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Tailoring thermal radiative properties with film-coupled concave grating metamaterials

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ABSTRACT

This work numerically investigates the radiative properties of film-coupled metamaterials made of a two-dimensional metallic concave grating on a continuous metal film separated by an ultrathin dielectric spacer. Spectrally-selective absorption is demonstrated in the visible and near-infrared regime, and underlying mechanisms are elucidated to be either localized magnetic polaritons (MPs) or surface plasmon polaritons (SPPs). The unique behaviors of MPs and SPPs are explained with the help of electromagnetic field distributions at respective resonance frequencies. An inductor–capacitor model is utilized to further confirm the excitation of MP, while dispersion relation is used to understand the behaviors of different SPP modes. Geometric effects of ridge width and grating period on the resonance absorption peaks are discussed. Moreover, directional responses at oblique incidences for different polarization states are studied. Fundamental understanding gained here will facilitate the design of novel metamaterials in energy harvesting and sensing applications.

1. Introduction

Spectral control of thermal radiation has numerous applications in energy harvesting [1–3], thermal management [4], radiative cooling [5], and optical sensing [6,7]. Metamaterials, which refer to a class of artificial materials with exotic electromagnetic properties, have been studied for tailoring thermal radiative properties [8]. Metamaterials are usually made of micro/nanostructures with feature sizes smaller than the wavelength of incident light. Recently, film-coupled metamaterials, consisting of subwavelength periodic patterns on a dielectric layer and a metallic ground plane, have drawn much attention [9]. Selective metamaterial absorbers or emitters with different patterns such as one-dimensional (1D) grating [10,11], 2D disk arrays [12], patch arrays [13–15], cross bars [16], and nanoparticles [17–20] have been investigated. Excitations of magnetic polaritons (MPs) [21–23] and surface plasmon polaritons (SPPs) [24,25] have been demonstrated as the main mechanisms responsible for the spectral selectivity in thermal absorption or emission in these metamaterials. MP refers to the coupling between external electromagnetic fields and magnetic resonance inside the structures, while SPP stems from collective oscillation of charges at the interface of dissimilar materials whose real parts of permittivity have opposite signs [26].

On the other hand, radiative properties of film-coupled concave grating structures with 2D periodic mesh-like patterns are little studied. Gou et al. [27] investigated spectral optical properties of a metal–insulator–metal stack with rectangular hole arrays but mainly focused on coupled SPP modes across different layers. Lee et al. [28] introduced a concave grating structure made of nickel, in which selective absorptance is explained by excitation of cavity resonance. There have been discussions on photonic

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crystals [29] and fishnet structures [30–32] with similar geometries, but the effects of MP and SPP in controlling the radiative properties of film-coupled concave gratings are not yet well understood or systemically studied by far.

In this work, we numerically investigate effects of magnetic and surface plasmon polaritons in tailoring the radiative properties of a film-coupled concave grating metamaterial structure with finite-difference time-domain (FDTD) simulation. Selective absorption in the visible and near-infrared regime is demonstrated, and electromagnetic fields are plotted to elucidate underlying mechanisms responsible for each absorption peak. Geometric effects of ridge width and grating period are also discussed. An inductor–capacitor (LC) circuit model and the SPP dispersion relation are utilized to theoretically predict MP and SPP resonance conditions. Moreover, optical responses at oblique incidences are investigated for both transverse magnetic (TM) and transverse electric (TE) polarized waves to gain a full understanding in MP and SPP behaviors.

2. Numerical method

Fig. 1(a) depicts the periodic film-coupled metamaterial structure under investigation, which is made of an aluminum (Al) concave grating on a silicon dioxide (SiO_2) spacer and Al substrate. Note that Al is chosen as the metal material due to its natural abundance. The 2D periodic mesh-like grating, which is considered to be symmetric in x and y directions for simplicity, has a cavity width b, ridge width w, grating period Λ, and grating height h, while the SiO_2 spacer thickness is t. An electromagnetic wave with a wavevector k_{inc} is incident onto the structure at an incidence angle θ, which is defined as the angle between k_{inc} and surface normal. The plane of incidence (POI), which is spanned by the surface normal and incident wavevector k_{inc}, is taken to be parallel to the x–z plane (i.e., y-direction incident wavevector $k_{y,inc}=0$), for which the conical diffraction would not occur. The electric field vector **E** is in the POI with TM polarized waves, as shown in the figure, but is perpendicular to the POI for TE waves. Note that the x-direction incident wavevector $k_{x,inc}=k_{inc}\sin\theta=0$ at normal incidence. A set of base geometric values, such as $\Lambda=1$ μm, $b=0.75$ μm, $w=0.25$ μm, and $h=t=30$ nm, was considered for the film-coupled concave grating structure.

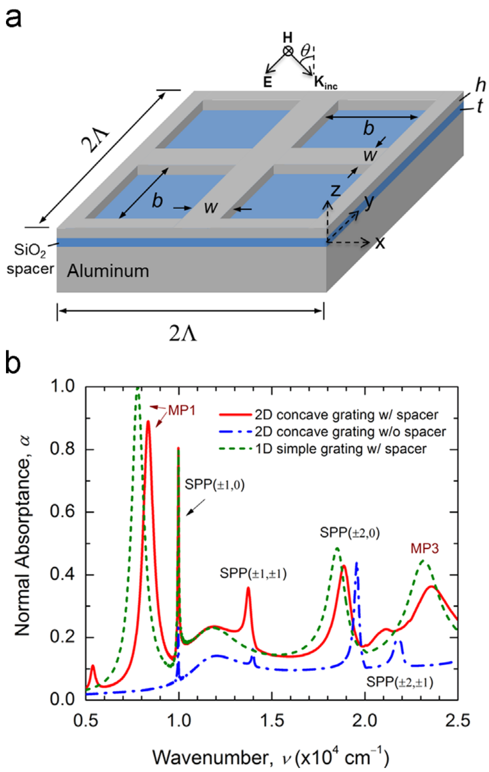

Fig. 1. (a) Schematic of a periodic film-coupled concave grating metamaterial considered in the present study. (b) Spectral normal absorptance spectra for the film-coupled concave grating, a concave grating structure without SiO_2 spacer, and a film-coupled 1D grating structure with the same geometric values from the FDTD simulation.

The FDTD simulation was implemented using a commercial package (Lumerical Solutions, Inc.). Frequency-dependent optical constants of both Al and SiO_2 were obtained from Palik's tabular data [33]. Manually refined meshes with sizes of 5 nm in both x and y directions and 1 nm in the z direction were used to ensure the numerical convergence. Periodic boundary condition was applied in both x and y directions at normal incidence to reduce the 3D simulation domain into one unit cell, while Bloch boundary condition had to be used at oblique incidences to account for the phase difference in neighboring unit cells. Perfectly-matched layers with a reflection coefficient less than 10^{-6} were placed along the z direction. A linearly polarized plane wave source was positioned at 1.2 μm above the structure surface, while spectral reflectance R was obtained by a frequency-domain power monitor placed at 1.5 μm above the structure. Note that the 200-nm-thick Al substrate is optically opaque. Therefore, the spectral-directional absorptance can be readily calculated by $\alpha=1-R$ according to the energy balance. The frequency range of interest is from 5000 cm^{-1} to 25,000 cm^{-1} in wavenumber with a spectral resolution of 10 cm^{-1}.

3. Results and discussion

3.1. Radiative properties at normal incidence

The spectral normal absorptance of the film-coupled concave grating structure with the set of base geometric values is presented in Fig. 1(b) at TM-wave incidence, though TE waves will yield the same results at normal incidence due to the geometric symmetry. Absorption peaks are observed at the several frequencies of 8350 cm^{-1} (with absorptance $\alpha=0.89$), 9970 cm^{-1} ($\alpha=0.80$), 13,740 cm^{-1} ($\alpha=0.36$), 18,870 cm^{-1} ($\alpha=0.43$), 21,150 cm^{-1} ($\alpha=0.23$), and 23,580 cm^{-1} ($\alpha=0.36$). These peaks were respectively labeled as MP1, SPP(±1,0), SPP($\pm1,\pm1$), SPP(±2,0), SPP($\pm2,\pm1$), and MP3 from lower to higher frequencies, which are associated with the excitations of different MP and SPP modes. Note that for SPPs, the numbers in the parentheses represent the diffraction orders of SPP in x and y directions, i.e., SPP