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Taming the thermal emissivity of metals: A metamaterial approach

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We demonstrate the possibility of realizing temporally coherent, wide-angle, thermal radiation sources based on the metamaterial properties of metallic gratings. In contrast to other approaches, we do not rely on the excitation of surface waves such as phonon-polaritons, plasmon-polaritons, or guided mode resonances along the grating, nor on the absorption resonances of extremely shallow metallic grating. Instead, we exploit the effective bulk properties of a thick metallic grating below the first diffraction order. We analytically model this physical mechanism of temporally coherent thermal emission based on localized bulk resonances in the grating. We validate our theoretical predictions with full-wave numerical simulations. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4719582]

Thermal radiation sources, such as a blackbody or the incandescent tungsten filament of a light bulb, are usually incoherent and omni-directional in nature.[1] Nevertheless, in the last decade, many theoretical and experimental works have demonstrated that temporally and/or spatially coherent (i.e., directional) thermal emission is possible. For example, in Refs. 2 and 3, the authors show that coherent and directional thermal sources for transverse magnetic (TM) polarized radiation can be obtained through the excitation of surface phonon-polariton waves in a suitably designed SiC grating at $\lambda \sim 10\,\mu$m. Similar results have also been obtained by coupling plasmon-polariton modes in metallic gratings; in particular both localized[4] and planar[5] surface plasmon-polariton waves have been exploited for this goal. In Ref. 6, the authors study a coherent thermal source in a photonic crystal film made of Ge at $\lambda \sim 1.5\,\mu$m mediated by the excitation of leaky modes which in principle can be excited for both transverse electric (TE) and TM polarization. All the above mentioned works[2–6] rely on the excitation of transverse surface waves, such as phonon-polaritons in gratings made of polar materials as in Refs. 2 and 3, plasmon-polaritons in metallic gratings as in Refs. 4 and 5, or guided mode resonances in photonic crystal slabs made of lossy dielectric materials.[6] Besides being temporally coherent, the thermal sources presented in these works are also directional; i.e., they only emit at a specific angle (with the exception of the results reported in Ref. 4 which are based on the excitation of localized surface plasmons). Omni-directional absorption/emission similar to our case, but based on different physical mechanisms, has been reported in Refs. 7–9. In Ref. 10, thermal emission from 2D periodic metallic photonic crystal slab has been numerically studied.

In this letter, we propose a different, yet powerful approach to realize temporally coherent thermal sources with emission over a broad angular range. The physical mechanism behind our approach is not based on the excitation of surface modes or on the absorption resonances of extremely shallow metallic gratings,[11] but it instead exploits the anomalous properties of a thick metallic grating in its metamaterial operating regime.

To provide some physical insights into the phenomenon of coherent absorption/emission from a metallic grating, we refer to the geometry described in Fig. 1 consisting of a screen of thickness l corrugated by slits of width w and period d, with one side of the grating closed by a back mirror. A plane, electromagnetic wave, TM-polarized (H field parallel to the grooves) impinges the structure at an angle ϑ, giving rise to a reflected wave.

For this configuration, the absorption of the structure (A) is given by $A = 1 - R$, where R is the reflected power, or reflectance. According to Kirchoff's law of thermal radiation,[1,12] the thermal emissivity of the structure is equal to its absorption A. Therefore, by studying its scattering properties, we can infer the emissivity properties. Here, we suppose that the grating periodicity is smaller than the radiation wavelength ($\lambda > 2d$) so that all diffraction orders, except the

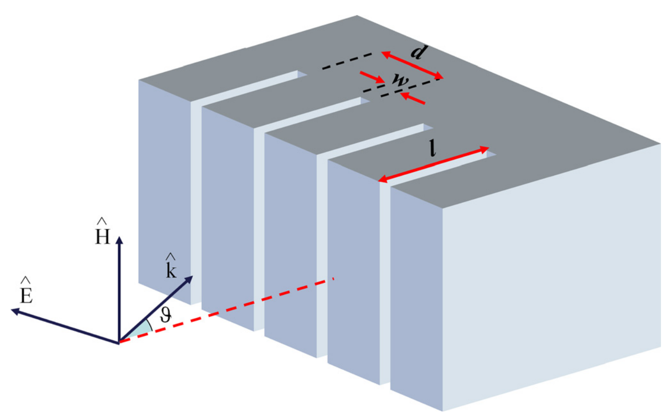

FIG. 1. Geometry under consideration: a plane, monochromatic, TM polarized wave impinges on a metallic grating of thickness l, slit aperture w and period d with one side of the grating closed by a back mirror.

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zero-th, are evanescent. The metallic grating can be viewed as an array of sub-wavelength, 1D, metal/dielectric/metal waveguides which support the fundamental TM mode.[13] Under these conditions, the grating behaves as an effective metamaterial slab whose constitutive parameters, including spatial dispersion effects, may be written as follows:[14]

$$Z_{eff} = \sqrt{\frac{\mu_{eff}^{(s)}}{\varepsilon_{eff}^{(s)}}}\sqrt{1 - \frac{\sin^2\vartheta}{\varepsilon_{eff}^{(s)}\mu_{eff}^{(s)}}} = \frac{1}{d}\int_{-d/2}^{d/2}\frac{E_x^{(WG)}(x)}{H^{(WG)}(x)}dx = \frac{w}{d}\frac{\beta_s}{k_0\varepsilon_w}, \tag{1}$$

where Z_{eff} is the effective impedance, ϑ is the angle of the incident/emitted radiation, $\varepsilon_{eff}^{(s)}$ and $\mu_{eff}^{(s)}$ are the effective electric permittivity and magnetic permeability of the metamaterial slab, $E_x^{(WG)}$ and $H^{(WG)}$ are the transverse components of the electric and magnetic fields of the fundamental TM mode of a sub-wavelength metal/dielectric/metal slit of core thickness w, ε_w is the dielectric constant of the material filling the slits ($\varepsilon_w = 1$ in our case), k_0 is the vacuum wave-vector, and β_s is the wave-vector of the fundamental TM guided mode. We suppose here negligible field penetration inside the metal, although we fully take into account its finite conductivity in the dispersion of β_s (which is therefore a complex number). As we will see in the following, the finite conductivity of the metal is fundamental for the physical mechanism we describe. By combining this equation with the requirement of momentum conservation for a homogeneous slab,

$$\varepsilon_{eff}^{(s)}\mu_{eff}^{(s)}k_0^2 = k_0^2\sin^2\vartheta + \beta_s^2, \tag{2}$$

we find the explicit expressions of the effective medium parameters:[14,15]

$$\varepsilon_{eff}^{(s)} = \varepsilon_w d/w, \quad \mu_{eff}^{(s)} = w(\beta_s^2/k_0^2 + \sin^2\vartheta)/d. \tag{3}$$

The homogenization procedure we have followed has been validated in previous works.[14,15]

Now, by using the usual boundary conditions at the input surface of our homogenized slab and the condition for an ideal mirror at the output surface we obtain after straightforward calculations the following formula for the reflectance:

$$R = \left|\frac{i\sin(\beta_S l) + \frac{d}{w}\frac{k_0\varepsilon_w\cos\theta}{\beta_S}\cos(\beta_S l)}{-i\sin(\beta_S l) + \frac{d}{w}\frac{k_0\varepsilon_w\cos\theta}{\beta_S}\cos(\beta_S l)}\right|^2. \tag{4}$$

From Eq. (4), we deduce that if a region of perfect absorption exists, it must satisfy the following equation:

$$\tan(\beta_S l) = -i\frac{d}{w}\frac{k_0\varepsilon_w\cos\theta}{\beta_S}. \tag{5}$$

It is noted that Eq. (5) *admits solutions only if* β_s *is a complex number*; i.e., we must explicitly take into account the finite conductivity of the metal when calculating the wave-number of the fundamental guided mode inside the slits. This is of course expected, because a real wave number (no loss in the metal) would necessarily lead to unitary reflection.

In Fig. 2(a), the absorption A is calculated according to our analytical model (4) at normal incidence ($\vartheta = 0$) in the (l, w) plane for an Al grating with period $d = 2.5\,\mu$m at $\lambda = 10\,\mu$m. We model the dispersion properties of Al by a Drude model whose parameters (plasma frequency and damping) are chosen according to experimental data.[16] Bands of coherent absorption/emissivity are clearly visible in the figure, with absorption that reaches 100%. The black spot on the A1 band indicates the particular parameters of the structure we analyze in Fig. 2(b). To test the validity of our theory, Fig. 2(b) shows also the emissivity calculated by full-wave simulations using the Fourier modal method (FMM).[17] The agreement between theory and numerical simulations is excellent. The small shift in the emissivity peak which is at 10.45 μm instead of the 10 μm predicted by the model is due to the fact that in our analytical model we neglect the evanescent fields corresponding to higher diffraction orders, which are fully taken into account in the numerical calculations.

We now analyze the coherence length of thermal radiation emitted by the grating at temperature T, and compare it with the emission of an ideal black body at the same temperature. According to the Wiener-Khinchin theorem,[18] the degree of temporal coherence for the radiation emitted by a thermal source can be calculated as[19]

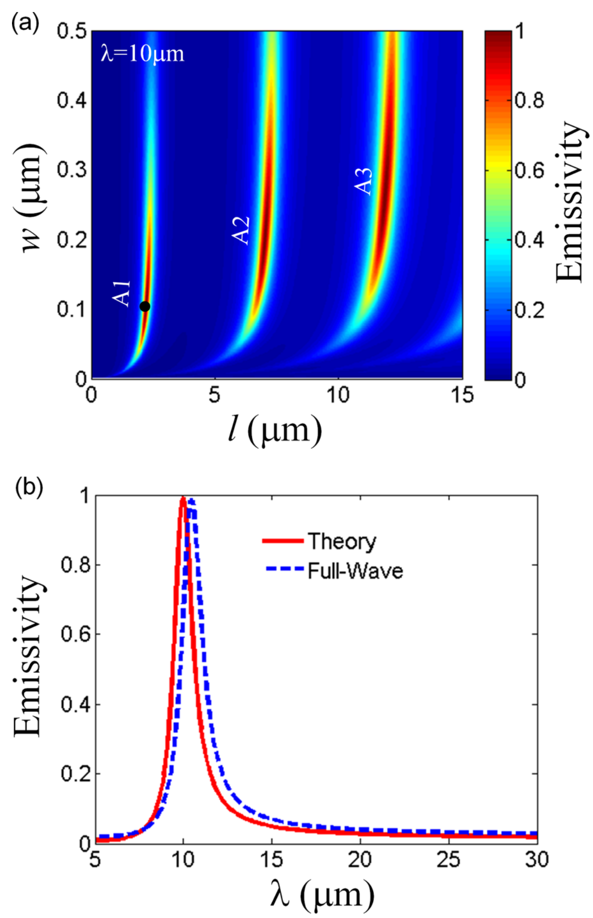

FIG. 2. (a) Emissivity at normal incidence for $\lambda = 10\ \mu$m in the (l, w) plane for an Al grating with $d = 2.5\ \mu$m. (b) Emissivity vs. λ for an Al grating with $l = 2.2\ \mu$m, $d = 2.5\ \mu$m, and slit aperture $w = 100$ nm: theory (continuous line), full-wave numerical simulation by the FMM (dashed line).

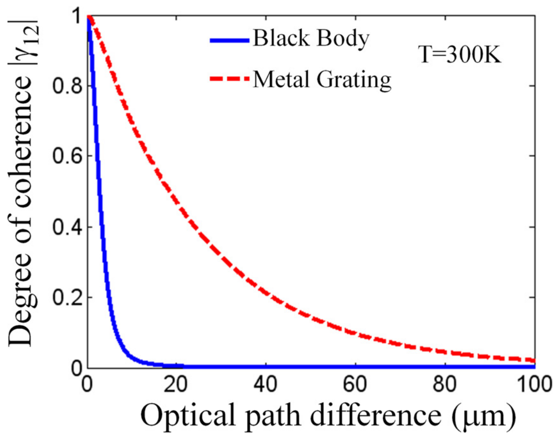

FIG. 3. Degree of coherence for a blackbody (continuous line) and the metal grating under analysis (dashed line) for a temperature $T = 300\,\mathrm{K}$, as function of the optical path difference $c\tau$, where c is the speed of light in vacuum.

$$\gamma_{1,2}(\tau) = \int_0^\infty A(\nu) g_{bb}(\nu) e^{-2\pi i \nu t} d\nu, \quad (6)$$

where $A(\nu)$ is the absorption/emissivity of the thermal source and $g_{bb}(\nu) \sim \nu^3 / \left[\exp\left(\frac{h\nu}{K_B T}\right) - 1\right]$ is the Planck distribution of the black body with K_B the Boltzmann constant, h is the Planck constant, and T is the temperature of the source. In Fig. 3, we compare the degree of coherence of the radiation emitted along the normal for the Al grating described in Fig. 2(b) at the temperature $T = 300\,\mathrm{K}$ and compare it with the one of a black body at the same temperature. The temperature $T = 300\,\mathrm{K}$ corresponds to a peak of Planck distribution approximately at $\lambda = 10\,\mu\mathrm{m}$, which is the absorption resonance of the grating, as shown in Fig. 2(b).

The coherence length (l_c) of the radiation emitted by the grating is one order of magnitude larger than the one of a black body. In particular, we have in this case $l_c \sim 70\,\mu\mathrm{m}$ for the metallic grating, while $l_c \sim 7\,\mu\mathrm{m}$ for the black body (the coherence length has been estimated for a value of the degree of coherence of 0.1, as it usually done[19]). We note, however, that the coherent emission still remains confined in a region close to the metal grating.

In Fig. 4(a), we show the emissivity in the plane (λ, ϑ) and in Fig. 4(b) we show the polar emissivity plot for $\lambda = 10\,\mu\mathrm{m}$. The emissivity pattern is fairly insensitive to the angle, thus achieving wide-angle coherent emission.

It is also instructive to briefly discuss the spatial coherence properties of our source. A detailed analysis of the spatial coherence for the radiation emitted by thermal sources is beyond the scope of the present work; the interested reader may consult, for example, Ref. 20. Roughly speaking, the transverse coherence length of the source can be estimated as $l_\perp \approx 2\pi/\Delta k_x$, where Δk_x is the spatial frequency bandwidth, in our case $k_x = k_0 \cos\vartheta$. At the resonant condition ($\lambda = 10\,\mu\mathrm{m}$), it is seen from Fig. 4(a) that the spatial frequency bandwidth spans basically the entire cone of light ($\Delta k_x \approx k_0$), giving therefore $l_\perp \approx \lambda$ in agreement with spatial coherence length calculated for a blackbody.[21] In other words, our source is indeed temporally coherent in contrast with a blackbody source, but nevertheless spatially incoherent in the far field similar to a blackbody source. Note, however, that, although the emission from our zero order grating is spatially incoherent in the far field, the near field emission is expected to be spatially coherent.[20,21]

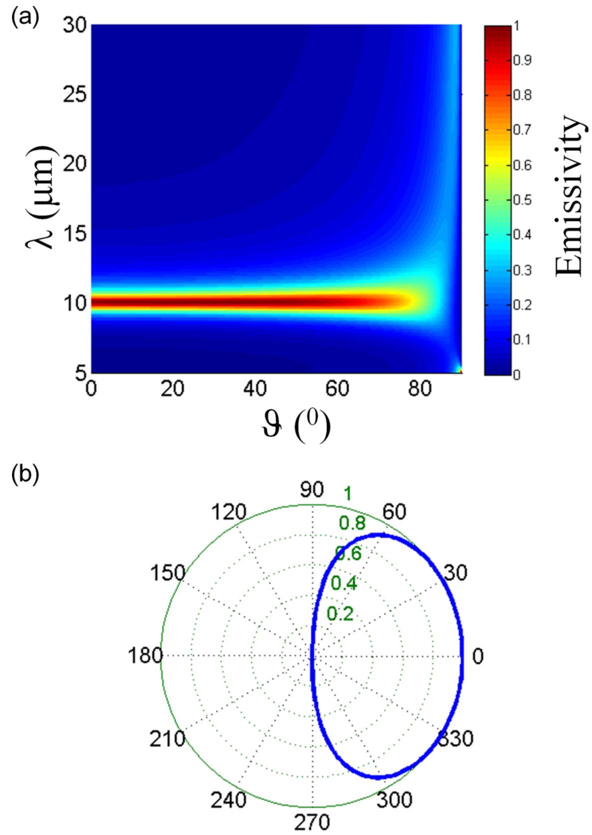

FIG. 4. (a) Angular emissivity for the metal grating described in Fig. 2(b) in the plane (λ, ϑ). (b) Polar plot of the emissivity at $\lambda = 10\,\mu\mathrm{m}$.

In conclusion, we have demonstrated that a thick metallic grating with extremely narrow slits can behave as an efficient, wide-angle, coherent source of thermal radiation in the mid infrared. We believe that the mechanism highlighted in this letter may be used, for example, in thermo-photovoltaic energy conversion devices,[22] for which coherent and wide-angle infrared sources could greatly improve the efficiency of the devices. We also expect that similar results may be extended to THz or even GHz frequencies by properly choosing the grating parameters. Finally, it is relevant to stress that, while in this work we have used an Al grating, similar results may be obtained with other metals like Au or Ag.

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