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Shadow optoacoustic method for measuring thermophysical characteristics of condensed materials under intense impulsive heating

A. Kuznetsov[a,b]*, A. Golubev[b,a], K. Gubskii[a], D. Koshkin[a]

[a] *National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe shosse 31, 115409, Moscow, Russia*
[b]*Alikhanov Institute of Theoretical and Experimental Physics, ul. Bol'shayaCheremushkinskaya 25, Moscow, 117218 Russia*

Abstract

The results of the development of a contactless remote technique for studying thermal characteristics of condensed matter underintense pulsed heating are presented. This technique involves measuring the speed of sound basing on the time of passage of a probing optoacoustic pulse in a target. To record an acoustic response, a schlieren system based on the shadow technique for visualizing optical phase nonuniformities was developed.

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1. Introduction

The studies in the field of physics of high energy density (HED) in matter are of great priority. Owing to the experimental facilities of new generation, it became possible to produce a substance with extreme parameters in

* Corresponding author. Tel.: +7-495-788-56-99 (ext. 9388).
E-mail address: apkuznetsov@mephi.ru

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macroscopic quantities in a laboratory, thus ensuring obtaining of critical data on radiation physics, shock waves, hydrodynamic stirring of substances, equations of state, and relativistic plasma. Presently, one of the pressing problems of experimental HED physics is the development of methods and instruments for measuring various thermal characteristics of substances and studying their equations of state. When a substance is exposed to intense heating, its thermodynamic characteristics (pressure - P, temperature T, and density ρ) change. The thermodynamic state of a substance can be characterized by at least two parameters in different combinations: (ρ, T), (ρ, ε), (P, T), and (P, ε), whereεis the internal energy. To characterize the thermodynamic state of asubstance, it is necessary to measure, e.g., $P = P(\rho, T)$,$P = P(\rho, \varepsilon)$, and $V_S = V_S(\rho, \varepsilon)$, where $V_S$is the velocityof sound.During heating, the substance in the region ofinteraction may undergo several phase transitions(melting, evaporation, and transition to the plasmastate). In each of these phases, the substance possessescertain acoustic characteristics, such as the speed ofsound propagation and the coefficient of absorption αof an acoustic wave. In this case, the studied regionitself is a source of ultrasonic waves of certain frequency and amplitude.The speed of sound propagation in a solid isdirectly related to the substance temperature. The acoustic wave passes distance L in the substance within time $t = L(T)/V_S(T)$. Differentiating this equation in with respect to the temperature yields [Fortov et al. (2008)]

$$\frac{dt}{dT} = \frac{V_S(T)\frac{dL(T)}{dT} - L(T)\frac{dV_S(T)}{dT}}{V_S^2(T)} \tag{1}$$

Because substances expand during heating, both speed of sound$V_S$and path length L in a substance generally depend on the temperature T. However, for most substances, $(dL/L)dT \sim 10^{-6}$ K^{-1}, while $(dV_S/V_S)dT \sim 10^{-4}$K^{-1}; therefore, the thermal expansion of substances during heating can be disregarded and L can be considered constant. Then,

$$\frac{dt}{dT} = -\frac{L}{V_S(T)}\left(\frac{1}{V_S(T)}\cdot\frac{dV_S(T)}{dT}\right) = -\mu\frac{L}{V_S} \tag{2}$$

where coefficient

$$\mu = \frac{1}{V_S(T)}\cdot\frac{dV_S(T)}{dT} \tag{3}$$

characterizes the temperature dependent change in the velocity of sound in the substance.

Optical methods are used to generate sound in a wide frequency range from quite low acoustic (10– 10^4 Hz) to hypersonic (10^6–10^9 Hz) frequencies; however, because of the low efficiency of the light to acoustic energy conversion, the optoacoustic effect became practically applicable only after the appearance of lasers. The high intensity and directivity of laser radiation and the possibility of being focused into a spot, the dimensions of which are actually diffraction limited, ensure the excitation locality of acoustic waves, and the short pulse duration (10^{-8}–10^{-10} s) is the required time resolution of measuring the velocity of sound in the target substance.

2. 2. Experimental setup

Figure 1 shows the optical diagram of the experimental setup for measuring the velocity of sound in a condensed matter subjected to pulsed heating. Radiation of a pulsed Nd:YAG laser (wavelength λ= 1.064 μm) is focused with lens $L1$ to the target surface. Pulse duration τwas varied in experiments from 15 to 40 ns; the energy range was 1–100 mJ. Radiation focused at the targetsurface excites an acoustic wave that, propagating in the substance at velocity V_S, reaches the surface on the opposite side of a sample within time t. If thickness h of the target is known, measuring delay time t of the acoustic response relative to the optoacoustic action allows calculation of the velocity of sound (Fig. 1, inset): $V_S=h/t$. [Kuznetsov et al. (2006)].