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Novel results on collinear mirage deflection

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In this paper we report on the strong influence of the polarization state of the probe beam on the amplitude and phase of the collinear mirage deflection. It is shown that the photoelastic effect, i.e. the change of the refractive index with stresses, is the responsible of this influence. Theoretical and experimental studies on isotropic materials have been performed. The influence on the measurement of the thermal diffusivity of these materials is analyzed.

Keywords thermal diffusivity, mirage technique, photoelasticity, thermoelasticity

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In a conventional collinear mirage setup a modulated heating beam is sent perpendicular to the sample surface while a low-power probe beam is directed parallel to the exciting beam and is periodically deflected inside the sample because of the dependence of the refractive index on temperature. One of the applications of the collinear mirage technique is the measurement of the thermal diffusivity of semitransparent materials. The method is based on the linear relation between the phase of the collinear mirage deflection (${}_c$) and the distance between heating and probe beams. Its slope (m) is related to the thermal diffusivity of the sample (D) through the expression[1]

$$m \qquad \sqrt{\frac{f}{D}} \qquad (1)$$

where f is the modulation frequency of the heating beam.
In this way the thermal diffusivity of polymers, glasses and liquids has been measured.[2] However, it has been shown recently that the polarization state of the probe beam greatly influences the amplitude and phase of the collinear mirage deflection due to the influence of the photoelastic effect.[3] In particular, the slope m in Eq. (1) depends on the polarization state of the probe beam. This result raises the question of whether the collinear mirage technique provides a reliable method to measure the thermal diffusivity of semitransparent materials.

In this paper we study theoretically and experimentally the influence of the photoelastic effect in the collinear mirage deflection. We focus on the conditions under which the linear method to retrieve the thermal diffusivity can be applied.

Thermal model

The geometry of the collinear mirage deflection is shown in Fig. 1. Considering a pure thermal model, i.e. = n(T), the collinear mirage deflection is written as

$$\overset{\&}{c} \qquad \frac{1}{n}\frac{dn}{dT} \; {}^{"}_{0} \; \overset{\&}{T} \quad dz \; k \qquad (2)$$

where n is the refractive index of the sample and " is the sample thickness.

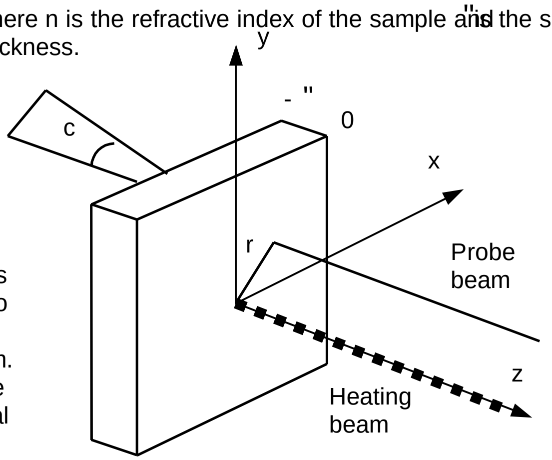

Fig.1. Geometry of the collinear mirage deflection.

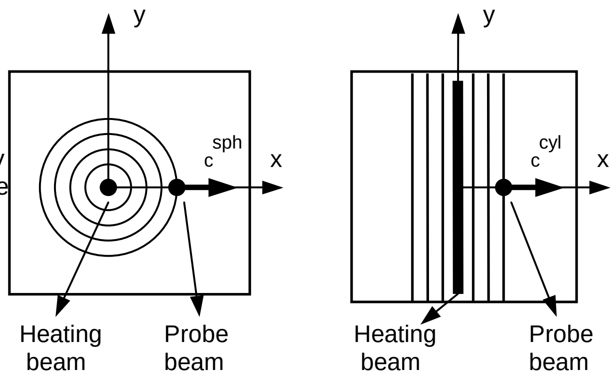

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Fig. 2. Mirage deflection in a transparent sample. Left: Heating beam focused by a spherical lens. Right: Heating beam focused by a cylindrical lens.

For simplicity we present the theory for weakly absorbing materials although the conclusions have general validity. Two experimental configurations are considered: (a) If the heating beam is focused by a spherical lens, cylindrical thermal waves are generated and T T(r) ; while (b) if the heating beam is focused by a cylindrical lens, planar thermal waves are generated and T T(x) (see Fig. 2). The corresponding expressions for the collinear deflections are respectively:

$$\&_{c}^{\,sph} \quad \frac{"}{n}\frac{dn}{dT}\frac{dT}{dr}\; j \qquad (3a)$$

$$\&_{c}^{\,cyl} \quad \frac{"}{n}\frac{dn}{dT}\frac{dT}{dx}\; j \qquad (3b)$$

It is worth noting that when dn/dT < 0 (e.g. liquids and polymers) the probe beam is deflected outward from the heating source, i.e. as in Fig. 2. However, when dn/dT > 0 (e.g. most glasses) it is directed inward to the heating source.

Since $_c$ is proportional to the temperature gradient its phase decreases linearly with the separation between heating and probe beams and the slope gives the thermal diffusivity of the material according to Eq. (1).

Influence of the photoelastic effect

Thermal waves produce a nonuniform temperature field and therefore inhomogeneous thermal stresses ( ) are developed in the sample (thermoelastic effect) that produce a change of the refractive index (photoelastic effect)[4,5]. Consequently, there is a direct modification of the index of refraction due to the temperature change, and an indirect modification due to the stresses n n(T,) In this section we account for the additional mirage deflection produced by the photoelastic effect. The main consequence is that the collinear deflection changes with the polarization state of the probe beam. Three polarization states of the probe beam are considered: linearly polarized along the x axis (||), linearly polarized along the y axis ( ), and unpolarized (*).

When the heating beam is focused by a spherical lens the collinear mirage deflection for the three polarization states we are working with are given by[3]

$$\&_{c}^{\,sph} \quad \frac{"}{n}\quad A\frac{dT}{dr} \quad C\frac{d}{dr}\quad \frac{1}{r^2}\quad Trdr \quad j \qquad (4a)$$

$$\&_{c||}^{\,sph} \quad \frac{"}{n}\quad B\frac{dT}{dr} \quad C\frac{d}{dr}\quad \frac{1}{r^2}\quad Trdr \quad j \qquad (4b)$$

$$\&_{c^*}^{\,sph} \quad \frac{c^{\,sph} \quad \&\ c||^{\,sph}}{2} \quad \frac{"}{n}\frac{A \quad B}{2}\frac{\&\ dT}{dr}\; j \qquad (4c)$$

Similarly, when the heating beam is focused by a cylindrical lens the collinear mirage deflection writes:

$$\&_{c}^{\,cyl} \quad \frac{"}{n}\, A\frac{dT}{dx}\; j \qquad (5a)$$

$$\&_{c||}^{\,cyl} \quad \frac{"}{n}\, B\frac{dT}{dx}\; j \qquad (5b)$$

$$\&_{c^*}^{\,cyl} \quad \frac{c^{\,cyl} \quad \&\ c||^{\,cyl}}{2} \quad \frac{"}{n}\frac{A \quad B}{2}\frac{\&\ dT}{dx}\; j \qquad (5c)$$

where

$$A \quad \frac{n}{T} \quad \frac{n^3}{2}\,\frac{E(\ _{11} \quad _{12})}{1}$$

$$B \quad \frac{n}{T} \quad \frac{n^3}{2}\,\frac{E2 \ _{12}}{1}$$

$$C \quad \frac{n^3}{2}\,\frac{E(\ _{12} \quad _{11})}{1}$$

being the thermal expansion coefficient, E the Young modulus, the Poisson ratio and $_{ij}$ the stress-optical coefficients of the sample.

(a) Cylindrical lens

It can be seen from a comparison of Eqs. (5) and (3b) that although the amplitude of the collinear deflection is affected by the polarization state of the probe beam, its phase remains unchanged with respect to the pure thermal model. This is due to the fact that A and B are real parameters and consequently the phase of the mirage deflection is governed by the temperature gradient, as in the pure thermal model. Thus, when using a cylindrical lens to focus the heating beam the thermal diffusivity can be obtained using Eq. (1).

This is shown in Fig. 3, where mirage measurements performed on a polycarbonate (PC) sample are presented. A conventional collinear mirage setup[1] was used where an Ar$^+$ laser focused by a cylindrical lens of 7 cm focal length was employed as heating beam. The polarization of the 10 mW He-Ne laser used as probe beam was selected by a linear polarizer. As expected the phase of the mirage deflection is only slightly affected by the polarization state of the probe beam.