Brewster angle for plasmonic gratings

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Abstract

In this paper, we analyze the transmission properties of metallic gratings at optical frequencies. In particular, we show that an inherently ultra-broadband tunneling mechanism may be obtained based on impedance matching between the guided modes supported by ultranarrow slits and free-space TM plane waves impinging at an oblique angle. This phenomenon is the analogous of the well-known Brewster transmission for dielectric slabs, but it is obtained here for mostly opaque metallic gratings. We focus on the transmission of short pulses in time domain through such grating, showing that broadband signals may be transmitted with weak distortion, very different from typical extraordinary optical transmission based on resonant phenomena.

1. Introduction

Extraordinary optical transmission (EOT) through sub-wavelength apertures in metallic screens has been widely investigated during the last years [1]. This phenomenon is typically based on resonant mechanisms, such as plasmonic resonances, "spoof plasmons" [2] and Fabry-Perot (FP) resonances [3]. For this reason, the aforementioned effects are inherently narrowband in nature, which limits their potential applications. For example, EOT based on surface plasmons may be achieved only in a particular narrow frequency band that depends on the properties of the metallic material of the grating and the background material. Here, we discuss an alternative mechanism to achieve complete transmission through an otherwise opaque metallic grating. The phenomenon is the analogous of the well-known Brewster total transmission effect, which is extended here to plasmonic grating structures, consistent with our recent findings in [4]. This extraordinary transmission is inherently broadband and slightly dependent on the structure's dimensions/losses, in contrast with the resonance EOT mechanisms described before. It works for transverse-magnetic (TM) polarized electromagnetic waves and for a narrow range of incidence angles, around the *plasmonic Brewster angle* of the structure.

2. Brewster angle of plasmonic metallic grating

The geometry under analysis is shown in Fig. 1, consistent with the setup analyzed in [5]. The metallic screen has thickness *l*, the grating has period *d* and the corrugations have width *w*. The polarization of the excitation is chosen to be transverse-magnetic. We illuminate the structure with oblique incidence at a given angle θ. Using a transmission-line approach, the effective wave number in the free-space region is $\beta_0 = k_0 \cos\theta$ and the characteristic impedance for one grating period is $Z_0 = d\eta_0 \cos\theta [m^{-1}]$, where $k_0 = \omega\sqrt{\varepsilon_0 \mu_0}$ and $\eta_0 = \sqrt{\mu_0 / \varepsilon_0}$. Inside the slits, the transmission-line wave number and impedance are independent of the incidence angle and satisfy [5]:

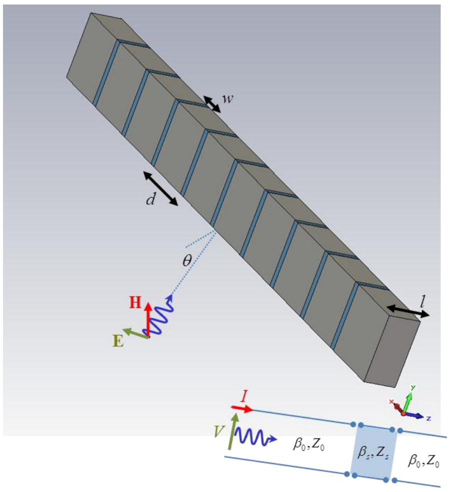

Fig. 1: Geometry under analysis: a metallic grating illuminated by a TM oblique incident plane wave.

$$\tanh\left[\sqrt{\beta_s^2 - k_0^2}\, w/2\right]\sqrt{\beta_s^2 - k_0^2} = -\sqrt{\beta_s^2 - k_0^2\varepsilon_m}\,/\,\varepsilon_m, \quad Z_s = w\beta_s/(\omega\varepsilon_0)[m^{-1}] \tag{1}$$

where ε_m is the permittivity of the metallic grating, assumed to be composed of silver in this scenario. This transmission-line model is consistent with the inset of Fig. 1 and the reflection coefficient at the interface of the metallic grating is equal to:

$$R = \frac{\left[Z_s^2 - Z_0^2\right]\tan(\beta_s l)}{\left[Z_s^2 + Z_0^2\right]\tan(\beta_s l) + 2iZ_s Z_0}. \tag{2}$$

FP resonances are obtained in transmission when Eq. (2) becomes zero for $\beta_s l = m\pi$. However, it is interesting that zero reflection [R=0 in Eq. (2)] and maximum transmission can be also achieved if $Z_s = Z_0$, i.e., when the structure is perfectly matched to the surrounding background. This condition can be interestingly met in the lossless scenario at the plasmonic Brewster angle θ_B [4]:

$$\cos\theta_B = (\beta_s w)/(k_0 d). \tag{3}$$

Similar to the Brewster transmission through a dielectric etalon, this condition is independent of the grating thickness l and slightly affected by losses. When the grating is illuminated at this specific angle, ultra-broadband EOT is achieved, which extends to frequencies up to the breakdown of this model $(d \approx \lambda_0)$. Due to the inherent broadband nature of this transmission, we can expect that ultrashort pulses in time domain may be squeezed through the plasmonic slits with small or low distortion, as we verify with full-wave simulations in the next section. This theoretical approach allows an elegant interpretation of the Brewster-like transmission, but analogous results may be obtained with rigorous numerical techniques, as in the next section, or with alternative analytical approaches [6].

3. Frequency and transient response of the metallic grating

We choose in the following simulations w = 12nm, d = 96nm and l = 200nm. The device is illuminated with an ultrashort pulse to test its performance. We isolate a broad frequency window (0 - 350 THz) to demonstrate the EOT performance of this device for normal incidence ($\theta = 0^o$) and for the plasmonic Brewster angle, which is approximately $\theta_B = 74^o$ for this case. The transmission coefficient (S_{21}) is plotted against frequency in Fig. 2 for this example. Almost perfect transmission is obtained at the

Brewster angle, as expected from the previous discussion. On the contrary, FP resonances are dominant at normal incidence and high transmission is achieved only in a narrow range of frequencies.

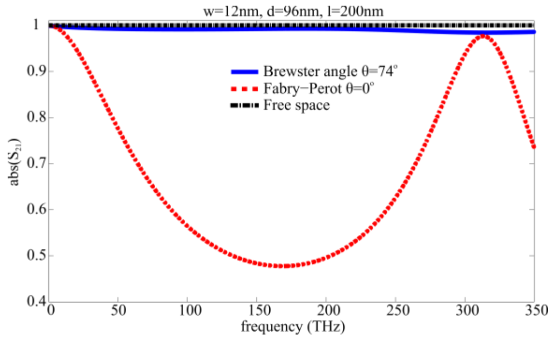

Fig. 2: Computed S_{21} for the metallic grating at normal and Brewster angle incidence.

An impulse-like time domain signal is launched towards the plasmonic grating at normal and Brewster angles of incidence, with bandwidth spanning the whole range of frequencies in Fig. 2. The transmitted pulse after passing through the sub-wavelength corrugations are monitored and shown in Figs. 3(a), (b) for the two incidence angles. The pulse propagating in free-space is also plotted for sake of comparison. Small distortions in time are obtained when the pulse propagates at the Brewster angle. However, the signal is severely distorted and spread in time for normal incidence, as expectable.

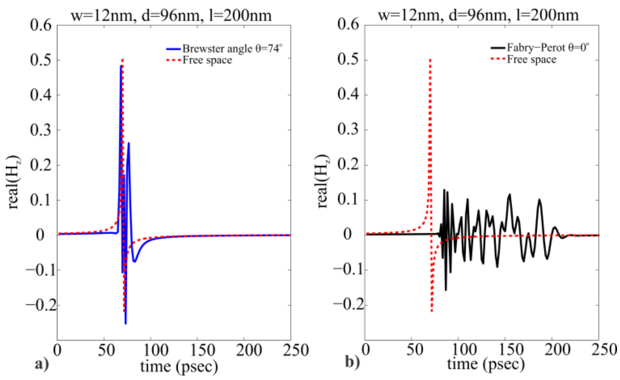

Fig. 3: Time-domain response of the metallic grating illuminated by a short pulse at a) Brewster angle and b) normal incidence.

4. Conclusions

The plasmonic analogue of the Brewster angle effect has been discussed here for metallic gratings, consistent with our results in [4]. Ultra-broadband EOT for an otherwise opaque metallic grating slab has been verified both in frequency and time domain. This effect may be applied to energy concentrators, polarization filters and novel absorbing devices.

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