configurations, such as the Otto configuration, for example, and may open alternative venues for achieving efficient plasmonic biosensors. Narrow slits in metallic screens with aspect ratios similar to those considered in this Letter may be obtained with advanced nanofabrication techniques, such as nanoskiving.[13] Other metals that have lower conductivities, such as copper, will also reduce the need for very narrow slits. A systematic study in the parameter space (l,w,d) for different metals can further improve the performances of the proposed device.

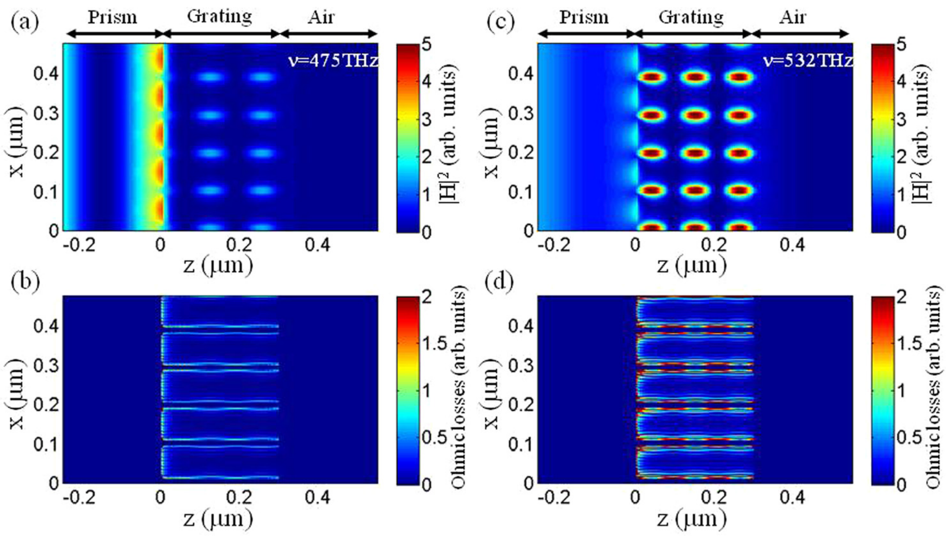

FIG. 4. Field localization and local ohmic losses for resonant reflection ((a) and (b)) and resonant absorption ((c) and (d)).

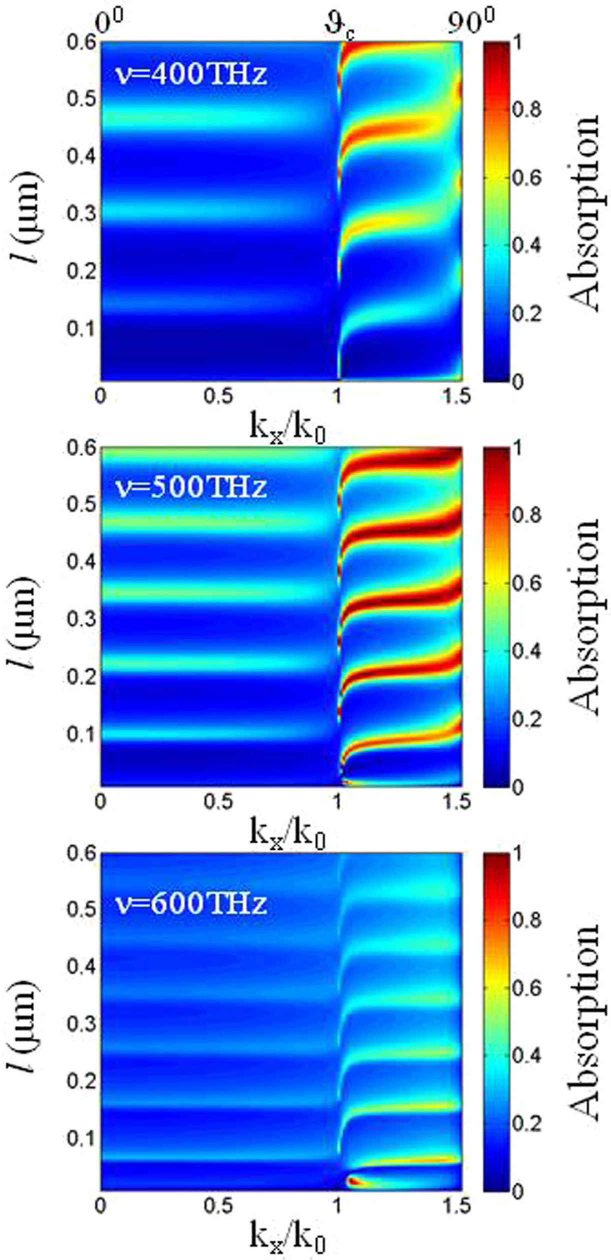

FIG. 5. Absorption in the (l,k_x) plane for different frequencies. The other grating parameters remain the same as in the previous cases.

Finally, while here we have investigated the visible and near-IR range, we predict that similar effects may also be achieved in the lower frequency range, such as the THz and GHz range. In those cases, the decrement of the ohmic losses due to a better metal conductivity, which hampers the critical coupling condition ($A = 1$), can be compensated by using ultra-narrow slits and thicker gratings with dimensions comparable to those of Ref. 14 in the GHz range, for example.

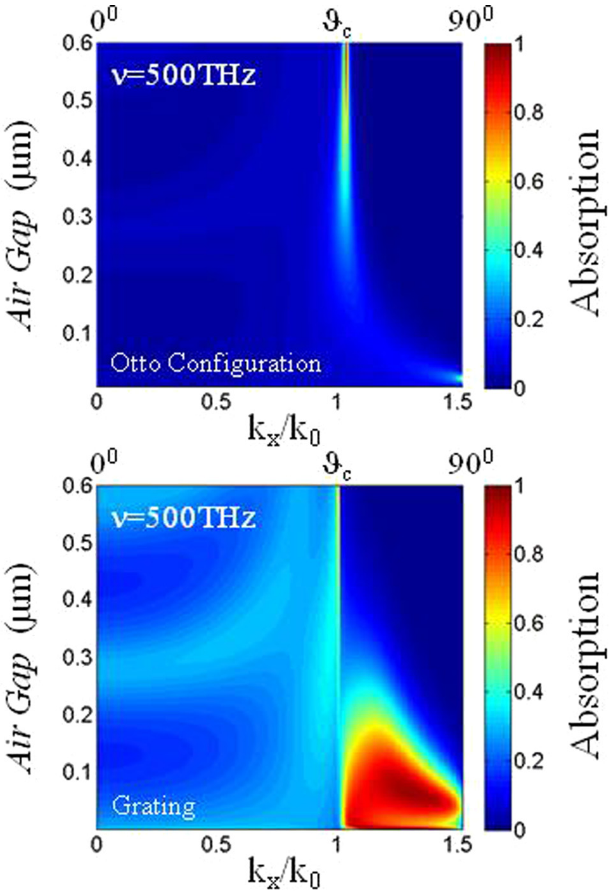

FIG. 6. Absorption vs. k_x/k_0 and air gap thickness for a smooth silver layer (Otto configuration) and for the silver grating. The grating thickness is in this case 331 nm, the other parameters remain the same as in the previous cases.

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