Near-surface beaming and non-plasmon suppression of specular reflection from metal gratings in THz

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Abstract

In this paper we present the study of THz laser beam reflection from a metallic grating. We show both theoretically and experimentally that unlike in visible and IR spectrum ranges, suppression of the specular reflection in THz is not associated with a surface plasmon resonance, but rather is conditioned by a resonance energy transfer to a near-surface propagating diffracted wave. Moreover, we suppose that this result is a general one for metal interfaces in the THz region, and all existing experiments are to be reinterpreted taking into account this fact.

1. Introduction

Terahertz band ($f = 0.3-10$ THz) offers unique possibilities for numerous sensing, imaging, and diagnostic applications [1]. The application potential of the THz radiation might be greatly improved by implication of surface plasmon-polaritons (SPPs) owing to their confinement to a metal-dielectric interface. The SPP is a surface electromagnetic wave propagating along an interface and decaying exponentially in both media [2]. However, in the THz region (in contrast to visible and IR regions) metals behave as perfect conductors, and the SPP has poor localization together with a huge free path length. A number of recent experiments proclaim the observation of the THz SPP on metals [3-5], although the estimated SPP localization and the free path length correspond to the metal dielectric permittivity of three orders lower than the real permittivity [5]. Another peculiarity of the THz SPP is an extremely small resonance width: $\delta f \sim 1\ldots100$MHz for good metals at $f = 1$THz . Meanwhile, typical THz-range experiments are carried out using pulse broadband THz sources with the spectral resolution of $6\ldots18$ GHz and the angular divergence of the order of 0.1 rad [3-5] that is much greater than the resonance width. In spite of this fact, a strong minimum of specular reflectivity is often detected. These discrepancies invoke a question: what is really observed in experiments and what corresponds to the specular reflectivity minimum? The aim of this paper is to answer this question.

2. Theoretical approach

Consider a TM-polarized plane monochromatic wave $\vec{H}^i(\vec{r}) = \vec{e}_y \exp(i\vec{k}\vec{r})$ with $\vec{k} = k(\sin\theta, 0, \cos\theta)$ incident at an angle θ on a metal grating with a periodic profile $z = \zeta(x) = \sum_n \zeta_n \exp(ingx)$, $\zeta_0 = 0$, $g = 2\pi/d$, where d is a grating period. We present the diffracted field above the interface, $z \le \zeta(x)$, as a Fourier-Floquet expansion, $\vec{H}(\vec{r}) = \vec{e}_y \sum_n h_n \exp(i\vec{k}_n\vec{r})$, with $\vec{k}_n = k(\alpha_n, 0, -\beta_n)$, where

$\alpha_n = \sin\theta + ng/k$, and $\beta_n = (1-\alpha_n^2)^{1/2}$ ($\mathrm{Re},\mathrm{Im}\beta_n \geq 0$). We suppose the grating to be shallow, $|d\zeta/dx|$, $|k\zeta| \ll 1$, and the surface impedance of the metal $\xi = \varepsilon^{-1/2}$ to be small, $|\xi| \ll 1$. Matching the incident and the diffracted field at the interface and solution of Maxwell equations in a single resonance approximation (see details in [6]) yields the amplitudes of the diffracted waves

$$h_r = \frac{2\nu_{r0}}{\beta_r + \xi + \Gamma_r}, \qquad h_N = \delta_{N,0} + \frac{\nu_{N0} + \nu_{Nr} h_r}{\beta_N + \xi}, \tag{1}$$

where $\nu_{mn} = ik(1-\alpha_m\alpha_n)\zeta_{m-n}$, $\Gamma_r = \sum_N |\nu_{Nr}|^2/(\beta_N + \xi)$. Here h_N are the amplitudes of non-resonant waves, and h_r is the amplitude of the resonant wave for which the approximate resonance condition $|k\alpha_r| \simeq q_{SPP}$ is fulfilled (q_{SPP} is the wave number of the SPP). The quantity Γ_r renormalizes surface impedance; this renormalization occurs due to the resonant wave backscattering to other diffracted waves and it results in resonance broadening and shift. Suppression of the specular reflectivity registered in experiments is usually treated as an evidence of the SPP resonance, thus we should examine the amplitude of the specular wave. From (1) it follows, that $|h_0|$ actually has *two* minima: the first one for $\mathrm{Re}\beta_r = 0$, $\mathrm{Im}(\beta_r + \xi + \Gamma_r) = 0$ corresponds to resonance diffraction order coupled to a surface wave (the true SPP-resonance), and the second one for $\mathrm{Re}\beta_r = |\xi + \Gamma_r|$, $\mathrm{Im}\beta_r = 0$ corresponds to a *propagating resonance wave*. It should be noted that in the latter case a substantial portion of the incident wave energy is redirected to a near-surface (volume) wave in contrast to the true SPP resonance for which a significant part of the incident radiation is guided into the surface wave (SPP) and then partly absorbed and partly re-scattered. Which of these two reflectivity minima is dominating mainly depends on the ratio $\mathrm{Z} = \xi/(\xi + \Gamma_r)$: if $|\mathrm{Z}| \sim 0.5\cdots1$ then it is the minimum of the first type, but if $|\mathrm{Z}| \ll 0.5$ then it is the second-type minimum.

3. Experimental and theoretical results

For illustration let us consider a simple harmonic grating $\zeta(x) = a\cos(2\pi x/d)$ in IR and THz spectrum regions. In order to compare both cases we use the same geometry with $r = -1$: in this case the only propagating wave is the specular reflected one. The wavelength λ and the grating period d in THz region are those for IR region scaled by a factor of 300 (see Table 1). For each region we present two characteristic grating amplitudes: a_1 corresponds to the grating that produces a *total* suppression of the specular reflection at the SPP resonance (first-type minimum), and a_2 produces the specular reflectivity minimum of the second type. In Fig. 1a it is shown that both types of minima are possible in IR. As for the THz range, we want to pay a special attention to the fact that the width of the SPP resonance here is $\delta\theta \sim 2\times10^{-4}$ deg (Fig. 1b) that is beyond the resolution capabilities of any real THz setup. At the same time, the deep grating with $a = a_2$ (see THz column of Table 1 and Fig. 1c) produces the wide and deep enough minimum of specular reflectivity that corresponds to the propagating resonance wave. Obviously, only the latter case can be experimentally observed in THz region.

Table 1. The two sets of parameters for example setups in IR and THz.

	IR	THz
λ	$1\,\mu\text{m}$	$300\,\mu\text{m}$
ε	$-42 + i3.3$	$(-7.3 + i53)\times10^4$
d	$0.75\,\mu\text{m}$	$225\,\mu\text{m}$
a_1	$0.02\,\mu\text{m}$	$2\,\mu\text{m}$
a_2	$0.08\,\mu\text{m}$	$12\,\mu\text{m}$

We support our theoretical investigations by experimental study of specular reflectivity of a brass grating (Cu 60%, $\varepsilon_{Cu} = -7.4\times10^4 + i6\times10^5$) produced by means of the standard optical lithography. The grating period was $d = 254\,\mu\text{m}$, the form of the grooves was close to semi-elliptical with the width $152\,\mu\text{m}$ and the depth $28\,\mu\text{m}$. As a light source we used the HCN laser with the wavelength $\lambda = 337\,\mu\text{m}$, the band width less than $0.1\,\text{MHz}$, and the beam divergence angle of $\Delta\theta = 0.36$ deg. The result of the experiment is shown in Fig. 1d. Measured reflectivity definitely indicates that the minimum corresponds to the propagating resonance wave and it is in a good agreement with the theoretical results.

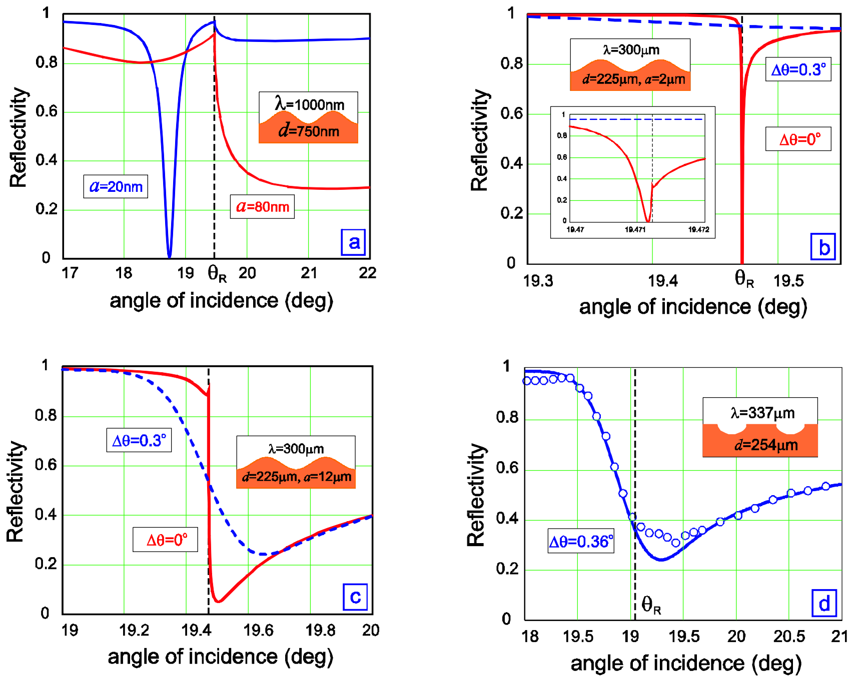

Fig. 1: Specular reflectivity $|h_0|^2$ of metal gratings versus the incidence angle. (a) IR region: both types of minima are possible; (b), (c) THz region: for shallow gratings (b) the ultra-narrow SPP resonance vanishes after angular averaging (dashed line), but for the deep grating (c) the reflectivity minimum is wide enough and survives after averaging; (d) the experimental reflectivity (markers) and the numerical simulation (line) with a beam divergence taken into account. Vertical dashed line indicates the Rayleigh angle θ_R (for the resonance wave), separating the region of the surface resonance wave ($\theta < \theta_R$) and that of the volume resonance wave ($\theta > \theta_R$).

4. Conclusion

We have shown both theoretically and experimentally that suppression of the specular reflection of the THz radiation from metal gratings is associated with a near-surface volume propagating resonance wave, and is not connected directly with the excitation of the surface plasmon-polaritons. The effect is polarization-sensitive and stipulated by the high dielectric permittivity of the relatively deep grating.

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