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Metallic metasurface as a directional and monochromatic thermal emitter

Francois Marquier^{*a}, Daniele Costantini^{a,d}, Anthony Lefebvre^{b,c}, Anne-Lise Coutrot^a, Ioana Moldovan-Doyen^a, Jean-Paul Hugonin^a, Salim Boutami^{b,c}, Henri Benisty^a and Jean-Jacques Greffet^a
^aLaboratoire Charles Fabry, Institut d'Optique, CNRS–Univ Paris-Sud, Campus Polytechnique, RD128, 91127 Palaiseau Cedex, France; ^bUniv. Grenoble Alpes F-38000 Grenoble, France; ^cCEA, LETI, MINATEC Campus, F-38054 Grenoble, France; ^dPresent Address: Saint Gobain Recherche, 39 quai L. Lefranc, 93303 Aubervilliers Cedex, France

ABSTRACT

Mid to far infrared is an important wavelength band for detection of substances. Incandescent sources are often used in infrared spectroscopy because they are simple and cost effective. They are however broadband and quasi isotropic. As a result, the total efficiency in a detection system is very poor. Yet it has been shown recently that thermal emission can be designed to be directional and/or monochromatic. To do so amounts to shape the emissivity. Any real thermal source is characterized by its emissivity, which gives the specific intensity of the source compared to the blackbody at the same temperature. The emissivity depends on the wavelength and the direction of emission and is related to the whole structure of the source (materials, geometry below the wavelength-scale...). Emissivity appears as a directional and chromatic filter for the blackbody radiation. Playing with materials and structure resonances, the emissivity can be designed to optimize the properties of an incandescent source. We will see how it is possible to optimize a plasmonic metasurface acting as an incandescent source, to make it directional and quasi monochromatic at a chosen wavelength. We will target a CO₂ detection application to illustrate this topic.

Keywords: Thermal radiation, emissivity, plasmonics, metasurface, MIM cavity, gratings

1. INTRODUCTION

Wavelengths beyond the visible and near-infrared range are pervading many applications notably for low-cost devices. For instance in absorption spectroscopy, many molecules have absorption lines in the mid and far infrared, related to vibrational and rotational modes of the molecular bonds. For the same reason, atmosphere is opaque for most of wavelengths. However it has transparency regions between 3 and 4 micrometers and between 8 and 12 micrometers in wavelength, which are interesting in many detection applications. Consequently, there is a strong demand for efficient and cheap light sources in the mid and far infrared. Simple semiconductor devices, as light emitting diodes, are not available in this frequency range. This is mainly due to the poor efficiency of the spontaneous emission process compared to very efficient non-radiative processes for these long wavelengths. To overcome this issue, sophisticated semiconducting devices have been developed: Quantum cascade lasers (QCLs) are comparatively to black-body very bright sources that can operate in a wide range of wavelength, even at room temperature in the mid infrared¹. These sources are directional and monochromatic, and slightly tunable around their average emission wavelength. However their threshold makes them power consumptive and they are also very expensive due to the epitaxial growth technique used to fabricate them. Incandescent sources are another kind of available sources in the infrared. They are cheaper but much less bright because they are isotropic as well as broadband, and thus inefficient for narrow band uses. Nevertheless, the landscape is changing and since the very end of the 20th century, many works have reported an increasing degree of control of the thermal emission spectrum of surfaces²⁻¹⁷ while spatial coherence of incandescent sources has also been demonstrated¹⁷⁻²¹. A 2012 study from Noda's group, dealing with a multi-quantum-well structure, has shown for the first time a device combining both properties of directionality and quasi-monochromaticity²². It is worth noting that the reduction of the number of radiative channels to release the thermal energy from the source will

allow to increase the overall efficiency of the device. Indeed, less power is needed to heat the sample at a given temperature.

In the next section, we will present the tools of interest to design and shape the emission from an incandescent source. After substantiating the concept of emissivity, we will show examples of structures optimized to have spatial or temporal coherent thermal emission. We will focus our efforts on an incandescent source that could be useful in CO₂ detection applications, hence emitting in a narrow band of wavelength around the CO₂ absorption lines (about 4.25 μm) and predominantly in a rather narrow angular aperture (around 25°) adapted to cheaper optics.

2. EMISSIVITY TO TAMM THE BLACKBODY RADIATION

The emission of a source at given temperature T , wavelength λ , and direction \mathbf{u} is characterized by the spectral radiance $L_\lambda(\mathbf{u}, T)$. The blackbody spectral radiance $L_\lambda^0(T)$ is well known, and depends only on the temperature. It gives the maximum power that can be emitted per surface, wavelength and solid angle units. The spectral radiance of a real thermal source is then described using the emissivity $\varepsilon(\lambda, \mathbf{u})$: $L_\lambda(\mathbf{u}, T) = \varepsilon(\lambda, \mathbf{u}) \times L_\lambda^0(T)$, as illustrated in Fig.1.

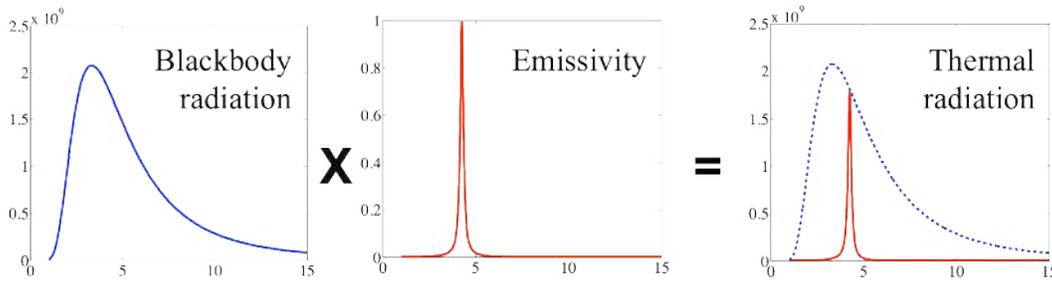


Figure 1. Illustration of the concept of emissivity in the wavelength domain. Compared to the case of a black-body at a given temperature (blue curve on the left, here given at a temperature of 600°C as a function of the wavelength in micrometers), the radiance from a real thermal source is given by the product of this blackbody radiance by the emissivity (Red curve in the middle), which is a function of the wavelength and (not shown) the direction of emission. When the emissivity equals unity, the radiance of the source is maximal.

For a given temperature, the emissivity contains the whole information on how the thermal source can emit. This coefficient depends on the wavelength as well as on the direction of emission. It is important to notice that the emissivity is not an intrinsic property of materials, but is strongly related to the geometry of the structure. The quickest way to grasp this is to remember that throughout all the thermodynamic demonstrations on black-body radiation, emission and absorption are reciprocal. That absorption can depend on the local (subwavelength) arrangement of materials is intuitive. The same indeed holds for emission through emissivity. It is hence possible to design devices whose emissivity allows the radiation in controlled directions and wavelengths. Emissivity acts as a filter of the blackbody radiation. From a computational point of view, optimization of structures is conveniently achieved using also Kirchhoff's law, since, it states in more detail that the emissivity for given direction and wavelength equals to the absorptivity at the same wavelength and for an incident plane wave illuminating the structure from the same direction²³. A directional and/or spectrally resonant absorption is then associated to a resonant emissivity. This concept has been exploited in a wide range of structures²⁻²².

3. SPATIAL AND TEMPORAL COHERENCE OF A THERMAL SOURCE

Let us first present two examples of incandescent sources showing coherence properties.

Spatial coherence is related to the fact that two separated dipoles of the source are (at least partially) correlated so that there is a given phase relation between them. As a result, the emission pattern shows constructive and destructive interferences, leading to an increase of the directionality of the source. To illustrate this concept, let us first take the example of a material which can support waves confined to the surface in the form of plasmon-polaritons or,

alternatively, surface phonon-polaritons²⁴. Consider first a plane interface between this material and a free space. When a surface wave exists on this interface, the in-plane component of its wave vector is larger than the free-space wave vector modulus, so that the wave is confined to the interface. It has been known for years that such a surface wave can be coupled to a propagative wave using a gentle periodic modification of the interface, but the fact that it would deeply affect the emissivity was not given much attention until recently. The emissivity of a relatively shallow tungsten lamellar grating¹⁸ is depicted in Fig.2 for two different wavelengths λ around 4 μm . The very sharp peaks in the diagram show that phase matching condition between thermally excited surface plasmons on the tungsten interface and propagating waves can lead to an extremely directional emissivity pattern. A different wavelength giving a different wave-vector in-plane component for the surface wave, the phase matching condition then results in a different direction of emission. Moreover, it has been demonstrated that the angular width of the peaks is inversely proportional to the propagation length of the surface wave²⁵. In the case of such a narrow width, it means that dipoles at locations on the surface as far as many wavelengths ($L \gg \lambda$) are correlated through the surface wave, exhibiting spatial coherence for the incandescent source.

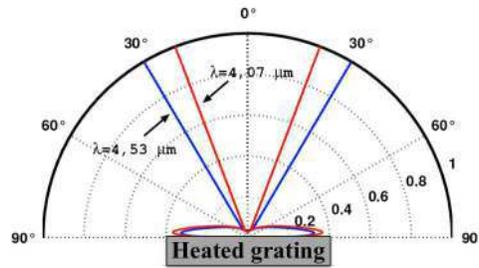


Figure 2. Emissivity of a tungsten lamellar grating. Period $p = 3 \mu\text{m}$, filling factor $F = 0.5$ and height of the lines $h = 125 \text{ nm}$. The emissivity angular diagram is calculated for two different indicated wavelengths and shows very directional peaks (from [18]).

Temporal coherence is related to narrow spectral peaks in the emission of the structure. According to Kirchhoff's law, it corresponds to a spectrally resonant absorption and a lot of examples are found in the literature²⁻¹⁷. Amongst them, resonant nanoantennas have demonstrated amazing results. The absorption cross-section of these antennas is indeed spectrally dependent on the shape and geometrical features of the antennas. For given shapes it has been confirmed that changes in the nanoantenna dimensions (thickness, width...) lead to substantial wavelength shifts in the emissivity spectrum^{14,15}. It is thus established that thermal sources can exhibit temporal coherence. These works pave the way to fully engineer the spectrum of thermal sources. Notably, the antenna attain a given wavelength by shape design, whereas a material-dependent absorption resonance most often cannot be tuned. However, the examples discussed above dealt with antennas much smaller than the wavelength, and which hence cannot present directional emission pattern due to the diffraction limit in the far-field. We will show now an example of a thermal source that can be both directional and quasi-monochromatic.

4. METASURFACE FOR DIRECTIONAL AND QUASI MONOCHROMATIC THERMAL EMISSION

To the best of our knowledge, the first demonstration of a thermal source featuring both directionality and monochromaticity has been reported in 2012²². In this paper however, the basic structure is a stack of more than 60 quantum wells, grown by epitaxy, and we can wonder whether it is possible to deal with simpler structures to reach similar spectral and directional properties. We propose here to achieve this goal with a very simple metasurface²⁶⁻³², consisting on a periodic array of metallic squares deposited on an homogeneous dielectric layer that lie on a metallic substrate. This structure forms a metal-insulator-metal (MIM) cavity and it is known to support in the thin gap between the two metal pieces a plasmonic mode, whose wavelength depends on the cavity geometry (thickness and in-plane boundaries). It is also known as a patch antenna. As for the directional design, we play with the periodicity: we manage to narrow the angular width of the emission by allowing new radiative channels in those angles where emission is not desirable, because these new channels can only decrease the absorption. The aim of the device is to demonstrate an

incandescent source at the CO₂ absorption wavelength (4.25 μm), which emits in a controlled solid angle, in order to build an efficient CO₂ detection cell, e.g. for portable or long-life applications.

4.1 The patch antenna as a monochromatic resonator

A patch antenna consists of a thin metallic patch (often a disk or a square) separated from a metallic ground plane by a thin insulating dielectric (hence also called MIM). This kind of geometry has already been used in previous papers¹⁵ to show monochromatic thermal emission. It is known that the geometrical parameters will give the resonant-absorption wavelength. For the proof of concept, we choose to perform calculation on a gold substrate surrounded by a silicon nitride (SiN) layer. We consider a periodic array of 100 nm-thick gold squares on top of this dielectric layer. The period is 3 μm and the wavelength of the normal incident plane wave is 4.25 μm. Fig.3 shows the result of a numerical computation in which the thickness of the SiN layer as well as the side of the gold squares are scanned. We used the dielectric constants given by Palik in the calculations³³. Here, 100% absorption occurs for L = 900 nm and h = 120 nm at the chosen wavelength. This absorption/emission resonance is nearly 200 nm-wide, that is $\frac{\Delta\lambda}{\lambda} \approx 5\%$. Even if the calculation has been performed for a periodic array of patches, it is worth noting that this resonance is due to a resonant absorption cross-section of the single patch antenna at the considered wavelength. That also means that, for a *single* antenna, this strong absorption must occur for a wide range of angles of the incident plane wave. The next subsection is devoted to the angular design of the emission, leveraging the specific physics of the array.

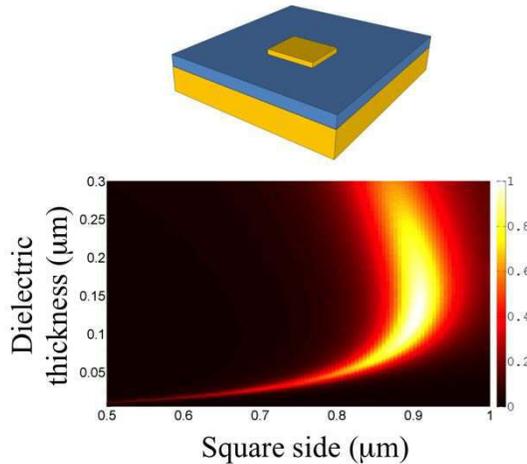


Figure 3. Top: sketch of the considered patch antenna. A dielectric whose thickness is controlled is deposited on a metallic substrate. On the thin dielectric layer, a metallic square acts as a nanoantenna. Resonant absorption can occur from this structure for a given set of parameters. Bottom: absorption of a plane wave at vertical incidence by a periodic array of gold squares on a SiN layer deposited on a gold substrate. The absorption is plotted as a function of the square side L and the SiN thickness h. 100% absorption occurs for L = 900 nm and h = 120 nm (with substantial margin). This resonant absorption is due to the geometry of the single gold patch antenna.

4.2 Role of the periodic structure in the directional emission

Let us focus on the emission pattern of the structure. Fig.4 (b) shows the calculated absorption for different frequencies and in-plane component $k_{//}$ of the wave vector of the impinging wave (which is related to its incidence angle by $k_{//} = \frac{\omega}{c} \sin \theta$).

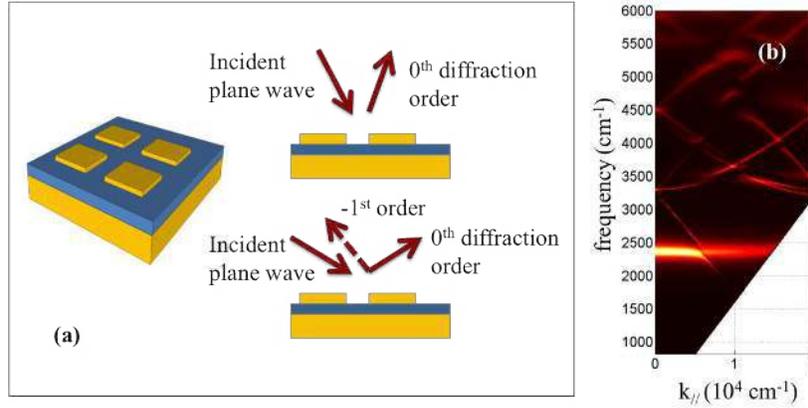


Figure 4. (a) Directional features are obtained taking advantage of diffraction orders appearance beyond cut-off angles. For small $k_{//}$ values, a single specular order exists whereas for larger values other diffraction orders appear leading to additional radiative channels. The critical coupling (i.e. the attainment of a maximum close to 100% in Fig.3) is not fulfilled anymore, and the absorption decreases. (b) Calculated absorptivity as a function of the frequency and the incident $k_{//}$ vector. The absorptivity is averaged over the two polarizations. The simulated structure is characterized by the gold-square side $L = 900$ nm, dielectric thickness $h = 120$ nm and period $p = 3 \mu\text{m}$ of the array.

It is shown that the absorption resonance appears at $\omega = 2353 \text{ cm}^{-1}$ ($\lambda = 4.25 \mu\text{m}$). As seen in the previous section, this resonance is related to the single patch nanoantenna, so that the strong absorption for such an isolated device occurs for all incident wave vectors (angles). In the diagram, the line associated to diffraction $\omega = ck_{//} - \frac{\pi c}{p}$ (c the speed of light) cuts the resonance horizontal line in two parts. For small $k_{//}$, the absorption/emissivity is 100%. For larger angle of incidence, the absorption/emissivity drops. That remarkable trend can be interpreted using the sketch of Fig.4 (a). On the left of the "grating" line $\omega = ck_{//} - \frac{\pi c}{p}$, the grating period allows only the specular wave to be diffracted. The antenna has been chosen such as its absorption is resonant and thus the specular reflected wave actually vanishes. On the right of the "grating" line, on the other hand, the -1st diffraction order is allowed: the radiative losses of the patch antennas array are modified and the critical coupling condition is no longer fulfilled. The periodicity thus helps us to introduce a large degree of directionality in the emission pattern. The angular width is then essentially characterized by a half-cone angle $\theta = 24.6^\circ$. This angle could be decreased by increasing the period of the array.

5. CONCLUSION

We have presented some examples in which spatial and/or spectral coherence of incandescent sources is demonstrated: based on surface waves in the underlying structure, notably, a far-field with narrow chromatic and spatial extent is achieved. We have numerically characterized a MIM metasurface, which can exhibit directional and frequency selective thermal emission while being easy to fabricate. The emission of the metasurface can be easily tuned with geometrical parameters and the concept can be adapted to multichannel emission using various MIM cavities of different sizes. The control of the radiative properties of incandescent sources paves the way to cheap, efficient mid and far infrared sources notably for spectroscopically specific application in gas, fluid or material detection. It is worth noting that wall-plug efficiency could also be optimized considering properly designed hot membranes, in which convection and conduction losses have been highly reduced³⁴. Recent works also shows it is possible to use emissivity to reach fast control of thermal emission³⁵⁻³⁷.

6. ACKNOWLEDGEMENTS

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*francois.marquier@institutoptique.fr