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Transmission properties of one-dimensional metallic and left-handed material gratings

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ABSTRACT

We provide rigorous numerical calculations (using the rigorous coupled-wave analysis) of transmission spectra of various metallic and metamaterial one-dimensional gratings and identify plasmonic resonances responsible for enhanced transmission. We argue that the most important mechanism which influences the resonant transmission is the coupling of incident electromagnetic wave with two types of plasmonic wave: lengthwise plasmon, which propagates along the grating, and crosswise plasmon excited in air gaps.

1. Introduction

Surface plasmon [1,2] represents the basic eigenmode of a metallic grating. Thanks to the spatial periodicity of the grating, surface plasmons could be excited by incident electromagnetic (EM) wave. The interaction of these two waves (surface plasmon and incident wave) strongly influences the transmission properties of the periodic grating. Enhanced transmission of EM waves through periodic metallic gratings has been experimentally observed in Ref. [3]. On the contrary, for very thin metallic gratings, transmission is smaller due to the absorption of plasmon energy [4]. Negative role of surface plasmons is also discussed in Ref. [5].

In this paper, we calculate the transmission of EM waves through various one-dimensional (1D) gratings and show that observed resonant frequency behavior of the transmission can be explained as an interaction of incident wave with excited plasmonic resonances. We distinguish two kinds of plasmons [6,7]. The first one, lengthwise (LW) plasmon, which propagates along the grating surface and can be excited only when Bragg's relation between the wave vector of surface plasmon and grating period is fulfilled [2,8]. These LW plasmons are also responsible for the extraordinary transmission through a single aperture, if the incident surface is periodically corrugated [9]. LW plasmon resonance appears as a sharp Fano-type peak in the spectrum. The second one, crosswise (CW) plasmon, is excited inside the gaps [10,11]. CW plasmon resonance appears as a broad Fabry–Perot type maximum in the spectrum. We provide quantitative estimation of resonant frequencies for both plasmons and show that they are in good agreement with rigorously calculated transmission resonances.

The paper is organized as follows. In Section 2 the transmittance of the EM wave through a metallic grating which is calculated with the use of the rigorous coupled wave analysis (RCWA) [12] is presented. In order to reveal the effect of grating geometry (grating thickness, grating period, width of gap), transmittance is calculated for different grating parameters. In Section 3, observed resonances in the transmission spectra are interpreted as a coupling effect of incident EM wave with the surface plasmons excited on the surface of the structure or inside it. Section 4 deals with the application of the model to left-handed material gratings. Discussion of obtained results is given in Section 5.

2. Transmission spectra

The reference 1D metallic grating is shown in Fig. 1. The grating is uniformly extended in the y-direction. Its thickness in the z-direction is d and its spatial period in the x-direction is p. The width of air gap is h. The metallic relative permittivity is ε_m. The embedding medium is air with relative permittivity $\varepsilon_d = 1$. The relative permittivity of the metal is given by Drude's formula:

$$\varepsilon_m(f) = 1 - \frac{f_p^2}{f^2 + \mathrm{i} f\gamma} \tag{1}$$

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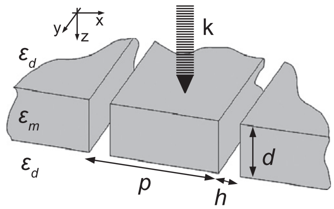

Fig. 1. Cross section of the 1D metallic grating. Incident EM wave has a wave vector **k**.

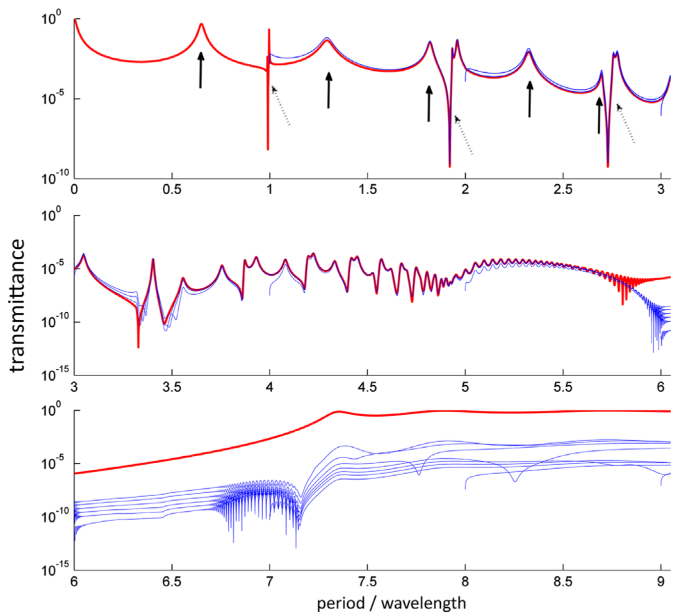

Fig. 2. Reference transmission spectrum of all diffracted orders versus the normalized frequency. Arrows indicate enhanced transmissions of Fabry–Perot type (continuous) and Fano type (dashed arrow) resonances. Red line shows the zeroth order spectrum, blue lines represent higher order terms. Parameters of the metallic gratings are $p=1000$ nm, $d=300$ nm, $h=10$ nm (refer to Fig. 1). Note the change of the transmission spectrum for $p/\lambda \sim 5.06$ and 7.16. At these frequencies the real part of ε_m becomes -1 and 0. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

where f_p is the plasmon frequency and γ is the absorption coefficient. For our calculations $f_p=2147$ THz and $\gamma=5$ THz, typical for Ag and Au [13].

Numerical simulations of the transmission were realized with our own numerical program based on the RCWA. In the RCWA, the structure is divided into multiple sandwiched layers along the direction of propagation. The permittivity is a periodic function of x in each sublayer. The numerical calculation involves spatial Fourier expansion of the EM field and of the dielectric function in each sublayer of the structure. The EM field determined by the RCWA satisfies Maxwells equation within each sublayer as well as the boundary conditions between adjacent layers. The numerical accuracy is only limited by the number of orders used in the Fourier expansion. The typical number of Fourier modes we used is 106. If not stated otherwise, the incident electromagnetic plane wave is normal to the grating plane and the vector of magnetic field is parallel to the y-direction (TM polarization).

Fig. 2 shows the calculated transmission coefficient against the normalized frequency p/λ. There are two types of enhanced transmission. The first one is a Fabry–Perot resonance (five lowest resonances at $p/\lambda=0.65$, 1.30, 1.82, 2.32) marked by arrows in Fig. 2. The second type, Fano resonances [14], observed at $p/\lambda=0.99$, 1.92, 2.73, etc. are marked by dashed arrows. Both resonances are present in all of the diffracted orders' transmission.

To identify the physical origin of these resonances, we gradually change one of the parameters of the structure and investigate how the transmission spectrum changes compared to the reference one shown in Fig. 2.

Fig. 3 shows how the transmission spectra change when the angle of incidence (in the xz plane) increases from 0° (this is the reference curve from Fig. 2) to 2°, 5° and 10°. While the Fabry–Perot transmission maxima have not changed, Fano resonances are split into two separate frequencies which strongly depend on the incident angle.

Transmission spectra for various grating thicknesses d are shown in Fig. 4. The position of the first Fabry–Perot type maximum increases for decreasing thickness d. On the other hand, the position of the first Fano resonance hardly depends on d. It is interesting to see how the Fabry–Perot peak interacts with the Fano resonance. The “traveling” Fabry–Perot peak actually transforms to Fano type peak and back. After further decrease in grating thickness a transmission minimum appears on interval $0<p/\lambda<1$ for $d<80$ nm.

Similarly, a changing air gap width h affects the position of Fabry–Perot type maximum (Fig. 5) while sharp Fano peaks remain unaffected.

Finally, we probe transmission against the grating period p. As it is seen in Fig. 6, position of Fabry–Perot maxima is left unchanged and the sharp Fano resonances are shifted to the right for decreasing grating period p and become less sharper.

3. Theoretical framework

In this section we present an interpretation of the origin of enhanced transmission phenomenon. We show that Fano-type sharp peaks are caused by the interaction of incident EM wave with surface plasmons propagating along the surface of the metallic grating. The excitation of these *lengthwise* (LW) plasmons is possible thanks to the spatial periodicity of the grating. Similarly, Fabry–Perot-type resonances are due to *crosswise* (CW) plasmons excited and guided along the air gap resonators (Fig. 7).

3.1. Lengthwise plasmons

Consider a homogeneous metallic slab with thickness d and negative relative permittivity ε_m given by the real part of Eq. (1). The metal slab is surrounded by dielectric relative permittivity ε_d. The dispersion relation for the TM polarized surface waves excited on both sides of the metal–dielectrics interface is given [1,15,2] as

$$\frac{\varepsilon_m}{\varepsilon_d} = -\frac{\kappa_z^m}{\kappa_z^d}\tanh\frac{\kappa_z^m d}{2} \qquad (2)$$

for the symmetric plasmon, and

$$\frac{\varepsilon_m}{\varepsilon_d} = -\frac{\kappa_z^m}{\kappa_z^d d}\coth\frac{\kappa_z^m d}{2} \qquad (3)$$

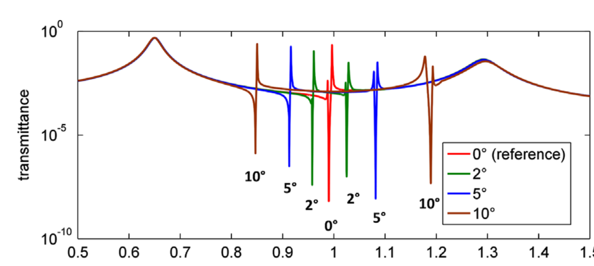

Fig. 3. Transmission spectrum of the zeroth diffraction order for various angles of incidence.