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Revisiting thermal radiation in the near field

Le rayonnement thermique revisité en champ proche

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ABSTRACT

Thermal radiation is generally assumed to be both spatially and temporally incoherent. In this paper, we challenge this idea. It is possible to design incandescent sources that are directional and spectrally selective by taking advantage of surface waves. We also report the discovery of the enhancement by several orders of magnitude of the energy density close to an interface at a particular frequency as well as the enhancement of the radiative flux between two interfaces when surface phonon polaritons can be excited. These results lead to the design of a novel class of infrared incandescent sources with potential applications in spectroscopy and thermophotovoltaic energy conversion.

RÉSUMÉ

Il est généralement admis que le rayonnement thermique est spatialement et temporellement incohérent. Nous montrons ici qu'en présence d'ondes de surface, il faut remettre en cause cette idée. Il est possible de concevoir des sources incandescentes qui sont directionnelles et spectralement sélectives. Nous décrivons également la découverte de l'exaltation de plusieurs ordres de grandeur de la densité d'énergie près d'une interface à une fréquence particulière ainsi que l'exaltation du flux radiatif échangé entre deux surfaces lorsque des ondes de surface existent. Ces résultats permettent d'envisager une nouvelle génération de sources incandescentes avec des applications possibles à la spectroscopie et à la conversion d'énergie par effet thermophotovoltaïque.

1. Introduction

Blackbody radiation is a topic that has been extensively studied at the beginning of the twentieth century [1,2]. It played an important role in the development of quantum physics with the pioneering work of Planck [1]. It also had many applications with the development of lighting with incandescent light sources. After these developments, a number of features have been attributed to thermal sources: light produced by thermal sources has been considered to be both

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spatially and temporally incoherent. Energy transfer mediated by radiation, i.e. radiative heat transfer, is bounded by the value of the blackbody flux density given by σT^4 where σ is the Stefan–Boltzmann constant. In the last twenty years, with the advent of nanophotonics, this old topic has been revisited and a new vision has emerged. It has been recognised that incandescent sources could produce narrow beams and that the emitted spectrum could be tailored at will. In other words, it has been recognised that thermal sources can be spatially and temporally partially coherent, particularly when surface waves such as surface plasmons or surface phonon polaritons can be excited. It has also been discovered that the presence of surface waves modifies drastically the blackbody radiation in the near field, namely, at a distance from the source smaller than $\lambda/2\pi$. The energy density can be increased by several orders of magnitude and becomes quasimonochromatic for some materials at distances in the order of 100 nm. As a consequence, the radiative heat flux between two surfaces can be increased by orders of magnitude as the gap distance enters the nanoscale regime. All these effects pave the way to novel applications such as the design of thermal sources with unprecedented new properties or thermophotovoltaic electricity generation. These properties can be analysed in the framework of fluctuational electrodynamics that was introduced by Rytov to discuss thermally generated radiowaves [3,4]. An account of recent work in the infrared range can be found in refs. [5–8].

2. Spatially coherent thermal radiation

The title of this section would have been very provocative twenty years ago. Thermal radiation was taken as the typical example of incoherent radiation. Obviously, blackbody radiation in a cavity much larger than the wavelength is incoherent. However, thermal light emitted by a surface can become partially spatially and temporally coherent. Before summarising how this unexpected property was discovered, let us briefly summarise why thermal light is expected to be incoherent. If we consider the light emitted by an interface separating an absorbing medium from vacuum, it is known that the emitted light can be characterised by a specific intensity or radiance. This is given by the product of the blackbody (equilibrium) radiance, which depends only on the material temperature and the emissivity of the material. The emissivity of a plane interface is given by $1-R$, where R is the intensity Fresnel reflection factor. Since the emissivity is smaller than 1, the emitted radiance is always smaller than the blackbody radiance. Since the emissivity is a smoothly varying function of angle and frequency, the emission is broadband and quasi isotropic. According to the Wiener–Kinchine theorem, which establishes that the power spectral density is the Fourier transform of the time correlation function, a broad spectrum means that the time correlation is very short and therefore that the field is incoherent. Conversely, a laser with a very narrow spectrum produces light with a long coherence time. Similarly, a laser can be very directional, while thermal radiation is quasi isotropic. This is also related by a Fourier transform to the spatial correlation function of the fields.

The above discussion based on the concept of emissivity is based on a purely phenomenological description. It is possible to gain further insight by analysing thermal radiation with an antenna point of view: electromagnetic fields are generated by time-dependent currents. With this point of view, the source of the thermally emitted electromagnetic fields is the current density due to the thermal random motion of charges (ions, electrons) in the material. This is the origin of the thermal radiation in an electrodynamic picture. This approach was already introduced by Lorentz in 1906 [2], but there was no correct statistical description of the current fluctuations available at that time. In order to actually compute the thermal fields, the random thermal currents need to be known. They are given by the fluctuation–dissipation theorem, which yields the following form for the correlation of the current density j [9]:

$$\langle j_n(\mathbf{r},\omega)\, j_m(\mathbf{r}',\omega')\rangle = 2\pi\,\delta(\omega+\omega')\delta(\mathbf{r}-\mathbf{r}')\delta_{nm}2\omega\epsilon_0\mathrm{Im}[\epsilon(\mathbf{r}',\omega)]\Theta[T,\omega] \tag{1}$$

where the brackets denote the ensemble average, ϵ is the permittivity, $\Theta[T,\omega] = \hbar\omega/[\exp(\hbar\omega/k_\mathrm{B}T)-1]$ and T is the temperature. This type of modelling of the thermal radiation was introduced by Rytov in order to analyse thermal radiation in radioelectricity [3]. The same formalism has been used by Lifshitz to study Casimir forces by real metals [10]. Note that the procedure that we have just outlined is a Langevin model. Indeed, computing the fluctuating electromagnetic fields by including in Maxwell equations a random source is similar to the introduction of a random force in Newton's equations to model the Brownian motion. It is interesting to note that the random currents are spatially delta-correlated. This is a consequence of the assumption of locality (no spatial dispersion) of the optical response. Hence, it seems reasonable to assume that close to the source, the radiated fields are spatially incoherent. This is the usual assumption in the statistical optics textbooks [11,12]. As a consequence, the fields emitted by different points of the source cannot interfere in the far field so that the thermal sources are expected to be quasi isotropic. This assumption is actually not valid in some cases, as we will see below.

2.1. *Questioning Kirchhoff law validity*

The investigations of coherence of thermal emission were triggered by the work of D. Maystre published in 1976. He predicted [13] the phenomenon of total absorption by a metallic sinusoidal grating. It was predicted that a grating ruled on a silver or a gold surface can absorb all the light incident at a specific angle for a particular frequency. This phenomenon was very surprising as a gold sinusoidal surface illuminated at 633 nm with a maximum slope of a few percents has a reflectivity that drops from over 0.97 (it is a mirror) out of resonance to less than 0.01 on resonance. Yet, it was confirmed

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