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N.E. Aver'Anov, Yu. A. Baloshin, K.F. Bukhanov, I.V. Pavlishin, Yu. V. Sud'Enkov, et al.. Optical-acoustic effect in laser optics investigations. *Revue de Physique Appliquée*, 1990, 25 (5), pp.463-467. 10.1051/rphysap:01990002505046300 . jpa-00246206

HAL Id: jpa-00246206

<https://hal.science/jpa-00246206>

Submitted on 1 Jan 1990

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Classification
Physics Abstracts
61.80Ba

Optical-acoustic effect in laser optics investigations

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(Reçu le 15 décembre 1988, révisé le 21 juin 1989, accepté le 24 novembre 1989)

Résumé. — Les paramètres des signaux acoustiques générés par des impulsions de lasers TEA-CO₂ et Nd-glass dans des miroirs massifs en Al, Be et Cu ont été étudiés. Nous avons trouvé des corrélations entre les signaux acoustiques et l'apparition de dommages variés induits par laser tels que l'évaporation de défauts isolés thermiquement, la fusion et le breakdown optique des surfaces illuminées. La possibilité de faire une prédiction non destructive de la résistance de miroirs métalliques à l'endommagement laser est démontrée.

Abstract. — Parameters of the acoustic signals (AS) excited in the massive Al, Be and Cu mirrors by TEA CO₂- and Nd : glass-laser pulses were investigated. Correlations between the AS parameters and an emergence of different types of laser-induced damage such as evaporation of heat insulated defects, melting and optical breakdown off irradiated surface have been found. The possibility to make a nondisturbing prediction of the metal mirror resistance to laser-induced damage has been shown.

Introduction.

One of the manifestations of laser radiation interaction with a substance is the acoustic waves generation so called optoacoustic effect (OAE) [1, 2]. Being well investigated in gases and liquids, OAE in solids is now paid much attention to.

Laser optics resistance to laser induced damage greatly depends on an ability to absorb the laser radiation because at intense fluxes even small absorption can cause deformation and irreversible changes of the surface and volume of an optical material, that is its damage. In laser optics, among well known methods of light absorption measurement, such as photometry, calorimetry and others, the optoacoustic method is characterized by a great sensitivity [3].

OAE is of special interest for the study of metal optics resistance to laser induced damage [4, 5]. Mechanisms of the acoustic waves generation in metals at intense fluxes of laser radiation are varied and depend on an energy density inside the medium and on the way in which the absorbed energy is dissipated [6, 8]. At small energy densities when no changes of the substance aggregate state is produced in the absorption region, the acoustic waves generation is accounted for by an expansion of the heated

volume and the main effect can be described in terms of a linear theory of dynamic thermoelasticity [9-12]. When the energy density is increased nonlinear effects due to the variation of thermophysical parameters with temperature become more pronounced and some aggregate state changes occur such as melting and evaporation accompanied by considerable changes in physical properties of a medium and in radiation absorption mechanisms. Such processes are described by the nonlinear theory of thermoelasticity and hydrodynamics in terms of phase transition kinetics [13]. The increase of the energy density inside the medium results in a breakdown in a vaporized substance followed by the appearance of a light-detonation wave. In this case the optical breakdown determines acoustic wave generation. The necessity to take into account the state of the substance in the breakdown region as well as accentuated nonlinearity of the hydrodynamics effects makes theoretical description of this process rather difficult. The qualitative description of the phenomenon can be obtained in the approximation of the instantaneous mass-free explosion.

The advantage of the using OAE for the study of metal optics resistance to laser induced damage consists in the possibility of determinating not only small absorption coefficients but also a correlation

between acoustic signal characteristic and the mechanism of radiation interaction with the metal surface. This interaction mechanism being determined by radiation absorption dynamics which is related to the optics surface quality, the use of OAE could help to determine the quality of a metal surface. The present work explores the possibility to use OAE in a study of laser optics resistance to laser induced damage [4, 5, 14, 15].

Experiment.

Figure 1 shows the experimental installation scheme. It included a multimode TEA CO₂-laser [16] with the energy per pulse up to 15 J and a pulse shape as shown in figure 2a and with plane spatial distribution

Fig. 1. — Experimental installation scheme: 1) TEA CO₂-laser; 2) Nd : glass laser; 3) calibrated attenuators; 4, 5, 13) beamsplitters; 6, 7, 11) lenses; 8) calorimeter; 9) Drag-photon detector or coaxial photocell; 10) photoelectric multiplier; 12) interferometer mirror; 14) examined metal mirror; 15) PZT-piezotransducer; 16) He-Ne laser.

Fig. 2. — Temporal shapes of a) TEA CO₂-laser, b) Nd : glass laser.

of the output intensity as well as Q-switched Nd : glass laser generating 25-ns full width at a half maximum (FWHM) pulses with energy up to 3 J (Fig. 2b). Laser radiation was focused on the sample surface in a focal spot of about 0.5 cm². We obtained plasma formation thresholds E_p^s (at $\lambda = 10.6 \mu\text{m}$) and melt thresholds E_m^s (at $\lambda = 1.06 \mu\text{m}$) weakly depending on the spot dimension. This can explain small values of E_p^s and E_m^s compared with those for the little spot, given in [17]. Acoustic signals (AS) were registered by a PZT-ceramics piezo-transducer in acoustic contact with the back side face of the examined mirror. The thickness of the piezo-transducer, 2 mm, was chosen so that the time required for AS double-pass across the transducer exceeded the rise front of the acoustic pulse. The temperature rise under the laser pulse action was deduced from mirror surface shifts measured with Michelson interferometer. The mirror under study was used as one of the interferometer mirrors. The energy of laser pulses was measured with a calorimeter. The shape and peak power of the TEA CO₂-laser were detected with a drag-detector. The measurements were carried out at the open air. The plasma ignition was detected with a photomultiplier. The same photomultiplier was used for detection of a fringe shift in the interferometer. Massive metallic Al, Be and Cu mirrors were studied.

Experimental results.

AS excited in the mirrors of different materials exhibited similar characteristics and the distinctions were due to different absorption coefficients and thermophysical characteristics of the mirrors. Single-polarity AS corresponding to a free expansion of the heated volume of an ideal metal mirror were detected only for Cu mirrors irradiated with CO₂-laser pulses with energy density less than $0.6 E_p^s$ (Fig. 3a). In other cases (i.e. Al and Be mirrors and $\lambda = 10.6 \mu\text{m}$ as well as for all the mirrors irradiated at $\lambda = 1.06 \mu\text{m}$) there were detected a two-polarity AS with the expansion signal preceded by a short compressive spike of duration approaching that of the irradiating laser pulse (Fig. 3b). Such a type of AS can be attributed to the fact that AS generated by the pulse in the main material is accompanied with the AS resulting from the heat insulated defects. So we can say that the concentration of defects on the surfaces of the Al and Be mirrors is appreciably greater than on the Cu mirrors. This fact agrees with the results obtained in [18]. At irradiation of the Cu mirrors with $1.06 \mu\text{m}$ laser pulses and with pulse energy density appreciably smaller than E_m^s , appearance of the compression spike proves that the radiation interaction with the defects apart from other factors is influenced by the wavelength and the pulse duration. An estimate (1)

Fig. 3. — Acoustic signals, excited in metal mirrors with diameter of 60 mm and thickness of 10 mm by laser pulses, a) Cu mirror, $\lambda = 10.6 \mu\text{m}$, $S_p = 0$, b) Al mirror, $\lambda = 10.6 \mu\text{m}$, $S_p = 0$, c) Al mirror 1: $S_p/S_0 = 1$; 2: $0 < S_p/S_0 < 1$; 3: $S_p/S_0 = 0$, $\lambda = 10.6 \mu\text{m}$, $\tau_p = 3 \mu\text{s}$ at a level of 0.1, d) Be mirror $\lambda = 1.06 \mu\text{m}$, $\tau_p = 25 \text{ ns}$ FWHM, $S_p = 0$.

[19] shows that the heat insulated layers with thickness ℓ_0 or the heat insulated spheres with radius $\ell_0/2$ attained the boiling point when the energy density equals E_1^s

$$E_1^s = \frac{\rho c \cdot T_{\text{boil}} \cdot \ell_0}{A}. \quad (1)$$

In (1) A , ρ , c and T_{boil} are the radiation absorption factor, density, thermal capacity and the boiling point of the heat insulated defect material. When the energy density is E_1^s appreciable vaporization takes place and the compression spike is produced. AS obtained in our experiments indicate the presence of defects with $\ell_0 \geq 0.3 \mu\text{m}$ at the surface of Al and Be mirrors, and this is in agreement with [19]. The presence of defects having different values of ℓ_0 is proved by the fact that at repeated exposure of the sample surface to the same energy density, the compression spike disappeared which is related to the elimination of the defects with $\ell_0 = \ell_0^{\text{min}}$. With increasing of the irradiation energy density the compression spike reappeared. Such type of AS persisted up to E_p^s . The appearance of the compression spike correlates with the pre-threshold light emission by the irradiated surface (defect vapors

ionization) with a high degree of probability which increased with the irradiation energy density. The above process took place when the temperature of the main materials was appreciable lower than its melting point.

An estimate of the temperature rise averaged over the thermal diffusion depth ΔT_{vol} during the pulse can be obtained by solving of the quasi-stationary problem of the thermoelasticity, valid there due to stresses on the irradiated surface is zero [15]. In the above-mentioned approximation ΔT_{vol} is related to displacement of the reflective surface U by the expression

$$\Delta T_{\text{vol}} = \frac{1 - \nu}{1 + \nu} \cdot \frac{U}{2 \alpha_T \cdot \sqrt{a \tau_p}}. \quad (2)$$

In (2) a , ν , α_T are the thermal diffusivity coefficient, Poisson coefficient and the coefficient of linear thermal expansion of the mirror material respectively, τ_p is the laser pulse duration. The value of U was measured with the interferometer. The surface temperature rise ΔT_{surf} may be related to ΔT_{vol} by the coefficient n that can be obtained by solving the heat-flow equation [20]

$$\Delta T_{\text{surf}} = n \cdot \Delta T_{\text{vol}} \quad (3)$$

$$n = 2 \sqrt{a \tau_p} \int_0^{\tau_p} \frac{f(t) dt}{\sqrt{t}} \times \left[\int_0^\infty dz \int_0^{\tau_p} \frac{f(t) e^{-\frac{z^2}{4at}} dt}{\sqrt{t}} \right]^{-1} \quad (4)$$

$f(t)$ is an expression describing the temporal shape of the laser pulse. The value of n is equal to about 4 for TEA CO_2 -laser pulse and to about 2 for Nd: glass laser for Cu and Al both.

Table I gives the values of E_p^s (at $\lambda = 10.6 \mu\text{m}$) or E_m^s (at $\lambda = 1.06 \mu\text{m}$) and the values of ΔT_{surf} of the bulk material of the mirror deduced from the mirror surface shifts under the pulsed laser irradiation with the energy density E_p^s or E_m^s . We see that in the above described experimental conditions the surface

Table I. — Plasma and melting thresholds (E_p^s and E_m^s) and surface temperature rise ΔT_{surf} of the bulk material of the mirrors irradiated with TEA CO_2 and Nd: glass laser pulses.

Mirror material	λ , μm	E_p^s , J/cm^2	E_m^s , J/cm^2	T_{surf} , K
Cu	10.6	22.0	—	280
Cu	1.06	—	5.0	350
Al	10.6	12.0	—	350
Al	1.06	—	1.5	520

temperature rise of the bulk material was less than 300 K when the energy densities were equal to E_p^s or E_m^s . This fact demonstrates a key role of the surface defects in the laser-substance interaction processes in this case. Under TEA CO₂-laser pulses the optical air breakdown was found to occur with a time delay of 100-150 ns when the leading spike falls off. The shape of AS under the optical breakdown off the sample surface and without the breakdown were differ and depended on the ratio of the area covered with plasma S_p to the total area of the irradiated spot S_0 (Fig. 3c).

Taking into account that at $\lambda = 10.6 \mu\text{m}$ $E_p^s < E_m^s$, for detecting AS at melting of the samples surface the samples were irradiated with Nd : glass laser which provides the inverse relation between thresholds. In this case the melting threshold corresponded to the sharp increase of AS amplitude caused by the jump of the absorption coefficient and of the thermophysical characteristics of the material at transition to the liquid state. The melting was registrated by the melt traces that surrounded the heat insulated defects at the surface. Figure 4a shows a relation between the amplitudes of AS U_{ac} excited in Cu mirrors by the Nd : glass laser and irradiation energy density E^s . Nonlinear rise of AS begins with melting of the mirrors material. The highest energy points of the graphs correspond to laser-induced breakdown threshold off the mirror surface.

It is clear that the quantities of E_p^s and E_m^s are related to the energy absorbed by the mirror surface. Pulsed character of the opto-acoustical measurements helps us to find relative values of the integral absorption coefficients more accurate [21] than with other methods as well as to establish their relation to E_p^s and E_m^s . In our experiments there was investigated a relation between the values of plasma and melting thresholds and the AS amplitudes excited in identical mirrors at some laser energy density below thresholds. Figure 4b shows graphs of AS amplitude U_{ac} as a function of energy density E^s for three Be mirrors (Tab. II) irradiated with CO₂-laser pulses. It was found that the greater is the value of E_p^s of the

Table II. — Plasma thresholds E_p^s near the surface of the Be mirrors having different surface characteristics.

No.	Mirror reflection coefficient R, %	E_p^s , J/cm ²	rms roughness Å	AS amplitude at $E^s < E^s$, rel. unit
1	96	8.4	110	1.0
2	98	12.0	25	0.45
3	98	10.0	50	0.60

Fig. 4. — Dependence of the acoustic signals amplitudes U_{ac} excited a) in two Cu mirrors by Nd : glass laser pulses, b) in three Be mirrors (Tab. II) by TEA CO₂-laser pulses on the irradiation energy density E^s .

sample, the less is the AS amplitude. It is to be noted that samples 2 and 3 have similar absorption factors as measured by the multiple reflection method, but however they exhibit different E_p^s values. This proves that the optoacoustical method is more accurate and permits first of all to eliminate error due to scattering of light. The observed relation between E_p^s and E_m^s on the one hand and the AS amplitudes on the other was established at the exposure of the Cu mirrors to the Nd : glass laser (Fig. 4a).

Conclusions.

These experiments have established a certain relation between the processes on a metal mirror surface and the acoustic response parameters under laser irradiation. In particular, the optical breakdown was found to cause a sharp fall of the AS expansion and the change of its form. At melting we observed a non-linear enhancement of the AS ampli-

tude. Heating and evaporation of the heat insulated defects give rise to a short compression spike preceding the expansion AS. It was shown that the optico-acoustic method allows one to distinguish between processes involving surface defects and those in the metal optics bulk.

There was observed a correlation between the AS amplitudes excited in identical mirrors by laser pulses having a fixed energy density and hot causing surface damage and the melting and plasma thresholds off the metal mirror surface. This correlation can be used for nondestructive control of the threshold effect on the metal optical surface.

For a practical use of the optoacoustic method in quality control of metal optics mirrors, further experiments at waves of different lengths and irradiation pulse durations as well as with different materials and surface treatment techniques are in progress. They are needed in order to find simple

empirical relationships between the AS parameters and the wavelength, irradiation pulse duration and the others (which is quite possible) parameters of the laser pulse.

The knowledge of the dependence of these relations on the optical surface quality as well as the availability of a set of calibration curves could permit a nondestructive quality control of the metal optics elements and to predict the damage thresholds of the metal mirror surfaces.

In conclusion it is to be noted that in order to eliminate the influence of acoustic properties of the bulk of mirror material on the AS parameters we are carrying out measurements with the use of interference methods for AS registration. This will allow us to increase the sensitivity of the optoacoustic method when measuring absorption coefficients and to go over from relative measurements to absolute ones.

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(¹) A cover-to-cover translation of this journal called « Quantum Electronics » in English is published by the American Institute of Physics, 335 East 45th Street, New York, N.Y. 10017 U.S.A.