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LOCAL LASER MEASUREMENT OF HEAT FLUX IN A PLATE

A.N.Magunov and S.V.Merkulov*
Plasma Physics Dept., General Physics Institute, Moscow, 117942, Russia
*Institute of Microelectronics, Yaroslavl, 150007, Russia

Abstract: Modulus of the local temperature gradient and heat flux along a transparent plane-parallel plate may be measured using a single-beam optical scheme and registering an amplitude of Fabry-Perot optical resonances by the spectral scanning over a narrow interval. This interval is of the order of nanometer at probing wavelength of ~1 mm when 1-mm-thick semiconductor single crystal is used as heat conductor and as flux sensor, simultaneously.
Keywords: heat flux, laser interferometry, fringe visibility.

1 INTRODUCTION

There are two ways to perform the experimental determination of a heat flux: firstly, the measurement of the time derivative dT/dt for the solid-state thermal probe in gaseous and liquid medium after a flux switching on, and secondly, the measurement of the coordinate derivative dT/dx along the thermal conductor which may be in gaseous, liquid or solid state. A number of laser techniques has been developed to measure locally the temperature of solids and to determine the time dependence of dT/dt [1]. But there is no laser technique for local measurement of heat flux within solids. Interferometric technique allows to determine a value of gradT in any transparent medium, but it is necessary in such measurement to register a variation of the spatial frequency of interference fringes, and because of this, a change of optical path difference must be as much as several tens of wavelengths. This limitation does not allow to use the conventional interference technique for measuring the little heat fluxes.

Temperature gradient dT/dx and heat flux P~dT/dt in solid plate may be determined experimentally using measurement of temperatures T at two spatially separated points with coordinates x_1 and x_2 using relation $dT/dx \approx [T(x_2) - T(x_1)]/(x_2 - x_1)$. It is necessary to decrease a distance $x_2 - x_1$ to measure the transient heat fluxes. The best possibility to register the non-stationary heat flux may be reached when the temperature gradient is measured locally. However there are a number of difficulties and errors in local measurements of heat flux using contact thermometers (thermocouples, etc.) due to a finite size of temperature-sensitive elements, mutual influence between them and distortion of the temperature fields. Contact techniques are ineffective when measurements are made under conditions of severe electromagnetic noise or high voltage on the object to be investigated. Here we present a new laser technique for local measuring the heat flux parallel to the surface of a plane-parallel transparent plate.

2 OPTICAL INTERFERENCE CONTRAST

When a monochromatic light is directed normally to the transparent plate having refractive index n and thickness h, the reflectance is given by well known expression:

$$R = [A - B\cdot\cos(2nkh)]/[C - B\cdot\cos(2nkh)] \qquad (1)$$

where $A = R_1 + R_2$, $B = 2(R_1\cdot R_2)^{1/2}$, $C = 1 + R_1\cdot R_2$; R_1 and R_2 are the reflection coefficients for front surface and back one; phase 2nkh is the difference of optical paths for two interfering beams; $k=2\pi/\lambda$ is the wavenumber, λ is the wavelength. Fabry-Perot resonances (or interference fringes) may be observed at constant temperature when the wavelength of probing light is varied. Wavelength change necessary for variation in phase 2nkh by 2π equals to $\Delta\lambda = \lambda^2/2nh$. When such change takes place, the interferogram is shifted by one fringe. For 1-mm-thick monocrystalline silicon plate at wavelength $\lambda \approx 1.3$ μm (it is in the spectral range of very low absorption, $\alpha \approx 10^{-3}$ cm^{-1}) and $n \approx 3.5$ we obtain $\Delta\lambda \approx 0.24$ nm, as shown in Fig.1. For monocrystalline gallium arsenide 1 mm in thickness $\Delta\lambda \approx 0.14$ nm at $\lambda \approx 1$ μm and $n \approx 3.5$. Such variation of the wavelength may be reached in a matter of microseconds by the use of semiconductor laser diode via pulse heating the resonator with a pumping current: when the resonator temperature changes by 1 K, wavelength change of 0.1 nm takes place.

Amplitude of optical resonances is usually characterized by a contrast (or so-colled fringe visibility)

$$V_R = (R_{max} - R_{min})/(R_{max} + R_{min}) \quad (2)$$

where both maximal (when cos(2nkh)=1) and minimal (at cos(2nkh)= -1) reflectances result from (1). To reach the maximal contrast, both reflectances R_1 and R_2 of plate must be identical, and there is no optical absorption in material. If the optical thickness (nh) of the plate changes along the surface coordinate x, the reflectance may be calculated by integration of R(x) over the light beam diameter, in so doing the tabulated integral is obtained. The contrast decreases as compared to the case when the optical thickness is uniform in a laser beam cross section. The observed value of V_R depends on the difference of optical thickness Δ(nh) within a light spot, as shown in Fig.2.

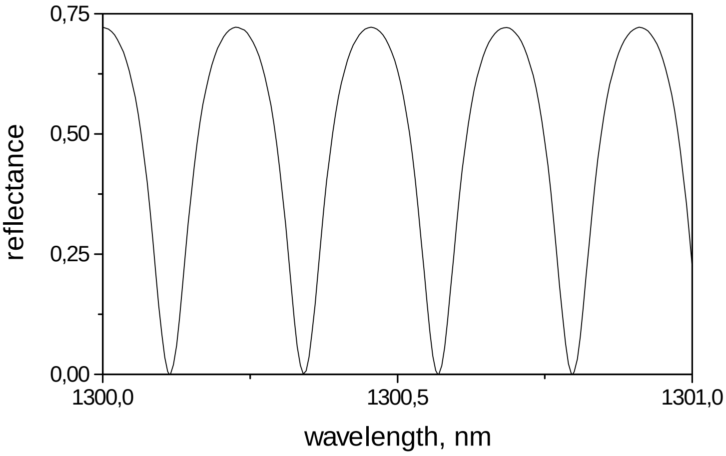

Figure 1. Spectral dependence of reflectance of 1-mm-thick silicon single crystal at normal incidence of light beam.

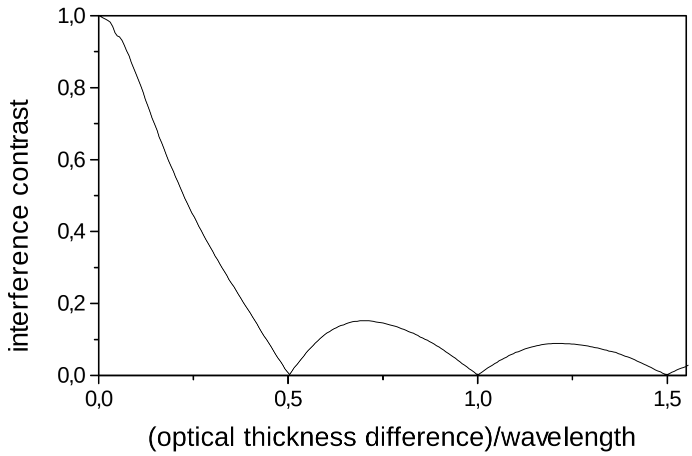

Figure 2. Interference contrast in reflection mode versus dimentionless variable $\Delta(nh)/\lambda$ characterizing an inhomogeneity of the plate optical thickness within a light spot.

3 DEPENDENCE OF CONTRAST ON THE TEMPERATURE GRADIENT

Let us consider a case when a plate in isothermal conditions has an uniform thickness h over the whole area. Both refractive index n and geometrical thickness h of a plate are temperature-dependent. Because of this, the presence of a temperature gradient parallel to the surface plane results in an inhomogeneity of the optical thickness of a plate across the light beam diameter, as both refractive index and thickness in non-isothermal mode become the coordinate functions. The presence of temperature gradient leads to the decrease of registered interference contrast [2]. The value of interference contrast is equal to zero when $\Delta(nh) = \lambda m/2$, where m =1,2,... One can obtain a temperature difference across a light spot corresponding to zeroth value of interference contrast at m=1:

$$(\Delta T)_1 = \lambda/2nh[n^{-1}\cdot(\partial n/\partial T) + h^{-1}\cdot(\partial h/\partial T)] \quad (3)$$

For 1-mm-thick silicon single crystal $(\Delta T)_1 \approx 2.6$ K at wavelength of 1.1 μm to 1.3 μm. The dependence of contrast on the product h·ΔT is shown in Fig.3. The gradient direction in the plane of plate does not play a role, the contrast depends only on the modulus of gradient $|dT/dx|$.

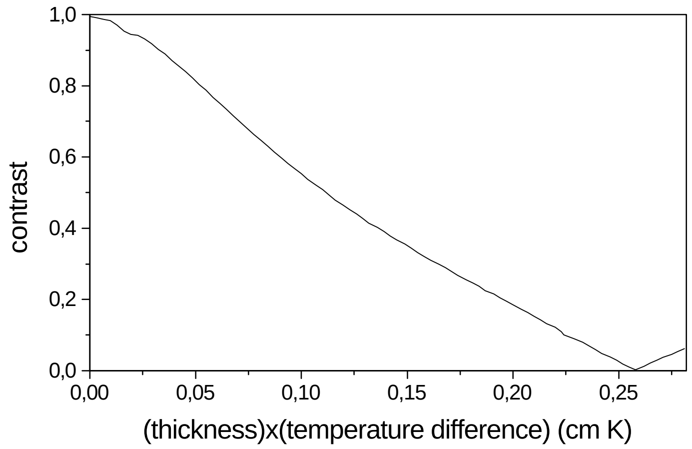

Figure 3. Interference contrast versus h·ΔT for silicon single crystal at wavelength of 1.3 μm.

To determine the sensitivity of contrast to the temperature difference across laser beam diameter, it is necessary to perform differentiation of V_R with respect to h·ΔT, as shown in Fig.4. There is a sensitivity greater than 3 $(cm\cdot K)^{-1}$ in most of the plotted region.

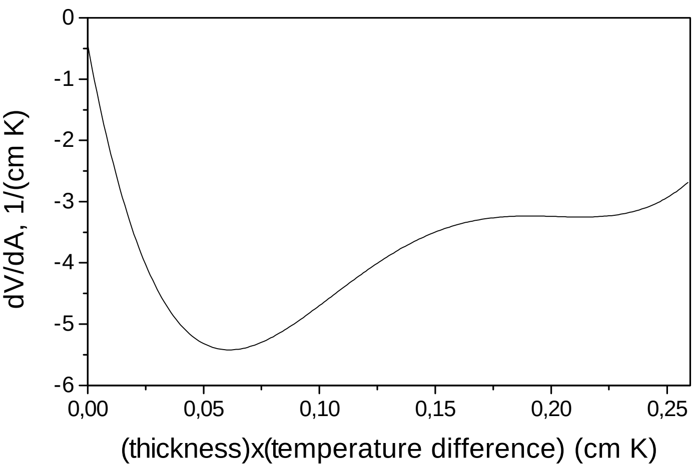

Figure 4. Derivative of contrast with respect to A ≡ h·ΔT versus h·ΔT.

Let us consider a minimal detectable value of dT/dx. Assume that $(dT/dx)_{min}$ causes a 3% reduction in the interference contrast, this reduction is quite sufficient to be observed. For determination of contrast it is enough to measure R_{max} and R_{min} by the use of spectral scanning over the range less than 0.2 nm. The contrast value of 97% corresponds to approximately h·ΔT ≈0.013 cm·K. Temperature difference necessary for such contrast reduction equals to $(\Delta T)_{min} \approx 0.13$ K for 1-mm-thick silicon crystal. If a laser is 1 mm in diameter, registered temperature gradient is equal to 1.3 K/cm and heat flux density is close to 2 W/cm^2. Temperature gradients in the range from $(dT/dx)_{min} \approx (\Delta T)_{min}\cdot D^{-1}$ to $(dT/dx)_{max} \approx (\Delta T)_1\cdot D^{-1}$ may be measured using Fabry-Perot resonances (here D is the laser beam diameter). The upper limit of dT/dx determined experimentally can be increased by means of decreasing beam diameter. In addition, the wavelength of probing light may be increased to achieve this goal. By the use of 0.1-mm-thick silicon crystal, wavelength of 1.3 μm and beam diameter of 0.1 mm it is possible to register the temperature gradient as much as 2600 K/cm. Heat power transferred in this case along the crystal 1 mm in width equals to 3.9 W.

The possibility to decrease a value of $(dT/dx)_{min}$ via a beam widening has some serious limitations. A characteristic time τ of heat flux variation must be much greater then the time of establishment of linear temperature profile across light beam diameter: $\tau >> D^2/\kappa$, where κ (cm^2/s) is the thermal conductivity of a material. As a result we obtain

$$\tau\cdot(dT/dx)^2 >> [(\Delta T)_{min}]^2\cdot\kappa^{-1} \quad (4)$$

For single silicon crystal from this condition we obtain $\tau\cdot(dT/dx)^2 >> 0.25\ s\cdot(K/cm)^2$. If $\tau \sim 1$ s, measured value of dT/dx must be much greater than 0.5 K/cm.

Due to very small values of $n^{-1}\cdot(\partial n/\partial T)$ for dielectrics, the temperature interval $(\Delta T)_1$ is much greater than for semiconductors. Rough estimation of measured values of dT/dx can be performed for any substances by the following expression:

$$dT/dx \sim \lambda\cdot[4Dh\cdot(dn/dT)]^{-1} \quad (5)$$

Typical values of dn/dT are equal to $(0.5\div3)\cdot10^{-4}\ K^{-1}$ for semiconductors (InP, GaP, GaAs, ZnS, ZnSe, etc.) at wavelengths of 1÷3 μm and $n \approx 2.8\div3.5$ [3], and to $(0.5\div2)\cdot10^{-5}\ K^{-1}$ for dielectric crystals at $\lambda \approx 0.3\div0.6$ μm and $n \approx 1.3\div1.5$ [4]. But typical values of heat fluxes for semiconductors and dielectrics are comparable because of essential difference (up to almost 2 orders of magnitude) between their thermal conductivities.

4 CONCLUSION

The decrease of interference contrast has been firstly observed in our study of silicon crystal heating in low-pressure plasma using laser interferometric thermometry, when the crystal was placed in a discharge region between reactor axis and wall; there is a large temperature gradient in this region [2]. When the temperature non-uniformity over the plate diameter takes place in heating or cooling mode, amplitude of Fabry-Perot resonances is smaller than in the case of the uniform temperature spatial distribution. But temperature scanning is less convenient technique for the measurement of heat fluxes as compared to spectral scanning, which may be used in both steady and transient temperature regimes. Amplitude of optical resonances is not used practically in intrferometric measurements of physical parameters. The technique described above is quite possible to be used in some applications, where traditional techniques are uneffective.

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AUTHORS: D.Sc. Alexander N. MAGUNOV, Department of Plasma Physics, General Physics Institute of Russian Academy of Sciences, Vavilov Str. 38, Moscow, 117942, Russia.
Phone Int. 7 095 1328320, Fax Int. 7 095 1358011, E-mail: almag@agmar.ru
M.S. Sergey V. MERKULOV, Institute of Microelectronics of Russian Academy of Sciences, Universitetskaya 21, Yaroslavl, 150007, Russia.
Phone Int. 7 0852 467403, Fax Int. 7 0852 116552.