COHERENT EMISSION OF LIGHT BY THERMAL SOURCES

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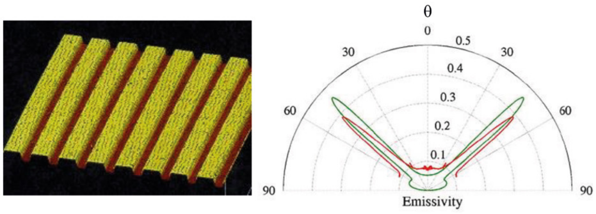

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While the light emitted by an incandescent body is generally quasi-isotropic, it was demonstrated in 2002 that a diffraction grating etched onto a silicon carbide (SiC) surface can exhibit highly directional emission, comparable to that of antennas operating in the radio domain. Directivity is the signature of the existence of spatial coherence of the field in the plane of the source, an unexpected property for a thermal source. This article describes the development of the ideas that led to this experiment and its current implications.

25 years ago "Coherent thermal emission" was an unexpected title as thermal radiation was usually taken as the typical example of incoherent light. In very simple terms, light with a narrow frequency spectrum is said to be temporally coherent and light with a narrow spatial frequency spectrum is said to be spatially coherent so that blackbody radiation has a low coherence whereas laser light is highly coherent. Nonetheless, it is now possible to engineer coherent light emission by tailoring hot bodies. Thermal metasurfaces consisting of hot nanostructured surfaces is today an active field of research and most features of the emission can be controlled including the angular emission pattern (spatial coherence), the emission spectrum (temporal coherence) and the polarization. A tutorial discussion can be found in ref. [1] and a recent rewiew [2] lists more than 500 references. The field was initiated in 1976 by the first experimental observation of a highly directional total absorption of visible light by a metallic grating [3]. Maystre and Hutley demonstrated that by ruling a shallow diffraction grating on a gold surface, a mirror could become totally absorbing for a particular angle and frequency. This highly directional absorption had been predicted theoretically and attributed to the resonant excitation of a surface plasmon. According to Kirchhoff's law derived in 1860 [4], emission is proportional to the absorptivity. Hence, if Kirchhoff law is valid, the thermal emission by a gold grating could be highly directional and behave as a coherent antenna. Hence, one had to conclude that either thermal emission can be coherent or that Kirchhoff's law is not valid, at least for gold gratings. As Kirchhoff's law had been derived in the framework of optical geometry which is not valid for gratings with periods on the order of the wavelength, it seemed reasonable to question Kirchhoff's law validity.

The experiment

The experiment that led to the observation of directional emission was triggered by Michel Olivier at CEA-Grenoble. He envisioned applications and proposed to use a grating ruled on a SiC sample. SiC is a material that supports surface phonon polaritons (SPhPs) which can mimick surface plasmons. When ruling a grating on the surface, an incident plane wave can be totally absorbed in the wavelength range 10-12 µm. Hence, thermal emission could be observed by increasing the temperature by only 100 or 200°C if Kirchhoff's law is applicable. As the angular position of the peak depends on the frequency, directional emission is only observed when detecting at a given frequency. The first design of the grating led to the fabrication of a grating that did not produce the expected directional peaks [5] neither in reflection nor in emission. This was due to the use of a perturbative model to design the surface. Total absorption is a non-perturbative resonant phenomenon that requires an accurate numerical simulation for the design and an accurate nanofabrication of the sample. We designed the surface profile in the team at Ecole Centrale. The team of Yong Chen did the fabrication of the samples at L2M/CNRS using optical lithography and reactive ion-etching. The measurements were made at CESTA/CEA by S. Mainguy in 2002 [6]. The reflectivity measurements displayed the expected total absorption as seen in Fig. 1. The sample was then installed on a heater and emission spectra were taken for different emission angles. As predicted by Kirchhoff's law, we observed highly directional emission by a hot body (see Fig. 1 lower panel). In this first experiment, the angular resolution was limited by the detection system. A second setup was later developed by F. Marquier to study in detail the measured coherence length and to improve the agreement with theory by accounting for the dependence of the refractive index on the temperature [7].

Discussion

At that point, it was clear that Kirchhoff law prediction was confirmed by the experiments. That result raised the question of the origin of the spatial coherence. It also suggested that Kirchhoff law could be derived without making the geometrical optics approximation. We managed to derive Kirchhoff's law beyond the geometrical optics approximation by using a wave equation framework [8]. We also

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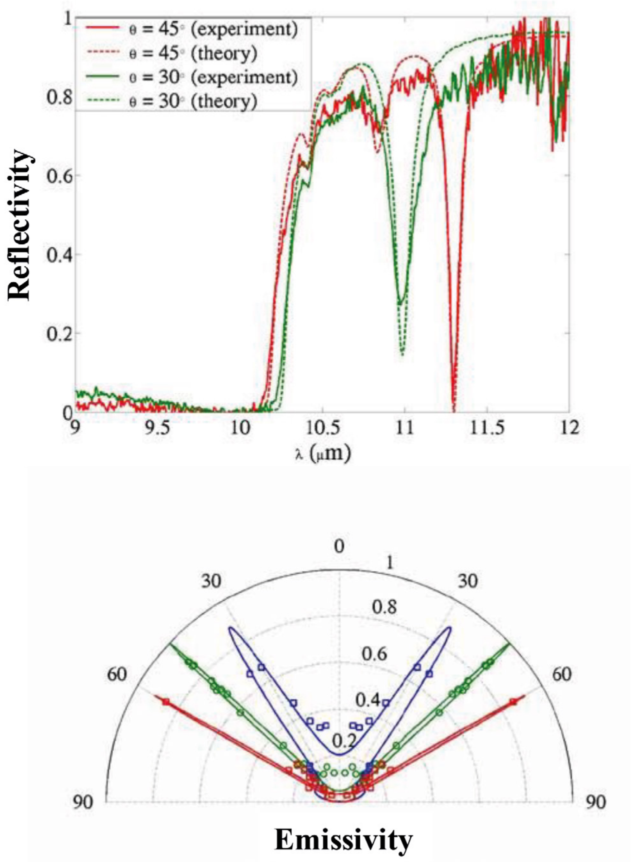

Figure 1. Upper panel: reflectivity of a grating ruled on a SiC sample. A total absorption peak is observed at 11.36 µm for a 45° incidence. Lower panel, emissivity measurement for three different wavelengths (blue: 11.04 µm, green: 11.86 µm, red: 11.36 µm). The experimental data are given by the circles, the theoretical results (solid line) are convoluted to account for the experimental angular resolution. The emissivity is given by the ratio of the emitted power by the power emitted by a blackbody at the same temperature. (reproduced from ref. [6]).

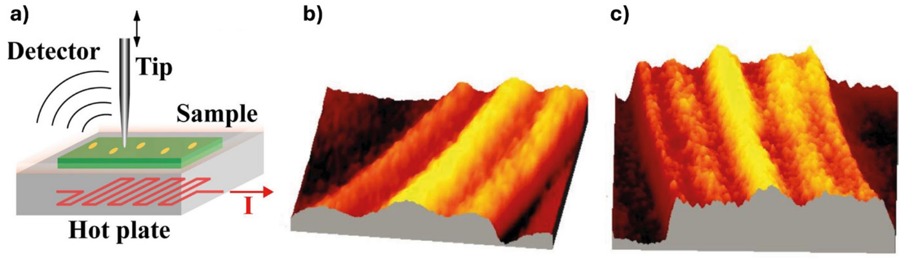

Figure 2. a) Schematic description of the scanning IR microscope. The sample consists of gold stripes deposited on a SiC sample. The sample is not illuminated but heated up to 170°C so that only thermal emission can be detected in the IR. A tip oscillates vertically above the hot sample. It scatters the thermal infrared near-field which is collected by a Cassegrain objective and sent to an IR detector, b) and c) cross section of the IR signal measured through a bandpass filter (centered at 10.9 µm, width of 1 µm) taken for stripe widths: 12 µm (b) and 25 µm (c). The fringe structure reproduces the local density of states. The fringe structure illustrates the spatial coherence of the thermally excited field when only a few modes are available due to the finite width of the stripe which is on the order of the wavelength. Reproduced from ref. [11].

found that another derivation of Kirchhoff law was already available in the framework of fluctuational electrodynamics [9]. This framework is extremely powerful and enables to compute the emitted field in the framework of Maxwell equations and statistical physics. It had been used to analyse Casimir forces and thermal fields in the microwave regime. We applied it to derive the correlation function of the electric field thermally emitted close to an interface separating a material from air. We found that when a surface wave propagates along the interface, a long-range correlation (i.e. spatial coherence) exists [10].

Since spatial coherence results from the excitation of a surface wave, it can only be measured directly in the near field. Near-field optical microscopy had just been introduced and enabled to measure directly the field of surface plasmons. However, the measurement of a correlation of the field measured at two different points was more challenging. To mitigate the experimental difficulty, we briefly attempted to measure the near-field correlation in the microwave regime at the interface between water and air as surface waves may propagate along this interface. K. Joulain did experiments in collaboration with Michel Gross at Ecole Normale but we could not observe the effect. It took some years before Y. de Wilde could directly observe fringes in the structure of a thermally emitted field [11] by a gold stripe with finite width using a near-field microscope as seen in Fig. 2.

The physical mechanism

To grasp the role of spatial coherence, we use a physical picture that emerges from the fluctuational electrodynamics framework. Each volume element of the emitting body contains random currents due the thermal motion of electrons and nuclei. These currents are spatially uncorrelated. If such a volume element is chosen much smaller than a wavelength, it can be described as a random dipole. The field emitted by the dipole can be represented as a sum of plane waves. If we consider that the emitting body is a half-space separating a medium from air, each plane wave emitted in the body may be reabsorbed before reaching the interface. However, if the volume element is close enough to the interface, the radiation may be transmitted (see Fig. 3 a). For a metal or SiC, the transmission factor is low and does not depend much on the angle of incidence so that the emission is low for all directions. A directional thermal source requires an interface whose transmission factor is low for all directions but one.

We now explain why a grating ruled on a SiC surface has this peculiar property. As discussed above, the emitted radiation is the sum of the intensities emitted by each volume element in the hot body. It turns out that a random

Figure 3. Sketch of the mechanism producing spatial coherence and directional emission. a) Thermal emission by a hot body. Each volume element (red disk) contains charges with random thermal motion. The corresponding current density emits light which is transmitted by the interface (red arrows). b) Thermal emission by a hot body sustaining a surface wave. In addition to the transmitted light, a surface wave (thick horizontal line) is excited. The dispersion relation of the surface wave is denoted $k_{sw}(\omega)$. The surface wave propagates along the interface and decays exponentially due to the losses in the material. As a consequence, the field is correlated over a distance limited by the surface wave decay length. c) Coherent thermal emission. When a grating with period d is ruled on the interface, the surface wave is diffracted in a direction θ given by the grating law $\omega/c \sin\theta = k_{sw}(\omega) - 2\pi/d$.

dipole close to the interface may also excite a surface wave whose wavevector $k_{sw}(\omega)$ is given by the dispersion relation at each frequency ω (see Fig. 3 b). The surface wave propagates over a typical decay length which is on the order of 100 µm before being absorbed. When ruling a grating on the interface, the different lines of the grating are coherently illuminated by the same surface wave which is thus diffracted in a well-defined direction given by the usual grating law (see Fig. 3 c). This is the mechanism that produces directional emission. In summary, the grating does not generate spatial coherence but reveals the existing spatial coherence of the field due to the excitation of a surface wave.

Applications and further developments

The experiment has proved that a source consisting of incoherent emitters can be turned into a directional source. It led to the understanding that Kirchhoff 's law validity is broader than initially thought so that the tool box of nanophotonics can be used to tailor thermal emission. This idea has been further developed to explore a large variety of thermal sources [2]. More recently, this idea has been applied to analyse and control visible luminescence by semiconductors and quantum dots [12, 13]. The basic mechanism is the same: the incoherent emitters must be coupled to a mode guided by a surface or by a planar guide whose radiative losses can be engineered to control the emission polarization and angular pattern. These features enable the design of light-emitting metasurfaces with a thickness of a few hundred nanometers. This could mark the advent of a new generation of light sources that do not require the use of bulky lenses and polarizers [14]. ●

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