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THERMAL DEFOCUSING OF A GIANT MONOIMPULSE IN A LINEARLY ABSORBING LAYER

D. SENDERÁKOVÁ[1]), P. VOJTEK[2]), Bratislava

In the paper presented thermal defocusing of a giant impulse of a ruby laser passively Q-switched in linearly absorbing layers has been investigated theoretically and experimentally. The absorbing medium were layers of nitrobenzene and ethanol solutions of a brilliant green with a thickness of $h = 1$ mm and transmittance of $T \in (0.3—0.6)$. The experimental results obtained have confirmed the assumption that the defocusing of the intensive part of the monoimpulse occurs by a thermal lens created by the part of the pulse generated and absorbed before its intensive part. The results have helped to obtain information connected with the parameters of the laser cavity as well. The paper demonstrates simultaneously the usefulness and accuracy of the experimental method used and based on the transformation of a Gaussian beam by an ideal lens.

ТЕПЛОВАЯ ДЕФОКУСИРОВКА ГИГАНТСКОГО ИМПУЛЬСА В ЛИНЕЙНО ПОГЛОЩАЮЩЕМ СЛОЕ

В данной рабoде рассматриваются теоретические и экспериментальные вопросы тепловой дефокусировки гигантского импульса рубинового лазера с пассивной модуляцией добротности в линейно поглощающих слоях. В качестве поглощающей среды использовались пленки растворов бриллиантовой зеленой в нитробензоле и спирте толщиной $h = 1$ мм и с коэффициентом пропускания $T = 0{,}3—0{,}6$. Полученные экспериментальные результаты подтверждают предположение, что дефокусировка интенсивной части моноимпульса происходит на тепловой линзе, возникающей за счет поглощения энергии длительного, но маломощного переднего фронта импульса. Результаты позволяют получить и сведения о параметрах резонатора лазера. В статье также продемонстрированы полезность и надежность использованного экспериментального метода, основанного на преобразовании гауссовского пучка идеальной линзой.

[1]) Inst. of Physics and Biophysics J. A. Komenský University, Mlynská dolina F2, 842 15 BRATISLAVA, Czechoslovakia.

[2]) Dept. of Exp. Physics, Fac. of Math. and Phys. J. A. Komenský University, Mlynská dolina F2, 842 15 BRATISLAVA, Czechoslovakia.

I. INTRODUCTION

Studying thermal changes of the refractive index of linear absorbers, occurring when pulses of a passively Q-switched ruby laser are passing through them, a change of radial energy distribution of the passing pulse has been obtained under certain conditions [1]. Investigating the nonlinear absorption of pulses of a passively Q-switched laser ($\lambda = 532$ nm) passing through solutions of organic dyes the same effect has been observed [2]. The effect was interpreted as the defocusing of an intensive monoimpulse by a thermal negative lens created by the absorption of energy which had been absorbed before the monoimpulse. Supposing the intensity of the absorbed light not to depend on time and to have the radial distribution expressed by the function cos, approximate calculations have confirmed this interpretation [2].

The purpose of this paper is to verify this model of the defocusing of a passively Q-switched laser monoimpulse under our conditions. We used linear absorbers and a ruby laser. The solution of vanadium phtalocyanine (VOPc) in nitrobenzene was used as a passive Q-switch. The experimental set-up ensured a definite radial distribution of the monoimpulse intensity. There is expressed the optical power of a thermal lens being created in the layer of an absorber if we suppose the model of defocusing [2] to be valid in the theoretical part of this paper. We supposed the radial intensity distribution to be Gaussian and the time development of it to be exponential. The experimental results have been obtained by using a method based on the transformation of a Gaussian beam by an ideal lens [3].

II. THEORETICAL PART

If a light impulse with the intensity

$$I(\xi, t) = I_0 f(t) F(\xi) \tag{1}$$

passes through a linearly absorbing layer with the absorption coefficient α, the refractive index n_0 and the thickness h, it induces a lens with the optical power [3]

$$\phi(\xi, z, t) = (1 - n_0)/R(\xi, z, t) \tag{2a}$$

in the layer where

$$R(\xi, z, t) = [1 + (\partial\Delta/\partial r)^2]^{3/2}/(\partial^2\Delta/\partial r^2) \tag{2b}$$

$$\Delta = \int_0^h \Delta n(\xi, s, t)\, \mathrm{d}s \tag{2c}$$

$f(t)$ is the time development of the light pulse and $F(\xi)$ is the Gaussian function $F(\xi) = \exp\{-\xi^2\}$; in our case, where $\xi = r/w(z)$, $w(z)$ is the radius of the intensity distribution at the distance z from the waist of the Gaussian beam created by the light pulse in space, $\Delta n(\xi, s, t)$ is the refractive index change in the plane s in the layer at the time t (Fig. 1).

We shall express the refractive index change $\Delta n(\xi, s, t)$ supposing the thermal influence upon the refractive index owing to the absorption of energy generated by the laser. The Lorentz-Lorenc relation for isotropic liquids gives the refractive index change as being connected with the heating of the layer, i. e. with the change of its density

$$\Delta n(\xi, s, t) = c_\varrho \Delta\varrho(\xi, s, t) \tag{3}$$

where

$$c_\varrho = [(n_0^2 - 1)(n_0^2 + 2)]/6 n_0 \varrho_0. \tag{3a}$$

The density change $\Delta\varrho$ can be obtained by solving the linear hydrodynamic equations either in the form [4]

$$\Delta\varrho_1(\xi, s, t) = \frac{\psi(\xi)}{w^2(s)} \int_0^t \mathrm{d}t' \int_0^{t'} p_T(0, s, t'')\, \mathrm{d}t'' \tag{4a}$$

for $t < t_s = \sqrt{2}\, w(s)/v$, where v is the velocity of sound in the medium, or in the form

$$\Delta\varrho_2(\xi, s, t) = c F(\xi) p_T(0, s, t)/v^2 \tag{4b}$$

for $t \geqslant t_s$. The expression of the function $\psi(\xi) = F'' + F'/\xi$ is $\psi(\xi) = 4(\xi^2 - 1)\exp\{-\xi^2\}$ for the Gaussian radial intensity distribution, p_T is the thermal pressure occurring in the layer as a result of light absorption

$$p_T(0, s, t) = \Gamma\alpha \int_0^t I(0, s, t)\, \mathrm{d}t \tag{5}$$

where $\Gamma \doteq 2$ for liquids [4].

The characteristic time development of the radiation intensity in the cavity (Fig. 2) follows from the analysis of the dynamics of the passively Q-switched laser generation [5]. The conditions necessary for lasing are not satisfied in the region A and the intensity expresses a noise level. Its value usually is $i = (1 - 100)$ W/m^2 for ruby lasers. The generation arises in the region B with the intensity of light increasing exponentially in the cavity. When it approaches the value I_1 the passive Q-switch begins to bleach. $I_1 = 2.5 \times 10^8$ W/m^2 for VOPc in nitrobenzene. The value $t_p \sim (10^{-7}$—$10^{-6})$ s depends on the conditions in the cavity. The region C belongs to the lasing of the monoimpulse of a duration $t_i \sim 3 \times 10^{-8}$ s [5].

If we suppose the refractive index change to be due to the part B of the pulse, we can choose the function $f(t)$ in the relation (1) in the form

$$f(t) = \exp\{at/t_p\}. \tag{6}$$

The constants I_0 and a can be determined from both the conditions $I((0, 0) = i$ and $I(0, t_p) = I_1$, i. e. $I_0 = i$ and $a = \ln (I_1/i)$.

The exponential time development of intensity in the cavity is valid if the time development of the population inversion in an active medium of the laser may be neglected. Its maximum change occurs during the bleaching of the Q-switch in the region C [5]. The transmittance of the Q-switch does not change in the region B, therefore we can neglect the time development of the population inversion for the sake of simplicity. In this case the system of equations, describing the feature of a passively Q-switched laser is reduced to the equation expressing the density of radiation in the cavity u [J/m³] [5]:

$$\frac{du}{dt} = v^*\left[k_a - k^+ - \frac{\alpha(v_g)l_a}{l}\right]u + \varepsilon^* \tag{6a}$$

where $v^* = c.l.n/(L + l.n)$, c is the velocity of light, l, n are the length and the index of refraction of an active medium of the laser, $L = l_R - l$, l_R is the length of the cavity, k_a is the coefficient of amplification of the active medium, k^+ is the coefficient determined by the reflectance of the cavity mirrors, the length and the absorption coefficient of the active medium, α, l_a is the absorption coefficient and the length of the passive filter (Q-switch). If we can neglect the other sources oscillating at the frequency of the generation v_g, i. e. $\varepsilon^* = 0$, then the exponential time development of intensity in the cavity may be obtained by solving equation (6a) in the form

$$I = I_0 \exp\{t/\tau\} \qquad [\mathrm{W/m^2}] \tag{6b}$$

where

$$1/\tau = v^*\left[k_a - k^+ - \frac{\alpha l_a}{l}\right]. \tag{6c}$$

By comparing the relations (6b) and (6) we can obtain the connection between the constants a, t_p determined experimentally and the cavity parameters influencing the time development of the intensity in it

$$[\ln (I_1/i)]/t_p = 1/\tau. \tag{6d}$$

As the time in the experiment $t_s \leq 7\times10^{-8}$ s and $t_p \sim (10^{-7}—10^{-6})$ s according to [5] we can suppose the time $t = t_p$ when the intensive monoimpulse C probes the refractive index change created to be $t > t_s$. Therefore the density change may be expressed according to relation (4b). The proportionality constant is determined from the condition

$$\Delta\varrho_1(\xi, s, t_s) = \Delta\varrho_2(\xi, s, t_s). \tag{7}$$

These considerations give the expression of optical power of the lens induced in the absorbing layer in the form

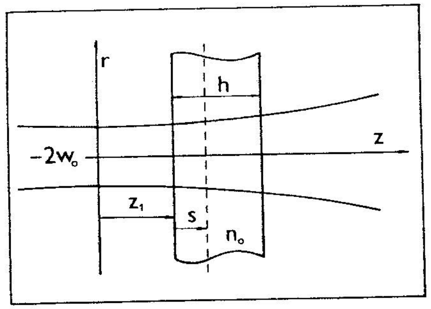

Fig. 1. Scheme for obtaining optical power of a lens created in the layer by a Gaussian beam.

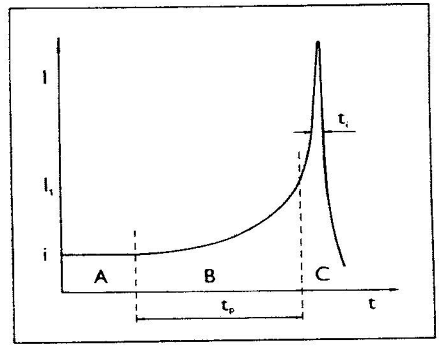

Fig. 2. Time development of a monoimpulse of a passively Q-switched laser.

$$\Phi(z_1, t_p) = \frac{16(n_0 - 1)}{w_0^4}\beta c_\varrho \alpha \Gamma i c_T \frac{w_0^2}{w^2(z_1)}\int_0^h \frac{\exp\{-\alpha s\}}{[w^2(s)/w_0^2]^2}\,ds \tag{8}$$

where

$$c_T = \frac{t_p}{a^3}\frac{\exp(x_s) - 1 - x_s - x_s^2/2}{\exp(x_s) - 1}[\exp(a) - 1] \tag{9a}$$

and $x_s = at_s/t_p$. The knowledge of both the propagation of the Gaussian beam in space and the linear absorption

$$I(0, s, t) = \beta i \exp\{-\alpha s\}\frac{w_0^2}{w^2(s)}f(t) \tag{9b}$$

where w_0 is the Gaussian beam waist, β is a coefficient determined by experimental conditions (it connects the axis intensity at the entrance plane of the layer in the waist and the intensity i in the cavity) was used to express the intensity $I(0, s, t)$ in relation (5). The radius of the beam was determined at the plane s of the layer as

$$w^2(s) = w_0^2\left[1 + \frac{(z_1 + s/n_0)^2}{k^2 w_0^4}\right] \tag{9c}$$

where $k = 2\pi/\lambda$ and z_1 is the distance between the entrance plane of the layer and the waist (Fig. 1). We supposed an ideal lens to have been created in the layer, i. e. $\Phi(\xi, z_1, t) = \Phi(0, z_1, t)$.

The Gaussian beam belonging to the intensive monoimpulse is transformed by the thermal lens having an optical power (8). Assuming the contribution of the monoimpulse to the induced change of the refractive index to be neglected during the existence of the monoimpulse, the relative energy density of the monoimpulse on the Gaussian beam axis at the distance $z' \gg w_0^2/\lambda$ depends on the optical power of the lens as

$$1/E_R = \Phi^2[Z^2 + k^2 w_0^4] - 2\Phi Z + 1, \qquad (10)$$

while

$$E_R = E(0, z', \Phi)/E(0, z', 0)$$

$$Z = z_1 + h_s/n_s + h/n_0$$

where h_s, n_s are the thickness and the refraction index of the wall of the cell filled with a linearly absorbing medium.

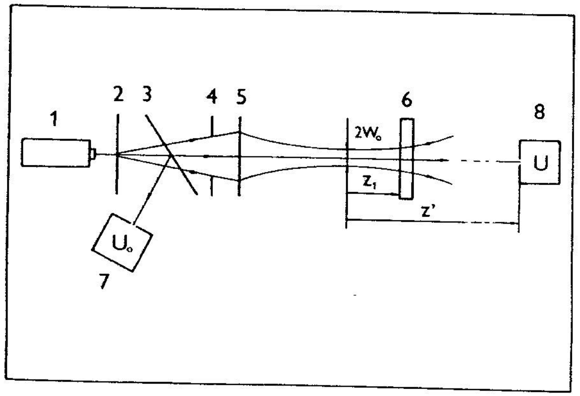

Fig. 3. Experimental set-up for the study of thermal defocusing of a monoimpulse in linear absorbers. 1 — passively Q-switched ruby laser, 2, 4 — apertures, 3 — beam splitter, 5 — positive lens ($f = 0.148$ m), 6 — cell filled with linear absorber, 7, 8 — energy detectors.

III. EXPERIMENTAL PART

The thermal defocusing of the monoimpulse irradiated by a passively Q-switched (VOPc in nitrobenzene) ruby laser has been studied in the experimental arrangement shown in Fig. 3. A ruby laser 1 operated in the monoimpulse mode. A set consisting of apertures 2 and 4 and a positive lens 5 ensured a Gaussian space intensity distribution of the pulse with the waist of $w_0 = 2.4 \times 10^{-5}$ m. The absorbing layer was formed by either an ethanol or a nitrobenzene solution of a brilliant green organic dye. The thickness of the layers was of $h = 1$ mm and their transmittance was $T \in (0.3—0.6)$. The solutions were placed in glass cells with walls of a thickness of $h_s = 2.6 \times 10^{-3}$ m and the refractive index $n_s = 1.52$. Moving the absorbing cell 6 along the axis of the beam ensured a defined continuous change of the intensity of light entering the investigated layer. The signal of a semiconductor detector 8 connected with an oscilloscope [7] was the measure of the axis energy density of the monoimpulse after it had passed through the layer 6. The signal of the detector 7 was the measure of the energy density of the monoimpulse entering the layer if we considered the position of the layer in the beam. The result obtained experimentally is the dependence of the relative energy density on the axis of the pulse at the far region $z' \doteq 1.5$ m, after the pulse has passed the absorbing layer, vs the position z_1 of the layer in the beam

$$E_R = E(0, z', \Phi)/E(0, z', 0) = f(z_1)$$

where $E = (U/U_0)/[w_0^2/w^2(z_1)]$. The value of $E(0, z', 0)$ was determined when the position of the cell 6 was $z_1 = z'$, i. e. we could suppose $\Phi \rightarrow 0$. The patterns of these dependences are in Fig. 4. The maximum of the dependence $E_R = f(z_1)$ in the

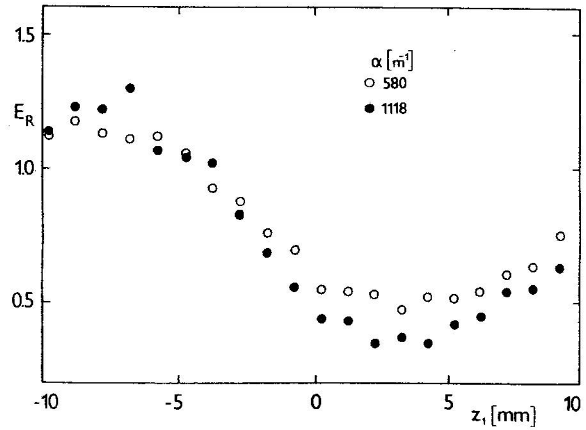

Fig. 4. Dependence of the relative energy density of a monoimpulse on the beam axis after it has passed through the absorbing layer vs the position of the layer in the beam.

converging part of the beam and its minimum in the diverging part are characteristic of the Gaussian beam transformed by a negative lens. It follows from the analysis of relation (10) for $\Phi \gtrless 0$. The negative lens may arise as a result of the absorption of light and the following local heating of the medium through which the intensive light wave is passing. The experimental results obtained show the thermal defocusing of a monoimpulse generated by a pawsively Q-switched ruby laser when it passes through a linearly absorbing medium.

IV. DISCUSSION

The experimental results obtained in the diverging part of the beam have been processed into the values of the optical powers of the negative lens induced in the layer by solving the quadratic equation (10). It follows from relation (8) that the dependence $\Phi(J)$ where

$$J = c_T \frac{w_0^2}{w^2(z_1)} \int_0^h \frac{\exp\{-\alpha s\}}{[w^2(s)/w_0^2]^2} \, ds \tag{11}$$

should be linear if the model presented in the theoretical part was valid in our experiment. It is necessary to know the duration t_p of part B (Fig. 2) of the monoimpulse for processing the experimental results so as to obtain the dependences $\Phi(J)$. Hence the time t_p was determined by solving equation (8) for each experimental value of Φ. Fig. 5 shows the dependence $t_p(z_1)$ obtained in such a way. In our calculations we used the value $i = 10$ W/m², $I_1 = 2.5 \times 10^8$ W/m² and

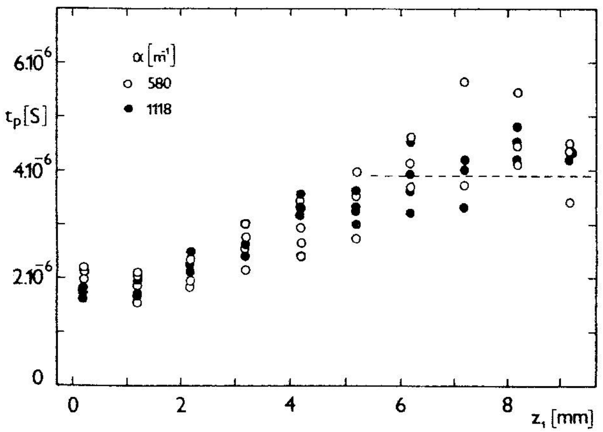

Fig. 5. Duration of generation of part B of the laser pulse, calculated from optical powers in different positions of the layer in the beam.

$\beta = 4.7$. The coefficient β is determined by the reflectance of the elements of the experimental set-up, by the diffraction loss and by the ratio $(r_c/w_0)^2$, where $r_c = 6.5 \times 10^{-5}$ m is the radius of the aperture 2.

The value of t_p may be changed only if the conditions in the laser cavity have been changed. We can see from Fig. 5 that t_p does not change in the wide beam, i. e. if the intensity of light entering the layer is small. Its fluctuations are only statistical and are connected with the random changes of conditions of lasing and the error of the experimental determination of the optical powers Φ. The value of t_p obtained in such a way was used for processing the experimental results obtained so as to get the dependences $\Phi = a_1 + a_2 J$ (Fig. 6).

We can suppose the dependence $\Phi(J)$ to be linear within the experimental errors in the region of small values of J, i. e. of small intensities and wide cross-sections of the beam. According to relation (8) we can get the parameters of the linear part of the dependence $\Phi(J)$ in the form

$$a_1 = 0 \tag{12a}$$

$$a_2 = \frac{16(n_0 - 1)}{w_0^4} \beta c_e \alpha \Gamma i. \tag{12b}$$

Since all the experimental results have been obtained in the same experimental set-up we can verify the validity of the model of the refractive index change by comparing the values of

$$q = (a_2/\alpha)_{C_2H_5OH} / (a_2/\alpha)_{C_6H_5NO_2}$$

which have been determined both experimentally and theoretically. Relation (12b) gives the value $q_{th} = 0.601$. To calculate it we have used the values

C_2H_5OH	$n_0 = 1.36$	$\varrho_0 = 0.789 \times 10^3$ kg/m³
$C_6H_5NO_2$	$n_0 = 1.55$	$\varrho_0 = 1.200 \times 10^3$ kg/m³

The value determined experimentally is $q_{exp} = 0.60 \pm 0.07$.

The fact that the average value of duration of generation in part B determined from all the experimental results in the wide beam is $\bar{t}_p = (3.9 \pm 0.2) \times 10^{-6}$ s confirms the correctness of the model of the monoimpulse defocusing, presented in the theoretical part. The value of $\bar{t}_p$ agrees with data mentioned in [5].

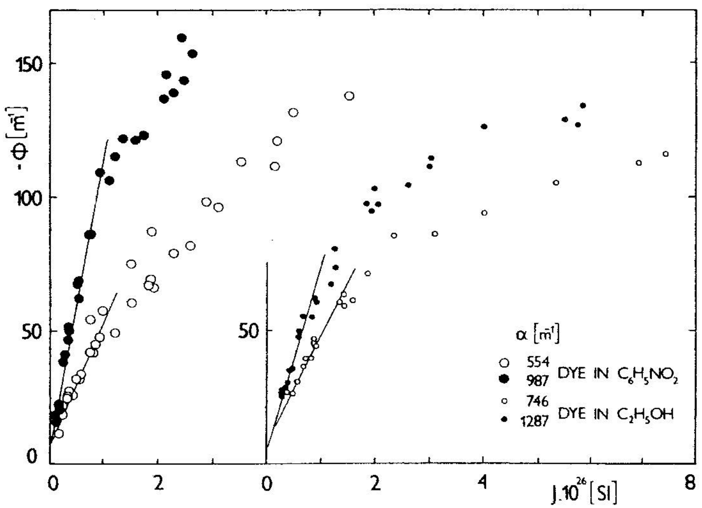

Fig. 6. The dependences of optical powers of the layer, obtained experimentally vs parameter J (11).

Assuming the exponential time development (6) of the intensity in the cavity we can get $t_p = 3.9 \times 10^{-6}$ s and the average energy irradiated by part B of the monoimpulse (Fig. 2) into the waist $\bar{W}_B \doteq 5 \times 10^{-7}$ J. The energy of the monoimpulse (part C) may be determined from studying the absorption of the monoimpulse of the same laser in a nonlinear absorber [8], $\bar{W}_C \doteq 5 \times 10^{-5}$ J, which means that the signal of the energy detector was a measure of energy of the monoimpulse C which has probed the refractive index change created by part B, as we have supposed.

As we can see from Fig. 6, the slope of dependences $\Phi(J)$ decreases with rising values of J, which means higher intensities. We suppose the inducing of a nonideal lens in the absorbing layer by a Gaussian beam to be the most probable reason of this decrease. The optical power of this lens is a function of a radial coordinate (2a). It may lead to an increase of the axis energy density measured experimentally, i. e. to determining the value of Φ less than it is in reality by solving Eq. (10). The experiments with pure solvents did not result in inducing an observable positive lens in the layer owing to either a high-frequency Kerr effect or electrostriction. Because of the fact that photographic records of the transverse energy density distribution of the monoimpulse have a discrete circular structure we suppose the refractive index change to be negligible during the probe monoimpulse C.

V. CONCLUSION

In the paper we have studied the thermal defocusing of the monoimpulse of a passively Q-switched ruby laser in linear absorbers. The experimental results have confirmed the theoretical model of this supposed defocusing. They were obtained by an experimental set-up which ensured the investigation into the thermal refractive index change at the time t, longer than the characteristic hydrodynamic time t_s. The use of lineár absorbers eliminated the possibility of a nonlinear absorption influence upon the result obtained. At the same time the experimental results have shown that the experimental method based on the transformation of a Gaussian beam by an ideal lens [3] is suitable and sufficiently precise. The results enable to get information on both the duration of generation before the monoimpulse is irradiated and the parameters of laser cavity if we know the values of I_1 and i. Hence the paper can be a contribution to the results of [2], where the authors used a different experimental set-up, nonlinearly absorbing layers, and observed the refractive index change at the time $t < t_s$.

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