Broadband selective thermal emitters and absorbers based on Brewster plasmonic funnelling

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Abstract

In this paper, we show the possibility to realize a plasmonic metallic grating with ultra-broadband selective thermal emission at IR and visible frequencies. By reciprocity, the proposed structure can also demonstrate broadband perfect absorption confined to a narrow angular beamwidth. With few modifications of the device dimensions, the plasmonic grating can also operate as a broadband omnidirectional absorber for visible, IR and terahertz radiation. The physical mechanisms at the basis of these phenomena lay on the recently introduced concept of plasmonic Brewster transmission, which, here, is combined with adiabatic metallic tapering to achieve strong localization and absorption of the electromagnetic energy. We believe that the proposed devices may potentially lead to the design of more efficient energy harvesting structures and novel directional thermal emitters.

1. Introduction

The Planck's law of blackbody radiation [1] describes a hypothetical object, which can absorb all the energy impinging on it from every incident angle and can re-emit the energy depending on its temperature. However, no practical object exists to behave in this ideal way and the absorption/emission is always limited by the material properties. Note that emission and absorption are reciprocal properties, when the device is in thermodynamic equilibrium, as it is stated by the Kirchhoff's law of thermal radiation [2]. The absorption takes equal values to emissivity and the structure's total emission can be, in general, calculated by multiplying the emissivity with the blackbody radiation spectrum.

Recently, increased research efforts have been dedicated to tame and manipulate the blackbody radiation [3], [4] and absorption [5], [6] using plasmonic gratings. Nevertheless, these designs were inherently narrowband because they are based on highly resonant mechanisms, such as surface plasmons. Here, we propose a different, completely nonresonant effect to achieve ultra-broadband emission/absorption, mimicking the behaviour of a perfect blackbody. Moreover, we will demonstrate a way to manipulate the broadband thermal emission in order to be confined within a particular narrow beamwidth in space, i.e. coherent selective thermal emission. To achieve these interesting properties, the concept of plasmonic Brewster angle broadband transmission [7]-[8] will be combined with adiabatic plasmonic taper waveguides [9].

2. Theoretical analysis of the plasmonic grating

The one-dimensional (1D) plasmonic grating design is reported in Fig. 1(a). The proposed device is built by narrow slits with width w carved on a tungsten (*W*) slab with period $d < 0.5\lambda$, where λ is the wavelength of the surrounding medium (free space). The structure is infinite along the *y*-axis and has length l towards the *z*-axis, similar to the grating proposed to realize Brewster angle transmission [7]-[8]. However, here, the grating is terminated with an adiabatic plasmonic taper waveguide with length l_{tap} to efficiently localize the input energy. This feature allows additional localization of the incident radiation and, as a result, efficient absorption/emission over a broad range of frequencies. Finally, the taper is terminated with a tungsten block to achieve zero transmission coefficient $(T = 0)$ of the structure. As a result, the emissivity E or, equally, absorption A can be calculated by the simple formula: $E = A = 1 - R - T = 1 - R$, where R and T is the reflection and transmission coefficients, respectively.

The tungsten slab of length l follows a relative Drude permittivity dispersion with parameters $\varepsilon_W = 1 - f_p^2 / \left[f \left(f + i\gamma \right) \right]$, $f_p = 1448$ THz, $\gamma = 13$ THz [6]. The taper has length l_{tap} and is also made of *W*, which follows a similar Drude model but with increased collision frequency $\gamma_{tap} = 130$ to take into account the temperature effects [6] and the reduced slit width. Alternative designs are also viable, and the concept may be extended to 2-D periodicities, becoming independent of the polarization plane.

The grating will exhibit near-zero reflection over a broad range of frequencies at and around the plasmonic Brewster angle, which is given in general form as [8]:

$$\cos\theta_B = \frac{\beta_s w}{\varepsilon_S k_0 d}, \tag{1}$$

where ε_S is the permittivity of the material loaded inside the slits of the structure. We have shown in [8] that the smaller is the ratio of the dimensions w/d or higher the loaded permittivity ε_S, the sharper angular beamwidth is found. In addition, the phenomenon is based on impedance matching, and therefore it is inherently nonresonant and nondispersive (apart from the natural dispersion of the plasmonic slits), and it does not depend on whether the slit absorbs energy, rather than transmits it. This is drastically different from any other extraordinary transmission phenomenon, which would be severely dampened by the presence of losses. These fascinating properties will be utilized here to design an ultra-broadband selective thermal emitter working at IR frequencies.

3. Results and discussion

The normalized omnidirectional thermal emission distribution of the ideal blackbody at T=1500 K is plotted in Fig. 1(b). Here, two designs of plasmonic thermal emitters are proposed with structures similar to Fig. 1(a). The absorption/emissivity of them is computed by numerical simulations based on the finite-integration method [10]. The devices' dimensions are: w=6nm, d=192nm, ε_s=1 and w=6nm, d=96nm, ε_s=2.25, and their thermal emission distributions at temperatures T=1500 K are shown in Figs. 1(c), (d), respectively. The emission for both cases is normalized to the maximum value of the blackbody thermal radiation. Note that the melting point of tungsten is T=3695 K, much higher than the current used temperatures of T=1500 K.

Broadband thermal emission, with essentially the same bandwidth of a black body, for both designs is clearly obtained in Figs. 1(c), (d), which is confined in a narrow angle range, i.e. perfect selective thermal emission. The directive IR radiation is confined around the plasmonic Brewster angle given by Eq. 1, which is approximately $\theta_B = 84^o$ for both emitters. Moreover, the emitted radiation is coherent, because it is produced by subwavelength plasmonic apertures, as it was demonstrated experimentally in [3]. Hence, perfect coherent selective thermal emitters were proposed with two similar plasmonic grating designs, which may potentially lead to simpler and more robust designs of directional light sources at terahertz and IR. In addition, by increasing the slit width to period ratio w/d perfect absorption/emission can be achieved even for broader angular range, leading to omnidirectional perfect absorber designs at optical, IR and terahertz frequencies. We will discuss these possibilities during the conference.

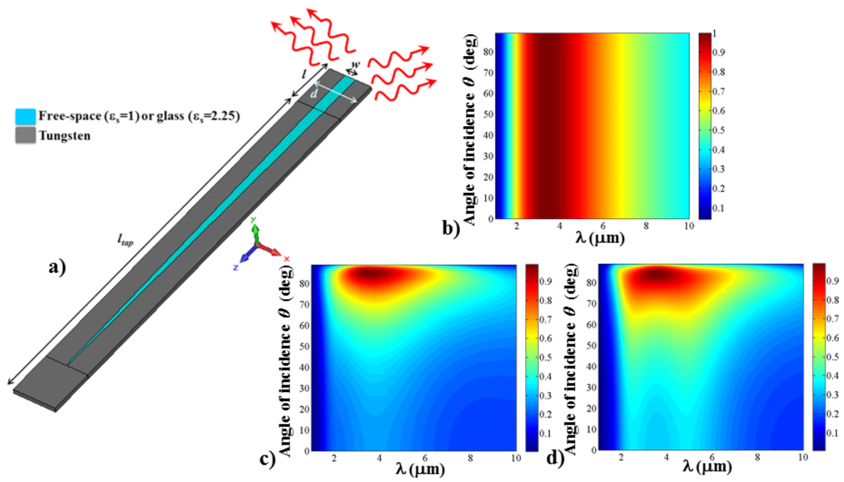

Fig. 1: a) Geometry of the unit cell of a broadband selective plasmonic thermal emitter. b) Normalized emission of the black body at T = 1500 K. c) Emission of a directional plasmonic emitter with dimensions w=6nm, d=192nm, ε_s=1 at T = 1500 K. d) w=6nm, d=96nm, ε_s=2.25 at T = 1500 K. Both emissions in (c), (d) are normalized to the maximum of the black body radiation.

4. Conclusions

Two different 1D plasmonic grating designs were demonstrated to efficiently tame the blackbody thermal radiation. Novel selective IR thermal sources exhibiting broadband and coherent emission can be built based on these structures. The physical mechanism of the proposed concept is based on the plasmonic Brewster ultra-broadband transmission combined with the properties of tapered plasmonic waveguides. With further optimization of the structure's dimensions, these concepts may also realize omnidirectional ultra-broadband absoption at visible and IR frequencies. We may also extend this idea to 2D plasmonic gratings, providing even more interesting applications, such as efficient energy harvesting devices, broadband selective thermal emitters and novel bolometer designs.

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