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Study of magnetic polaritons in deep gratings for thermal emission control

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Recently, it has been shown that convex cavities or 2D grating structures can enhance thermal emission for energy conversion systems. The mechanisms, however, cannot be well explained by either the conventional cavity resonance modes or surface plasmon polaritons. The present study elucidates the fundamental mechanism by considering the excitation of magnetic polaritons (MPs) in deep gratings. Rigorous coupled-wave analysis (RCWA) is employed to calculate the radiative properties by solving Maxwell's equations numerically. The LC-circuit model is employed to predict the resonance conditions. The current and field distributions further confirm the excitation of magnetic resonances. It is shown that MPs and cavity modes agree with each other when the kinetic inductance is negligibly small. However, when the kinetic inductance is sufficiently large, the maximum resonance wavelength can be more than twice that predicted by the cavity mode. Furthermore, different materials are considered and the frequency range is extended from the near-infrared to the microwave region to illustrate the scalability of the MPs. This study clarifies one of the underlying mechanisms of optical resonance in deep gratings and will benefit the design of wavelength-selective thermal emitters.

1. Introduction

Generated by the thermal motion of charged particles in matter, thermal radiation is usually incoherent. Researchers have put significant effort towards controlling thermal radiation for applications such as solar cells [1–4] and thermophotovoltaic (TPV) systems [5–9], in which it is desired to have a receiver (or emitter) that can absorb (or emanate) radiation only in certain wavelength regions. One-, two-, or three-dimensional (1D, 2D, or 3D) micro/nanoperiodic structures of wide profile diversity and dimensionality can enable tailoring the radiative properties for developing spectral selective absorbers and emitters [10]. As a matter of fact, 1D and 2D gratings have been extensively investigated both theoretically and experimentally.

Hesketh et al. [11,12] experimentally demonstrated the resonance in the emission spectra with 1D doped-Si deep gratings, and explained them with an acoustic analog of the organ pipe mode. Later, Maruyama et al. [13] used the cavity resonance modes to explain the resonance conditions in 2D-microcavity gratings. Sai et al. [6] and Kusunoki et al. [14] also experimentally demonstrated resonances in similar structures as cavity modes. Though the cavity resonance theory has successfully explained the resonances in the certainty periodic structures [15], it cannot predict the maximum (or cutoff) resonance wavelength in a grating with narrow slits or trenches. As an example, the resonance wavelength can be about ten times the grating depth (or height) [16] while the cavity resonance formulation yields a maximum resonance wavelength four times the grating depth. Finite inductance [17,18], coupled surface plasmon polaritons (SPPs) [19,20], and trapped modes theory have been used to explain the mechanisms of resonances and the increase of the cutoff wavelength in gratings [21], grating/thin-film structures [22],

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holes [17], and slits [18]. Mattiucci et al. [16] evaluated the impedance of the grating using coupled SPP modes and successfully predicted the emittance of grating structures with the metamaterial effective media approach. However, the resonance peaks could not be obtained explicitly. Pardo et al. [23] explained the funneling of light into narrow grooves etched on a metal surface as a result of magnetoelectric interference, but did not quantify the resonance condition. To guide the engineering design of nanostructures [24], it is desirable to develop simple models to predict resonance wavelength for certain kind of structures.

The theory of magnetic polaritons (MPs) has successfully been used to predict the resonances in metallic grating/thin-film structures [9,25] and narrow slit arrays [26]. Wang and Zhang [27] also used the excitation of MPs to explain the phonon-mediated resonances in SiC deep gratings. In addition, MP resonance has been used to explain the responses in the structures mentioned in [16,23]. Since the resonance in deep gratings shows different geometry dependence in different wavelength ranges, it is worthwhile to explore the possibility of using MPs to explain the anomalous maximum wavelength in deep gratings for various materials and spectral regions. In this paper, the inductor–capacitor (LC) circuit model [28,29] is used to predict the fundamental MP resonance mode in deep gratings. The results are compared with rigorous-coupled wave analysis (RCWA). The electric field and current–density distributions at the resonance condition are used to elucidate the magnetic resonance or the diamagnetism effect. Silver (Ag), heavily doped semiconductor (Si), and tungsten are considered. The resonance wavelengths are extended from the near-infrared to the microwave region by scaling the geometric dimensions of the gratings along with the wavelength.

2. Theoretical analysis

2.1. Classical cavity resonance model

Fig. 1 illustrates the 1D metallic grating structure considered in this paper. The grating is described by a period Λ, ridge width w, height (or depth) h, and trench width b. The metal filling ratio in the grating region is defined as $f=w/\Lambda$. The region below the grating is made of the same material and thick enough to be treated opaque. Consider radiation incident from air (medium above the grating) to the grating. Due to the high reflectivity of the metallic material, the reflectivity of the grating is generally high except when resonance occurs that can cause a sudden reduction of the reflectance (i.e., increase of the absorptance or emittance). The cavity resonance model has often been used to explain the emittance peaks for 2D grating or cavity structures [6,13,14]:

$$\lambda_{lmn} = \frac{2}{\sqrt{(l/L_x)^2 + (m/L_y)^2 + ((n+\frac{1}{2})/L_z)^2}} \tag{1}$$

where l, m, and n are integers (0, 1, 2, …), and L_x, L_y, and L_z define the cavity dimensions. For a 1D grating, L_y is infinitely long such that only L_x and L_z (which are referred as b and h in Fig. 1) can affect the resonance wavelengths. The maximum value of λ_{lmn} is called the cutoff wavelength and can be determined by setting $l=n=0$ in Eq. (1), resulting in a resonance wavelength (λ_R) that is four times the grating height (4h). However, this value may be much smaller than the resonance wavelength in a deep grating with a high aspect ratio (h/d), as shown in the example below.

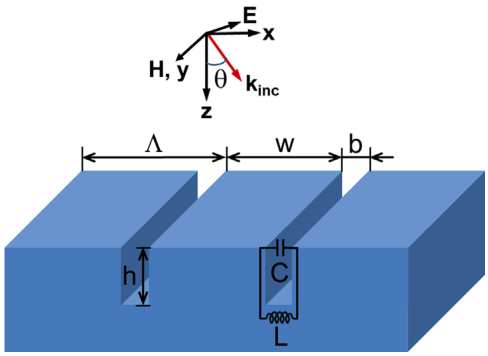

Fig. 1. Schematic of the 1D metallic grating with a period Λ, height or depth h, ridge width w, and trench width b. The equivalent LC circuit model is also shown with the capacitance C and inductance L. Only TM wave is considered so that $\mathbf{H}$ is always parallel to the y-axis. The wavevector $\mathbf{k}_{inc}$ of the incident plane wave is in the x–z plane at an angle θ with respect to the z-axis.

Fig. 2(a) shows the normal emittance spectrum of transverse magnetic (TM) waves for a Ag grating with $\Lambda=400$ nm, $h=200$ nm, and $b=5$ nm. The calculation is based on RCWA that solves the Maxwell equations numerically to determine the spectral reflectance and then calculate the emittance as one minus the reflectance [7,25]. The optical properties of Ag are obtained using the Drude model with the following parameters [30,31]: plasma frequency $\omega_p=1.39\times10^{16}$ rad/s, scattering rate $\gamma=2.7\times10^{13}$ rad/s, and a high-frequency constant $\varepsilon_\infty=3.4$. The emittance spectrum is characterized by a peak as high as 0.85 at the wavelength of 2.74 μm. The emittance enhancement is remarkable since the emittance is less than 0.005 for a smooth Ag surface at this wavelength. Note that λ_R for this mode is nearly 14 times the grating height. This resonance cannot be explained by SPP or Wood's anomaly since both of which would occur at much short wavelengths on the order of period [7,30]. Furthermore, the high emittance is almost omnidirectional as seen from the contour plot displayed in Fig. 2(b), which shows the directional spectral emittance in terms of the wavenumber and parallel wavevector $k_x=k_{inc}\sin\theta$. Emittance values at $k_x=0$ (i.e., along the ordinate) correspond to normal incidence with an emittance peak located at 3650 cm^{-1}. A quantitative explanation is given below using the MP model that takes account of the geometry and material's properties.

2.2. Magnetic polaritons and the LC-circuit model

Magnetic polaritons refer to the strong coupling of the magnetic resonance inside a micro/nanostructure with the external electromagnetic waves. Under a time-varying magnetic field parallel to the y-direction, an oscillating current is produced around the grooves in the x–z plane, and this induced current generates a magnetic field (i.e., diamagnetism) according to Lenz's law. Fig. 3(a) and (b) shows the electromagnetic and current–density field