Temperature Dependent Polarization of Thermal Radiation Emitted by hot Tungsten Wires

A. F. Borghesani1, G. Carugno2, and G. Ruoso3

1 Dipartimento di Fisica & Astronomia dell’Università di Padova, Padova, Italy.
2 INFN, Sezione di Padova, Padova, Italy.
3 INFN, Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy.

INTRODUCTION

We report the measurements of the temperature dependence of the linear polarization of the thermal radiation emitted by thin, incandescent tungsten wires. We investigated the temperature range 500K ≤ T ≤ Tm, where Tm ≈ 3695K is the melting temperature of tungsten and the wavelength range 1µm ≤ λ ≤ 15µm.

The properties of thermal emission of hot bodies is a central topic in Modern Physics [1]. The dependence of the Planck’s law only on the body temperature T but not on its material properties make pirometry a universal pyrometric technique [2]. The blackbody emission consists of unpolarized, incoherent radiation for bodies whose size is larger than the typical thermal wavelength, \( \lambda_T = \frac{hc}{kT} \), where \( h \), \( c \) and \( k \) are the Planck’s constant, speed of light, and Boltzmann’s constant, respectively.

However, if the radiator dimensions are of the order of \( \lambda_T \) or smaller, thermal radiation shows a high degree of spatial and temporal coherence in the near-field region, and shows a quite large degree of polarization. Thin wires are thus very suitable objects to study the polarization properties of thermal radiation [3, 4]. For wires whose radius is \( r > 1.5\lambda_T \), the emitted radiation is linearly polarized in a direction perpendicular to the wire axis [5, 6].

Previous measurements in the visible region have confirmed this expectations [7]. These measurements were carried out at an approximately constant temperature \( T ≈ 2400K \). We have now measured the polarization of the emitted light in a very wide temperature range. The polarization of the emitted light can theoretically be calculated by computing the cross section of a cylindrical wire and by using the Kirchhoff’s law, according to which the emission equals absorption at thermal steady state.

EXPERIMENT

In Fig. (1) and in Fig. (2) the experimental apparatus is shown. The wires (either 9µm or 25µm in diameter) are mounted inside an evacuated tube. They are powered by a bias dc current that sets the average working temperature plus a small ac (≈ 1Hz) current that modulates the intensity of the emitted light. A set of two lenses focuses the emitted light on a LN2-cooled HgCdTe detector whose signal is amplified and detected by lock-in techniques. On the optical path, a rotating polarizer is inserted. The lock-in output is thus given by Malus’ law

\[
I = I_u + I_p \cos \theta^2
\]

where \( \theta \) is the rotation angle of the polarizer. \( I_u \) and \( I_p \) are the strengths of the unpolarized and polarized components of light, respectively. The degree of polarization is thus calculated as \( P = \frac{I_p}{(2I_u + I_p)} \). A typical lock-in output signal is displayed in Fig. (3).

The resistance of the wires (some tenths of an ohm at room temperature up to several ohms near melting) was measured by the Kelvin technique for each settings of the bias current \( i \). In this way, the electrical power \( Vi \) dissipated by Joule heating in the wires is measured. To relate the measured quantity \( Vi \) to the wire temperature \( T \), we have both integrated numerically the equation of thermal conduction and compared the measured resistance with that computed by evaluating the known temperature dependence of the tungsten resistivity. Moreover, we have used a CCD camera to record the temperature profile along the wire. In
The measured degree of polarization $P$ is reported as a function of $T$ in Fig. (5). Both types of wires show a marked decrease of $P$ with increasing $T$, the thicker wires emitting a bit more polarized radiation than the thinner ones.

The polarization degree can be calculated as follows:

$$\langle P(T) \rangle = \frac{\langle Q_{abs}^\perp \rangle - \langle Q_{abs}^\| \rangle}{\langle Q_{abs}^\perp \rangle + \langle Q_{abs}^\| \rangle}$$  \hspace{1cm} (1)

where $Q_{abs}^\perp$ and $Q_{abs}^\|$ are the absorption cross sections for longitudinal and transversal modes relative to the wire axis. Moreover,

$$\langle Q_{abs}^{(j)} \rangle = \int D(\lambda) E(\lambda, T) Q_{abs}^{(j)} d\lambda \quad (j = \perp, \|)$$  \hspace{1cm} (2)

Here, $D$ is the detector responsivity and $E$ is the Planck’s distribution for the intensity. The absorption cross section is computed from the extinction and scattering cross sections as $Q_{abs}^{(j)} = Q_{ext}^{(j)} - Q_{sca}^{(j)}$, where

$$Q_{ext}^{(j)} = 2(kr)^{-1} \text{Re} \left( \alpha_0^{(j)} + 2 \sum_{m=1}^\infty \alpha_m^{(j)} \right)$$

$$Q_{sca}^{(j)} = 2(kr)^{-1} \left| \alpha_0^{(j)} \right|^2 + 2 \sum_{m=1}^\infty \left| \alpha_m^{(j)} \right|^2$$  \hspace{1cm} (3)

The coefficients $\alpha_{m}^{(j)}$ are obtained by matching the solutions of the wave equation in cylindrical symmetry at the wire boundary. They and, hence, the cross sections depend on the refraction index $n(T, \lambda)$ of the metal.

We used a Drude-type formula for the permittivity [8], whose parameters have been determined only for $T \leq 2400$ K and for $\lambda \leq 2.6 \mu m$. As the wavelength range spanned in the present experiment is $1 \mu m \leq \lambda \leq 15 \mu m$ and the melting temperature $T_m \approx 3700$ K has been reached, we extrapolated the parameters of the Drude formula proposed in literature to the $T$ and $\lambda$ ranges of our experiments. The agreement of the theoretical model with the data is good, thereby extending the validity of the Drude formula well beyond the original limits.

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