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Design of Coherent Thermal Emission Source by Excitation of Magnetic Polaritons between Metallic Gratings and an Opaque Metallic Film

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Abstract**—**The present paper studies a structure consisting of a periodic metallic grating, coated on a dielectric spacer atop an opaque metal substrate, using coherent thermal emission source in the infrared region. It has been theoretically demonstrated that by exciting surface magnetic polaritons between metallic gratings and an opaque metallic film, separated by a dielectric spacer, large emissivity peaks are almost independent of the emission angle and they can be achieved at the resonance frequencies. The reflectance spectrum of the proposed structure shows two resonances dip, which leads to a sharp emissivity peak. The relations of the reflection and absorption properties and the influence of geometric parameters on the radiative properties are investigated by rigorous coupled-wave analysis (RCWA). The proposed structure can be easily constructed, using micro/nanofabrication and can be used as the coherent thermal emission source.

Keywords**—**Coherent thermal emission, Polartons, Reflectance, Resonance frequency, Rigorous coupled wave analysis (RCWA).

I. Introduction

THERMAL emission sources are commonly regarded to be incoherent electromagnetic radiation sources, that the thermal emission usually exhibits broadband spectrum and quasi-isotropic angular behavior, since the thermally excited charged particles generate randomly oriented dipoles in the medium [1], [2].

Tailoring of the spectral and directional selectivity of the radiative properties has important applications in photonic and energy conversion devices, such as radiation detectors, solar cells and solar absorbers, thermo-photovoltaic systems, radiation emitters, filters and radiative cooling devices [3]-[5].

Recently, there has been increased interest in developing micro/ nanostructures to achieve coherent thermal emission, such as one-dimensional gratings made of a metal [6], [7] or a polar material [8], truncated photonic crystals [9], and bilayer structures composed of single-negative materials [10]. Depending on the wavelength and structure characteristics, the radiative properties are mostly attributed to either one or the interplay of several different physical mechanisms such as surface plasmon/phonon polaritons (SPPs/SPhPs), Wood's anomaly (WA), cavity resonance (CR), effective medium behavior, wave interference and magnetic resonance [11]-[13]. Coherent thermal emission is characterized by the sharp spectral peaks and/or narrow angular lobes in well-defined directions in the emissivity and has been demonstrated by exciting surface polaritons using grating structures. The surface polariton (or surface wave) is a resonance phenomenon in which electromagnetic waves are coupled to the collective oscillation of electrons or optical phonons [4].

Besides excitation of magnetic and/or surface plasmons polaritons (MPs/SPPs), wave interference effects in planar structures, such as in a resonance cavity with highly reflective coatings can also be utilized to achieve coherent emission [14]-[16]. More recently, it has been shown that an asymmetric Fabry–Perot resonator made of a SiO_2 cavity, sandwiched between a thin Ag film and an opaque Ag film, exhibits spectral selectivity with deep reflectance valleys at near normal incidence, suggesting that sharp spectral emissivity peaks (i.e., temporal coherent) can be used as a coherent thermal emission source [1].

This paper describes an innovative idea for tailoring the thermal emission and absorption characteristics, using metallic gratings and an opaque metallic film, separated by a dielectric spacer and an IR emitter [17]. The magnetic response existing between the metallic gratings and an opaque metallic film allows the proposed structure to behave as a single-negative material, with a negative permeability (real part) and positive permittivity. At the same time, an opaque metallic film also serves as a nonmagnetic material with a negative permittivity (real part) and positive permeability in the near infrared [5]. Consequently, surface magnetic polaritons [18] can be excited to produce coherent thermal emission.

Rigorous coupled-wave analysis (RCWA) was used to study the reflection and absorption properties of the design. It allows the calculation of the spectral - directional reflectance at any given wavelength. The influence of the geometric parameters on the radiative properties has also been investigated.

This paper is organized as follows. In Section II the proposed structure was described. The simulation results and comprehensive discussion are given in Section III, and in Section IV we concluded with a summary.

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II. Proposed Structure

The proposed structure consists of a periodic metallic grating with a dielectric spacer (a waveguide layer) deposited on a metallic substrate, as depicted in Fig. 1 (a). For simplicity, gold is selected as the material for the gratings, and silicon dioxide is used as the spacer (a waveguide layer). In practice, the gold film, whose thickness is much greater than the radiation penetration depth, can be deposited on a substrate, which is not shown in the figure. The geometry of the one-dimensional grating is denoted by grating period (Λ), width of the metallic grating (ω), fill factor $\left(f=\frac{w}{\Lambda}\right)$ thickness (*h)* and its complex relative permittivity (ε_m), where, $\varepsilon_m=\varepsilon_{mr}+i\varepsilon_{mi}$. Between and above the grating grooves the relative permittivity is denoted by ε_{Air}. The thickness of SiO_2, waveguide layer, is assumed to be *d* and its relative permittivity is ε_w. The electromagnetic wave is incident from air at an incidence angle θ is assumed to be linearly polarized. The input wave is TM-polarized, in which the magnetic vector is parallel to the grating grooves (i.e., parallel to the *y*-axis). The oscillating magnetic field, parallel to the grating grooves, can cause anti-parallel currents in the metal gratings and the metal substrate surface. Since no magnetic response is associated with the transverse electric waves [5], only the transverse magnetic (TM) wave is considered in the present study. The frequency-dependent optical constants of Au and SiO_2 are obtained from [19].

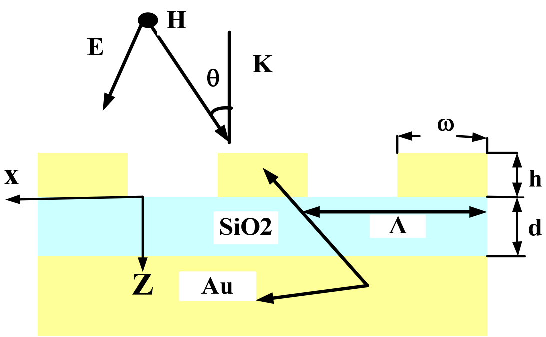

Fig. 1 (a) Schematic of the proposed structure with coherent thermal emission characteristics. Here, Λ is the grating period, w is the width of the metallic gratings, and *h* is the thickness of the metal gratings. The thickness of the dielectric spacer is *d*. The coordinates system is also shown for a TM-polarized plane wave with a wave vector, **k,** and incident at the angle θ

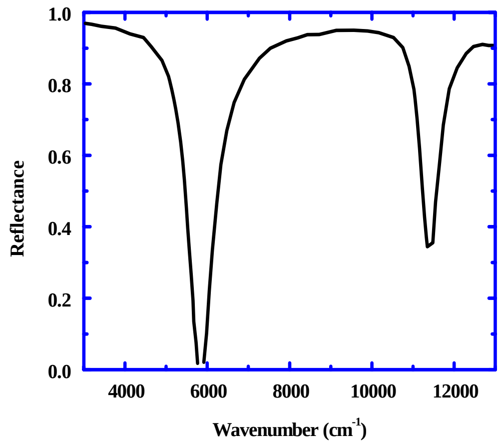

Fig. 1 (b) Spectral reflectance in the near -IR spectral for the TM at θ = 25^0 .The geometric parameters Λ=500nm, ω=250nm and h=d=20 nm

III. Results and Discussion

The reflectance spectra of the proposed structure with gratings period of 500nm, width of the metallic gratings of 250nm and thickness of Au and SiO_2 (h = d = 20 nm), at incidence angle (θ= 25^0), is shown in Fig. 1 (b). The selected wave-number range is from 3,000 to 13,000cm^{-1} (the frequency unit is expressed in terms of wave number). There are two sharp reflectance dips (R) which appear at frequency 5814 and 11490cm^{-1}, corresponding to the fundamental and second harmonic modes respectively, besides the one caused by the surface Plasmon. These reflectance dips are arising from the resonance in the dielectric spacer and are attributed to the excitation of magnetic polaritons. The existence of reflectance dips suggests that the proposed structure can be used as a coherent thermal emission source. Since the semi-infinite metallic substrate is opaque the emissivity can be obtained as $\varepsilon = 1 - R$ according to Kirchhoff's law [3].

The reflectance dips effects by the gratings width (w) are studied with different fill factor (0.5, 0.7 and 0.9), and with fixed gratings period Λ=500nm .The results in Fig. 2 show the dependence of the reflectance dips on the fill factor. Since the fill factor is proportional to the grating width, it is clear that the dips are strongly affected by the grating width(w). This is because the magnetic polariton is not induced by the diffracted evanescent waves, but induced by the magnetic element formed in the modulated structure [5].It should be noted that the resonance frequency can be easily tuned by varying the grating width (w) to match particular thermophotovoltaic cells to potentially enhance power generation with improved conversion efficiency.

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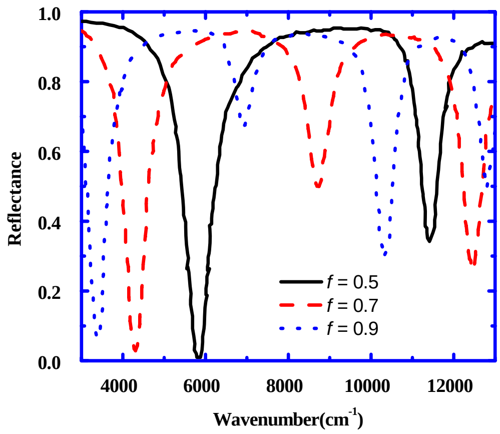

Fig. 2 Spectral reflectance in the near -IR spectral for the TM at θ = 25^0 with different fill factor, and with Λ=500 nm and h=d=20 nm

The effect of the grating period Λ on the reflectance dips is shown in Fig. 3.The results show that the reflectance dips are hardly dependent on the gratings period.

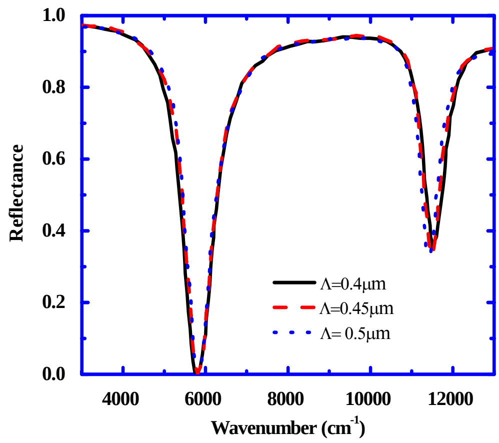

Fig. 3 Spectral reflectance in the near -IR at θ = 25^0 with different gratings period, W =250nm and h=d=20nm

The dependence of the emissivity on the thickness of the SiO_2 and the top Au gratings is shown in Fig. 4. In both cases the value of the reflectance dip at the first resonance frequency decreases as the thickness of either the Au or the SiO_2 increases. The figures also show that the position of the resonance frequency is more sensitive to the SiO_2 thickness than to that of the Au [1].

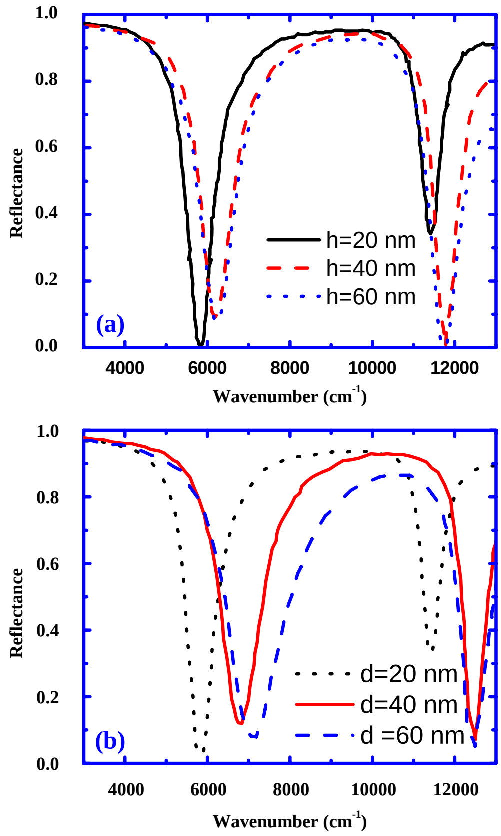

Fig. 4 Spectral reflectance in the near –IR spectral at θ = 25^0 with different (a) Au thicknesses (b) SiO_2 thicknesses

The multiple reflections result in strong absorption in the top Au gratings. The absorptivity of the top Au gratings is $\alpha=1-R$ .The SiO_2 layer is non-absorbing in the spectral range of interest. The absorption of the top Au gratings and the bottom Au layer are shown in Fig. 5, for different top Au gratings thickness, h , SiO_2 thickness, d = 20nm, Λ =500nm, W =250nm, $\theta=25^o$ and at resonance wavenumbers 5814and 11,490cm^{-1} . As shown in Fig. 5, there exist thickness values where the absorption peak is maximum. However, the maxima of the absorption for the top and bottom do not occur at the same h. It is interesting to see that more energy is absorbed by the thin Au gratings than by the bottom Au layer. For the first resonance frequency, the absorption of the top Au gratings is close to 0.8 when h= 21nm. In this case, about 75% of the energy is absorbed by the top gratings. For the second resonance frequency 11,490cm^{-1}, a close-to-0.5 the absorption is achieved when h= 23nm. In this case, about 50% of the energy is absorbed by the Au gratins.

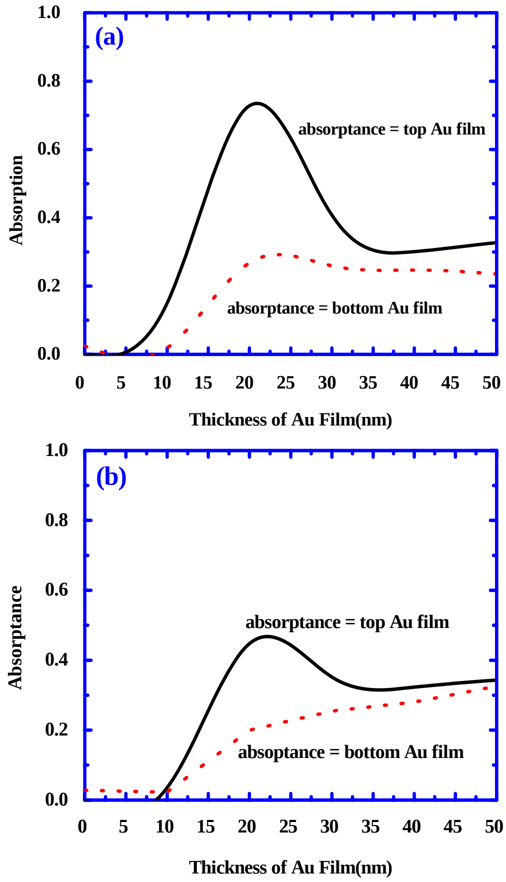

Fig. 5 Absorptivity of unpolarized waves at $\theta = 25^0$, with respect to the top Au gratings thickness. d = 20 nm at the resonance frequency: (a) 5814cm $^{-1}$; (b) 11490 cm $^{-1}$

Figs. 6 and 7 show the spectral reflectance and the directional emissivity, respectively, for different incident angles.

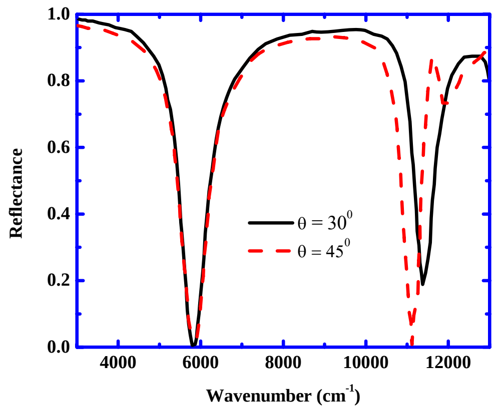

Fig. 6 Spectral reflectance in the near-IR spectral region at 30^0 and 45^0 incidence angles for TM wave

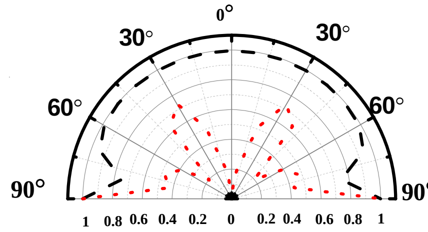

Fig. 7 The directional emissivity for the proposed structure with different incident angles at the resonance frequency5814cm $^{-1}$(long dashed line), 11490 cm^{-1}(short dashed line)

Fig. 8 shows the contour plot of the spectral-directional emissivity in terms of wavenumber and the parallel wavevector component k_x (divided by 2π). Note that $k_x = 2\pi v \sin\theta$ .The emissivity for the proposed structure exhibits several additional bands with enhanced emissivity as shown in Fig. 8. The multiple magnetic polariton branches correspond to the fundamental and second harmonic resonances modes are denoted by MP1 and MP2, which are associated with the reflectance dips at ν = 5,814 and 11,490cm^{-1}, respectively, shown in Fig. 1 (b). In contrast to the surface magnetic plasmon, wavevector component has little effect on resonance conditions for the magnetic polaritons, because the magnetic resonance conditions are largely determined by w rather than Λ . The emissivity peak resulted from the surface magnetic polariton becomes nearly independent of the emission angle and exhibits diffuse characteric that is desirable for thermo-photovoltaic radiators. Furthermore, surface plasmons can strongly interact with magnetic polaritons at certain frequency and wavevector component values. The interaction of surface magnetic plasmons with magnetic polaritons can result in either enhancement or suppression of the emissivity. The first order magnetic polaritons constructively interact with the surface plasmon, resulting in high emissivity values and a spectral broadening of the emissivity peak, as illustrated in Fig. 8.

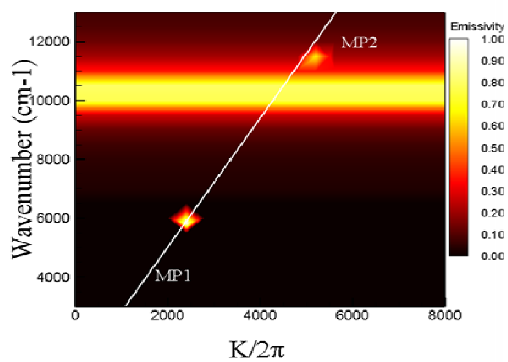

Fig. 8 Contour plot of the spectral-directional emissivity. The geometric parameters are the same as those in Fig. 1 (b). At θ = 25°, the magnetic polaritons are labeled as MP1and MP2 for the fundamental and second harmonic modes, respectively

IV. Conclusion

The present work has demonstrated that coherent thermal emission can be achieved by exciting magnetic polaritons using a periodic metallic grating, coated on a dielectric spacer coupled with an opaque metal substrate. Sharp reflectance dips are observed for TM polarization at several incidence angles. It is found that the reflectance dips are arising from resonances in the dielectric spacer and are attributed to the excitation of magnetic polartitons. The dips are affected strongly by the grating width (w), but they remain almost unchanged with change of the grating period.

The top Au gratings thickness dominantly affects the minimum reflectance or peak emissivity values, but the position of the resonance frequency is more sensitive to the SiO_2 thickness. Narrow angular lobes of the emissivity are also shown at λ = (0.87 and 1.72) μm, which indicates strong directional selectivity and spatial coherence of the proposed structure. The proposed structure can be readily constructed using available micro/nanofabrication techniques and using coherent thermal emission source. This study will facilitate future design optimization for practical applications and development of wavelength-selective emitters/absorbers in energy conversion systems, such as thermo-photovoltaic devices, as well as in thermal management by modifying radiative energy transfer and infrared radiation detectors.

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