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Temperature dependent polarization of the thermal radiation emitted by thin, hot tungsten wires

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ABSTRACT

We report measurements of the temperature T dependence of the linear polarization $\langle P \rangle$ of the thermal radiation emitted by thin, incandescent tungsten wires in a range from a little above room temperature up to melting $T_m \approx 3700$ K across the visible and infrared range. These are the first measurements in such wide a temperature range. We found that $\langle P \rangle$ decreases with increasing T. The theoretical prediction based on Kirchhoff's law satisfactorily reproduces the experimental data if a Drude-type formula for the optical properties of tungsten is used, provided that its validity, assessed in literature only for $T \leq 2400$ K and for wavelengths in the range from visible up to $\lambda \approx 2.6$ μm, is extended to the ranges investigated in the present experiment, namely for T up to T_m and for λ up to ≈ 15 μm.

1. Introduction

The study of thermal emission by hot bodies is a very important topic because the celebrated Planck's result about the spectrum of a blackbody radiator paved the way for the development of Quantum Mechanics [1]. Planck's law is independent of the characteristics of the blackbody material and only depends on the temperature T, thus making pyrometry a universal thermometric technique [2]. According to Planck's derivation, the blackbody emission consists of unpolarized, incoherent radiation for bodies whose size is larger than the typical thermal wavelength, $\lambda_T = hc/k_B T$, where h, c, and k_B are Planck's constant, light speed, and Boltzmann's constant, respectively. However, early measurements with a few μm thick W- [3] and Au [4] wires have shown that thermal radiation has a high degree of linear polarization, up to ≈30% and more, orthogonal to the wire axis that is explained in terms of plasma oscillations of the electron gas in the metal that scatter, absorb, and emit light.

More recently, an experimental study about the degree of linear polarization of incandescent W wires of diameter 5- to 100 μm in the visible range has confirmed the early observations that for wires of radius $r > \lambda_T$ the thermal radiation is polarized in excess of 20% perpendicularly to the wire axis. Unfortunately, no attempt was done to measure the wire temperature that was estimated to be ≈2400 K [5].

In recent years, there has been a renewed interest on the properties of thermal radiation because of the availability of radiators of size comparable to or smaller than λ_T. Actually, sub-wavelength patterning of the properties of metallo-dielectric surfaces at nanoscale has led to the discovery of the near-field coherence properties of the thermal radiation emitted by nanoheaters [6], including carbon nanotubes [7–9], that have great relevance in applied physics and engineering [10–12]. It has been observed that in nanoheaters with $r \lesssim \lambda_T$ the radiation is polarized along the wire axis, becoming fully polarized as $r \to 0$ [12,13]. Standing waves of thermally driven collective charge oscillations are affected in different ways whether they are parallel or perpendicular to the heater axis when r is shrinked. In the near field, surface plasmon polaritons only propagate along the direction of charge oscillations. For $r < \lambda_T$ longitudinal charge fluctuations are strongly correlated by the coupling with surface plasmons and light is polarized along the heater long axis, whereas, for $r \geq \lambda_T$ transversal charge oscillations get correlated via the interaction with surface plasmons and the emitted light is polarized perpendicular to the heater axis. Actually, a rotation of the linear polarization of light emitted by Pt nanoheaters has been observed when their width changes from submicron-to micron size, the crossover occurring for $2\pi r/\lambda_T \sim 1.5$ [14].

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In these latter studies, the nature of the nanoheaters material is not really important as only the ratio r/λ_T determines the direction of light polarization. However, the coupling with surface plasmons is ruled by the optical properties of the materials, including the dielectric constant and the emissivity [15], which depend on T, on the wavelength λ, and on the nature of the metal [16]. Actually, theoretical studies have addressed the issue of how the optical properties of the material, not only its size, influence the features of the radiation emitted by long cylinders and have shown that the polarization curves for W may shift by a factor of 10 when T is changed from 300 K to 2400 K [17,18].

The optical properties of tungsten are relatively well known in a fairly wide range from room temperature up to $T \approx 2400$ K and in a wavelength range up to $\lambda \leq 2.5$ μm. The width of these ranges gives the researchers the opportunity to investigate how the polarization of the thermal radiation emitted by thin tungsten wires varies as a function of the variation of the material properties with either T or λ. For these reasons we have carried out measurements of the degree of linear polarization of the radiation emitted by tungsten wires heated by Joule effect in a temperature range from a little above room temperature up to melting in a wavelength band across the infrared and visible regions. We have used W wires of radius $r = 9$ μm, 25 μm, and 50 μm, respectively. Their size is such that the emitted radiation is always polarized perpendicular to their axis. Thus, the variation of the polarization can solely be ascribed to the temperature and wavelength dependence of the optical properties of tungsten.

The paper is organized as follows: in Sect. 2 we describe the experimental apparatus. In Sect. 3 we present the experimental data In Sect. 4 we discuss the polarization data in connection with the theoretical predictions. The conclusions are drawn in Sect. 5. The lengthy procedure of finding out the relationship between the electric power dissipated in the wires and the radiation temperature is described in Appendix A.

2. Experimental details

The experimental apparatus consists of two independent subsystems. The first one is the mechanical and optical setup necessary to support the wires and to collect the emitted light. The second one consists of the electronics required to energize the wires and to reveal and analyze the detector signal.

2.1. Mechanical and optical setup

The mechanical and optical parts of the apparatus are schematically shown in Fig. 1. Tungsten wires (W) of nominal purity > 99.95%, supplied by LUMA (9 μm) and SIT (25 μm and 50 μm), are mounted inside a 50 cm long metal pipe of 2.5 cm in diameter, evacuated to a working pressure $p \leq 10^{-3}$ Pa. The wires are stretched and clamped on supports connected to the power supply with vacuum feedthroughs. They are ≈ 7 mm long with radius r either 50-, 25-, or 9 μm. Four identical wires are mounted in parallel in order to increase the amount of light impinging on the detector while keeping the electrical resistance at a manageably low value. For the 50 μm, only one single wire was used. The wires are mounted with their cylindrical axes perpendicular to the axis of vacuum pipe, whose internal surface is mat and coated with Aquadag in order to minimize polarized reflections from the inner walls. Three equally spaced optical baffles (ob), consisting of drilled washers with a central hole of ≈ 6 mm in diameter, are located along the optical axis to further prevent internally reflected light from reaching the detectors and to reduce the contribution of nonparaxial rays. The light eventually exits the pipe through a ZnSe optical window (ZW) of ≈ 1 cm in diameter, located ≈ 30 cm from the wires.

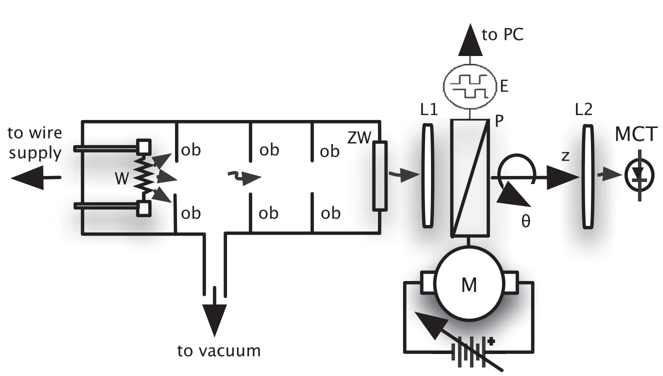

Fig. 1. Schematics of the optical setup. W = wires, ob = optical baffles, ZW = ZnSe window, L1 and L2 = lenses, P = rotating analyzer, E = encoder, MCT = HgCdTe detector, M = motor.

Two ZnSe lenses, (L1) and (L2) with focal lengths of 15 and 6.5 cm, respectively, image the wires on the liquid N_2 cooled, photovoltaic HgCdTe detector (Fermionics, mod. PV-12-0.5) that has a circular active area of 1 mm^2 and a spectral range 0.5 μm $\leq \lambda \leq 15$ μm.

The thermal radiation emitted by the wires is analyzed by means of a ZnSe wire grid, infrared (IR) polarizer (P) (Thorlabs, WP25H-Z) mounted on a rotary frame coupled to a computer-driven, d.c. motor by means of a scaler gear so that it can rotate about the optical z-axis of the system. The rotation of the scaler gear shaft is measured by a 12-bit digital encoder (E) interfaced to a computer. One complete turn of the shaft corresponds to a 2° rotation of the polarizer.

A second polarizer can be inserted in the optical path to verify that no residual light outside the accessible spectral range still reaches the detector and to determine the polarization direction with respect to the wire axis orientation. It turns out that the polarization of the emitted thermal radiation is always perpendicular to the wire axis.

2.2. Electronics

In the IR range, where the detector is most efficient, all bodies are readily emitting. As the area of the wires is extremely small, their contribution to the detected thermal radiation would normally be obscured by that of the environment. In order to detect only their contribution, the wire emission is modulated by superimposing a small, low-frequency (≈ 2 Hz) a.c. current to the steady d.c. current that sets the average wires temperature. Owing to the negligible thermal inertia of the wires, their temperature and emission instantaneously follow the current changes, whereas the time constant of the surrounding environment is ≈ 1 h so that its temperature and emission remain constant as long as the d.c. current in the wires is kept constant. By so doing, the a.c. wire signal is completely decoupled from the environment contribution and standard lock-in techniques are used to detect it.

A scheme of the electronics required to power the wires and to measure the emitted light is shown in Fig. 2. A home-made, linear, modified audio power amplifier (PA), with high-precision, adjustable internal d.c. source (Vdc), can deliver currents up to 12 A from d.c. to a few tens of kHz to very low impedance resistive loads [19]. The a.c. contribution is supplied by a signal generator Vac (HP, mod. 3312A), which also issues the reference for lock-in detection. The output of PA directly feeds the wires whose resistance ($0.2\Omega \leq R \leq 1\Omega$ at room temperature) is measured with the Kelvin technique by using the ammeter A (Tektronix, mod. DMM914) and