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Application of collinear mirage detection for thermal diffusivity measurements of solids at high temperatures

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Abstract: This work explores the performance of the collinear mirage technique to measure the thermal diffusivity k_s of bulk homogeneous solids in the temperature range from 300 K to 1000 K. A 3D conductive-radiative model is used to find a linear relation between the phase and the probe-pump offset to measure k_s . Experimental results confirm the validity of the method.

1. INTRODUCTION

In this paper we analyze the performances of the collinear mirage technique in order to measure the thermal diffusivity of bulk homogeneous solids at temperatures up to 1000 K. This study completes our work on the perpendicular mirage configuration for the measurement of the temperature dependence of k_s [1]. In the collinear mirage setup pump and probe beams are sent parallel through the sample which must be semitransparent to the probe laser. Recently [2], we have shown theoretically and experimentally that there exist, for a fixed frequency, a linear relation between the phase of the collinear signal and the probe to pump offset. Its slope directly yields the thermal diffusivity of the sample. This relation is particularly useful since it does not depend on the sizes of the exciting and probe beams. The technique has been applied with success to the determination of k_s in the case of samples with low thermal diffusivity ($k_s < 1 \text{ mm}^2/\text{s}$). The aim of this work is to study theoretically and experimentally whether the above mentioned linear relation can also be applied at high temperatures in the range 300-1000 K.

2. THEORY

In this section we shall calculate the collinear mirage deflection of the probe beam when the sample under study has a temperature higher than that of the ambient. In such a case the radiative heat transfer must be taken into account and incorporated into the purely conductive model, which is widely known to be valid at room temperature.

2.1 Thermal field

We assume that the sample is homogeneous and isotropic and that it is surrounded by air. The air temperature can be obtained by solving the heat diffusion equation in each medium with the appropriated boundary conditions, that include the radiative losses [1,3]. The temperature of the sample in a depth z is given by:

$$T_s = \frac{1}{2} \exp(i\omega t) \int_0^\infty \delta J_0(\delta r) \Gamma(\delta) \left[\exp(\alpha z) - \frac{B(\delta)}{H(\delta)} \exp(\beta_s z) - \frac{C(\delta)}{H(\delta)} \exp(-\beta_s z) \right] d\delta \quad (1)$$

where $\beta_s^2 = \delta^2 + i\omega/k_s$, and

$$\begin{aligned} B(\delta) &= (1+\theta)(p+\theta) \exp(\beta_s l) - (1+\theta)(p-\theta) \exp(-\alpha l) \\ C(\delta) &= (1-\theta)(p+\theta) \exp(-\beta_s l) - (1+\theta)(p-\theta) \exp(-\alpha l) \\ H(\delta) &= (1+\theta)^2 \exp(\beta_s l) - (1-\theta)^2 \exp(-\beta_s l) \\ \Gamma(\delta) &= \frac{P_o(1-R)}{\pi K_s} \frac{\alpha}{\beta_s^2 - \alpha^2} \exp\left[\frac{-(\delta a)^2}{8}\right], \quad p = \frac{\alpha}{\beta_s}, \quad \theta = \frac{4\sigma\epsilon T_o^3}{K_s \beta_s} \end{aligned}$$

Here P_o is the exciting beam power, R the sample reflectivity, α the absorption coefficient of the sample, a the radius of the exciting beam at $1/e^2$ of the intensity, K_s is the thermal conductivity of the sample, l the sample thickness, ω the modulation angular frequency, J_o the Bessel function of zeroth order, T_o is the sample temperature, σ the Stephan-Boltzman constant and ϵ the sample emissivity. In the above equations we have neglected terms containing K_g/K_s . This factor is negligible (K_g : Thermal conductivity of the air).

2.2 Collinear mirage deflection

In the collinear configuration the total deflection of the probe beam is the sum of the deflections it suffers in the gas of the front and rear regions and in the sample itself. However, in most cases of interest the main contribution to the deflection is produced in the sample, being the other two negligible [2]. Thus, the collinear deflection for a probe propagating perpendicular to the sample surface can be written

$$\vec{\phi}_c(r_o) = -\frac{1}{n_s} \left(\frac{dn}{dT} \right)_s \int_0^l \left(\frac{\partial T_s}{\partial r} \right)_{r_o} dz \hat{\theta}_o \quad (2)$$

Here n_s is the refractive index of the sample and r_o is the beam separation. Now, substituting eq (1) into this last one we finally obtain

$$\begin{aligned} \vec{\phi}_c(r_o) &= -\frac{1}{n_s} \left(\frac{dn}{dT} \right)_s \frac{P_o(1-R)}{2\pi K_s} \exp(i\omega t) \int_0^\infty \delta \left\{ \frac{\partial}{\partial r} [J_o(\delta r)] \right\}_{r_o} \exp\left[\frac{-(\delta a)^2}{8}\right] \frac{1}{\beta_s} \frac{p}{1-p^2} \times \\ &\times \left\{ \left[\frac{\exp(-\alpha l) - 1}{\alpha} \right] - \left[\frac{\exp(-\beta_s l) - 1}{\beta_s} \right] \frac{B(\delta)}{H(\delta)} + \left[\frac{\exp(-\beta_s l) - 1}{\beta_s} \right] \frac{C(\delta)}{H(\delta)} \right\} d\delta \hat{\theta}_o \quad (3) \end{aligned}$$

2.3 Numerical evaluation

We solved eq. (3) numerically after a separation into real and imaginary parts. We focused our interest on the behaviour of the phase of the collinear deflection $\psi(\phi_c)$ as a function of the beams separation r_o . At room temperature we found a linear relation between these two parameters with a slope of $m = -1/\mu_s = -(\pi f/k_s)^{1/2}$ (μ_s is the thermal diffusion length of the sample). Thus the thermal diffusivity of the specimen can be obtained [2]. The purpose of this section is to evaluate the influence of the sample temperature on this slope.

In Figure 1 we present the results of the computation for two frequencies (1 Hz and 20 Hz) and two thermal diffusivities (0.5 mm²/s and 10 mm²/s). In all cases the sample emissivity has been taken to be 1. Four sample temperatures have been studied: 0, 700, 1000 and 2000 K. The results can be summarized as follows: (a) In general, the radiative effect introduce a change in the slope of the linear relation between $\psi(\phi_c)$ and r_o . A simple analysis would yield a thermal diffusivity value higher than the actual one. This effect increases with T_o . (b) There is not difference in the phase behaviour between transparent and opaque samples to the exciting beam. (c) For a given thermal diffusivity of the sample, the radiative effect

decreases as the frequency increases. (d) For a given frequency the radiative effect decreases as the thermal diffusivity increases. (e) For thermal diffusivities down to $0.1 \text{ mm}^2/\text{s}$ and temperatures up to 1000 K a frequency of 20 Hz is most appropriate since it is high enough to neglect radiative transfer, but yields a low enough factor a/μ_s giving a good signal to noise ratio.

Figure 1: Theoretical relation between the phase of the collinear mirage deflection $\psi(\phi_c)$ and beam separation r_0 . In these calculations $a = 0.1 \text{ mm}$ and $\epsilon = 1$. Solid line $T_0 = 0 \text{ K}$, dashed line $T_0 = 700 \text{ K}$, dashed-dotted line $T_0 = 1000 \text{ K}$, and dotted line $T_0 = 2000 \text{ K}$. Top: $k_s = 0.5 \text{ mm}^2/\text{s}$, bottom: $k_s = 10 \text{ mm}^2/\text{s}$.

3. EXPERIMENTAL RESULTS

We used a conventional collinear mirage setup [2] including a furnace for sample heating (see Figure 2). The oven is a commercial one from Heraeus with internal dimensions $100 \times 100 \times 150 \text{ mm}$ and able to reach 1000°C . The temperature is electronically controlled by a thermocouple and adjusted by an analog set point with a precision of $\approx 5^\circ\text{C}$. Small cylindrical holes were drilled in the furnace walls and

covered internally and externally by quartz windows. They allow the passage of the two beams and suppress air motions resulting from temperature gradients between the furnace and its surroundings. Due to the furnace size we had to use focal lengths of 15 cm to focus the beams, a value larger than that we use at room temperature [2]. Separation between the two lasers is obtained by moving the exciting beam lens vertically. This method requires the pump beam to be carefully focused, otherwise the displacement of the lens does not coincide with the actual beams separation on the sample [4].

As a check of the validity of the collinear mirage method for thermal diffusivity measurements at high temperatures, we have measured two samples of different diffusivities and different temperature dependences: A Schott infrared blocking glass filter and a Ruby crystal. The retrieved thermal diffusivities shown in Figure 3 are in good agreement with published values [5].

We conclude that the collinear mirage technique provides a powerful method for thermal diffusivity measurements of bulk homogeneous materials, with the unique restriction that they must be semitransparent to the probe beam. The technique can be improved by reducing the furnace size in order to use focal lengths as small as possible.

Figure 2: Diagram of the experimental setup used for the collinear mirage detection when used at high temperatures. 1: Probe beam; 2: Modulated exciting beam; 3: Lenses; 4: Beam splitter; 5: Furnace; 6: Quartz windows; 7: Sample; 8: Exciting beam blocking filter; 9: Quadrant detector.

Figure 3: Thermal diffusivity experimental data. Left: Ruby crystal, right: Infrared blocking Schott filter.

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