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Acoustic processes in RF excited CO_2 laser plasma in pulse regime

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Acoustic response to the CO_2 laser pulse generation in the arrangement of the slab-waveguide structure is considered. The velocity of an acoustic wave in the carbon dioxide laser gas medium is calculated, and simulation of the wave intensity distribution during the laser plasma pulse developing in the laser cavity is shown. Representation of the laser spectral phenomena in the acoustic signal shape is investigated. The influence of the acoustic wave on the laser frequency operation is considered.

Keywords: CO_2 laser, molecular laser, gas laser, pulse operation, thermodynamic phenomena.

1. Introduction

Application of the CO_2 lasers in industry is known [1]. The CO_2 laser, very often called a "laser horse", is an excellent tool in laser material processing, *e.g.*, cutting, welding, and hardening [2]. As known, a pulse regime of the laser is the most effective in the laser material processing. In some applications, it is important to have a single mode laser operation at a chosen emission line even in a pulse regime. It is known that some plastic materials, like polyethylene, have relatively narrow absorption bands in the region of CO_2 laser radiation for the chosen laser lines [3]. In this work, we consider acoustic processes in CO_2 laser plasma to get information about spectral behavior of the laser in a pulse regime. The experiments base on observations of the thermodynamic processes in a gas CO_2 laser. In pulse regime, we can expect changes in pressure, temperature, density of the gas and finally in the refractive index. The thermodynamic processes in gas are inseparably connected to acoustics. We give a theoretical background to explain acoustic wave propagation in the laser plasma.

2. Acoustic wave generation in laser plasma

Delivery of thermal energy to a gas volume unit as a result of the laser medium excitation or optical beam power changes can cause fluctuations of the gas physical parameters. In this work, the following parameters are taken: $P + p$ – total gas pressure (static gas pressure + change in pressure related to thermal energy); $\rho + \delta$ – total gas density (static gas density + change in density related to thermal energy); $T + \tau$ – total gas temperature (static gas temperature + change in temperature related to thermal energy); $S + \sigma$ – total gas entropy (static gas entropy + change in entropy related to thermal energy); where "static" means the value of the parameter in an equilibrium state of gas – without introducing any external energy [4].

Introducing thermal energy to the gas volume creates an acoustic wave. The equation of the wave can be calculated from the equation of continuity for mass flow:

$$\frac{\partial \rho}{\partial t} + \operatorname{div}(\rho \mathbf{u}) = \rho q(r, t) \tag{1}$$

where: ρ – gas density, t – time, $\mathbf{u}$ – gas velocity vector, q – volume growth of a gas coefficient caused by introducing energy.

Changes in gas density are the result of pressure and temperature changes:

$$\delta = \left(\frac{\partial \rho}{\partial P}\right)_T p + \left(\frac{\partial \rho}{\partial T}\right)_P \tau = \gamma \rho \kappa_S (p - \alpha \tau) \tag{2}$$

where: δ – change in gas density, κ_S – isothermal expansion, p – change in gas pressure (acoustic pressure), τ – change in temperature, $\alpha = (\partial P/\partial T)_V = \beta/\kappa_T \to P/T$ (for a perfect gas), $\gamma = c_p/c_v$, c_p – heat capacity per unit mass at constant pressure, c_v – heat capacity per unit mass at constant volume.

Change in gas density with time can be written using expression (2):

$$\frac{\partial \rho}{\partial t} \equiv \frac{\partial \delta}{\partial t} \cong \gamma \rho \kappa_S \frac{\partial}{\partial t}(p - \alpha \tau) \tag{3}$$

Inserting Eq. (3) into Eq. (1), we obtain:

$$\gamma \rho \kappa_S \frac{\partial}{\partial t}(p - \alpha \tau) + \operatorname{div}(\rho \mathbf{u}) = \rho q(r, t) \tag{4}$$

After some mathematical manipulations Eq. (4) can be rewritten as:

$$\rho \kappa_S \frac{\partial p}{\partial t} - \frac{\gamma \rho \kappa_S \alpha \xi}{c_p} + \rho \operatorname{div}(\mathbf{u}) = \rho q \tag{5}$$

where ξ denotes thermal energy per unit mass.

After differentiating the Eq. (5) with respect to time and Euler equation substitution, we obtain:

$$\rho \kappa_S \frac{\partial^2 p}{\partial t^2} + \operatorname{div}\left[-\operatorname{grad}(p)\right] = \frac{\partial}{\partial t}\left(\frac{\gamma \kappa_S \alpha}{c_p} H\right) \tag{6}$$

where H denotes density of thermal energy (thermal energy per unit volume), and $H = \rho \xi$.

The expression multiplied by the pressure differentiated with respect to time is the constant value, which can be written as a sound velocity

$$c^2 = \frac{1}{\rho \kappa_S} \tag{7}$$

The coefficients accompanied by thermal energy in Eq. (6) are (for a perfect gas):

$$\frac{\gamma \kappa_S \alpha}{c_p} = \frac{\gamma - 1}{T \beta c^2} \rightarrow -\frac{\gamma - 1}{c^2} \tag{8}$$

Finally, inserting Eqs. (7) and (8) to Eq. (6), we obtain an equation which links pressure changes and introduces thermal energy. It is the wave equation:

$$\frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} - \nabla^2 p = \frac{\gamma - 1}{c^2} \frac{\partial H}{\partial t} \tag{9}$$

The introduction of power to a laser plasma and fluctuations of an optical (laser) beam are the sources of acoustic waves in the laser gas media.

3. Velocity of the acoustic wave in the laser gas mixture

The medium of the researched laser is a gas mixture (CO_2, N_2, He). During the laser operation, plasma reaches the temperature of 600 K. In such medium, sound velocity is much more different than in the air.

The sound wave propagation is described by the wave equation

$$\frac{\partial \rho}{\partial t} = -\frac{1}{c_D^2} \frac{\partial p}{\partial t} \tag{10}$$

where: ρ – change in medium density, p – change in pressure, c_D – sound velocity, t – time.

The ratio of pressure increment to medium density increment is constant. It defines sound wave propagation velocity [4]:

$$c_D = \sqrt{\frac{\mathrm{d}p}{\mathrm{d}\rho}} \tag{11}$$

The medium density change caused by medium perturbation related to sound propagation is related to volume change

$$\mathrm{d}\rho = -\frac{m \mathrm{d}V}{V^2} \tag{12}$$

where: m, V – mass and volume of the medium where acoustic wave propagates.

Thus sound velocity dependence (11), after taking into account a relation (12), is

$$c_D = \sqrt{-\frac{V^2 \mathrm{d}P}{m \mathrm{d}V}} \tag{13}$$

where P is the total pressure in a certain point (static pressure + pressure change).

According to the Laplace theory, acoustic wave propagation is considered as the adiabatic process. Thus from adiabatic equation we obtain:

$$PV^{\gamma} = \text{const} \tag{14}$$

where γ is the ratio of heat capacity per unit mass at constant pressure to heat capacity per unit mass at constant volume.

The product of pressure and volume is a constant value, so the differential expression (14) must be equal to zero:

$$V^{\gamma}\mathrm{d}P + \gamma V^{\gamma-1} P \mathrm{d}V = 0 \tag{15}$$

After transformation we obtain:

$$\frac{\mathrm{d}P}{\mathrm{d}V} = -\gamma \frac{P_0}{V} \tag{16}$$

where P_0 is the static gas pressure – without acoustic perturbations.

After substituting the relation (16) to the formula (13) and using the Clapeyron equation, we obtain the sound velocity formula in gas

$$c_D = \sqrt{\frac{\gamma R T}{M}} \tag{17}$$

where: R – Boltzman constant, M – medium mole mass.

It should be mentioned that the Clapeyron equation concerns the perfect gas. According to this assumption, a sound velocity is non-pressure dependent. In non-ideal gases, the velocity depends on the gas pressure. However, the above assumption approximates well the reality. The researched medium is a three-gas mixture, so parameters γ and M are calculated as mean values according to the expression below, taking into account the fraction of the gas in the mixture (CO_2 – 20%, N_2 – 20%, He – 60%):

$$\bar{x} = f_{CO_2} x_{CO_2} + f_{N_2} x_{N_2} + f_{He} x_{He} = \frac{1}{5} x_{CO_2} + \frac{1}{5} x_{N_2} + \frac{3}{5} x_{He} \tag{18}$$

where $x = \gamma$ or M depending on the calculated parameter.

Assumed values and obtained results are presented in the Table. By comparison, the data related to the air are also shown.

Ratio γ/M of the laser gas mixture is much higher than that in the air. Therefore, a sound velocity in the mixture grows faster with temperature than in the air. Outside

T a b l e. Values of medium parameters assumed to sound velocity calculations.

	CO_2	H_2	He	Mixture	Air
γ	1.300	1.398	1.660	1.5356	1.4398
M [g/mol]	44.009	28.014	4.003	16.8064	1.29
R [J/(K mol)]	8.31434	8.31434	8.31434	8.31434	8.31434

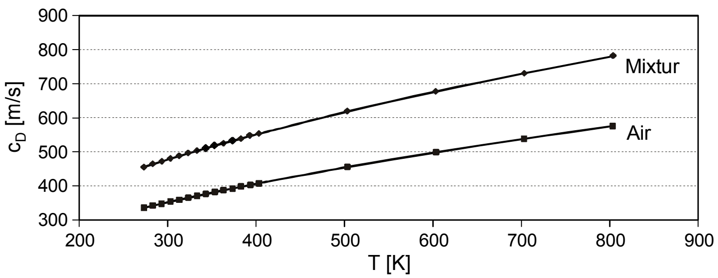

Fig. 1. Sound velocity c_D in laser CO_2 mixture and in the air versus temperature T.

the laser plasma region we assumed the mixture temperature to be equal to 288 K (because of water cooling the laser electrodes). For this temperature, a calculated mean sound velocity is 468 m/s (see Fig. 1). This value is assumed in further calculations as the sound velocity in the mixture.

In the applied experimental system, a sound wave (created in the laser waveguide) reaching the diaphragm (the drilled hole in the bottom electrode of the laser waveguide – see Section 5) moves into a loss acoustic system (plasticized polyvinyl chloride tube leading the acoustic wave to the microphone). In this case, the sound velocity must be different than the sound velocity determined for a laser reservoir space.

4. Results of simulations

The wave Eq. (9) given by Morse can be easy solved using the MatLab. Calculations were performed using partial differential equations (PDE) library. The library uses final elements method (FEM). The solution of the wave equation is the surface distribution of the pressure versus time. We assumed the initial parameters, *i.e.*, dimensions of the laser reservoir and the laser plasma parameters. In our experiment we used laser mixture CO_2:N_2:He in the proportion 1:1:3.

The velocity of the acoustic wave in the mixture and the pressure 40 torr were calculated as 368 m/s. For this conditions, the coefficient $\gamma = 1.5356$. In our slab-waveguide laser resonator structure, the energy is delivered to the plasma volume of 400 mm × 20 mm × 2 mm. Calculations were performed for the input power 400 W. The calculated density of thermal energy $H = 25$ mW/mm^3. According to our experimental results, we assumed the laser pulse development time of 250 μs and the pulse rise time of 5 μs. Taking into account the right side of the wave equation, we assumed a suitable profile of the function which was the derivation of the input power pulse. Figure 2 shows the visualization of acoustic wave propagation for assumed conditions for the time: 40, 100, 180, and 230 μs. Figure 3 shows a graph of pressure changes versus time calculated for the point situated in the middle of a laser waveguide cross-section. At the beginning of the pulse developing, the increase in pressure is observed. After 40 μs the pressure reaches the maximum point. After that, the pressure starts to fall. (The calculated results are derived from the simulations shown partly in Fig. 2).

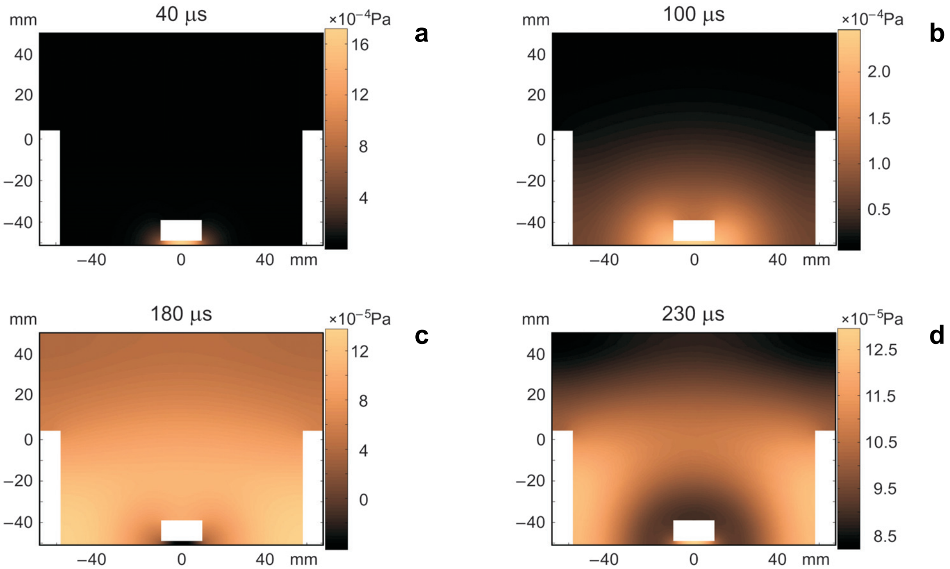

Fig. 2. Cross section of the laser reservoir (laser top electrode is placed directly, 2 mm gap, over the bottom of the reservoir – bottom laser electrode). A few phases of the pressure changes in laser reservoir caused by input pulse energy are shown, after: 40 μs (**a**), 100 μs (**b**), 180 μs (**c**), 230 μs (**d**). It is visible in the pattern **c** that pressure in the center of the laser waveguide can be lower than outside the waveguide.

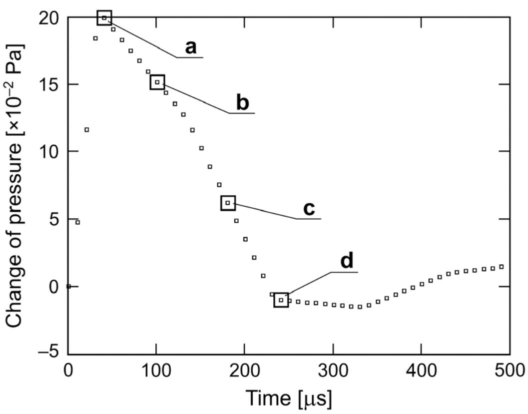

Fig. 3. Change in pressure with time in the center of the cross-section of laser CO_2 active area – simulation result, see Fig. 2.

A power pulse delivered to the laser causes changes in plasma pressure. It is a strong acoustic wave that can be observed by a microphone placed inside the laser chamber. After the strong pressure changes, created by plasma excitation, we have the "stabilization" of the medium thermodynamic parameters. The decay of the sound signal is observed. The decay time is related to a geometry of the laser reservoir and material that creates the laser system. The acoustic pressure measurements can be used to plasma temperature calculations in a pulse initial phase (hundreds microseconds) [5].

5. Experimental setup and results

Figure 4 presents a simplified arrangement of an experimental setup. The microphone is used for measurements of pressure changes generated in a laser medium. It is placed inside a laser reservoir. In photoacoustic applications, the microphone (very often the electret one) is usually mounted in a measurement cell wall or fused to a glass laser excitation tube. In the considered case, this kind of solution is not possible because:

– The condenser microphone is used that has a hole in an enclosure for pressure compensation. This hole should be placed in the same medium as a microphone diaphragm;

– Electrode configuration makes placing the condenser microphone directly near the laser plasma impossible (this type of a microphone has larger dimensions than the electret one);

– There is no possibility to fuse a microphone directly to the electrode because of electric and technological reasons.

Because of the above mentioned reasons, the microphone is connected to the laser plasma by an elastic, plasticized polyvinyl chloride hose of 2 mm in diameter and 150 mm in length. The hose is put in a sleeve connected directly to a microphone diaphragm, whereas the connection waveguide to plasma is made by the drilled hole of diameter equal to 1 mm in the bottom electrode. As a result, the length of the whole waveguide (the hole plus the connector to the electrode) is 175 mm. The received sound

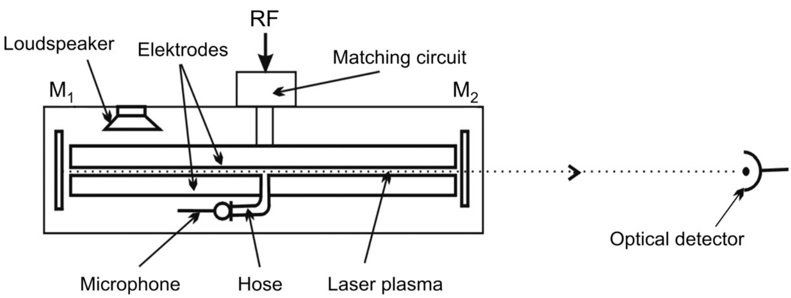

Fig. 4. The laser slab-waveguide structure placed inside the reservoir. The measurement system used to investigate the acoustic wave in a laser plasma is shown.

signal is transmitted outside to a sound level meter and further to an oscilloscope. To eliminate the transfer of laser construction vibrations to a microphone, the microphone is situated on a rubber pad. The application of such a waveguide as a hose causes:

1. Reflection portion of the power of an acoustic signal from discontinuity of the waveguide cross-section;
2. Attenuation of the acoustic wave and sound velocity dispersion;
3. Delay of the measured acoustic signal;
4. Change in the frequency characteristics of the microphone.

5.1. Microphone

During the laser pulse operation, the thermodynamic parameters of the laser plasma change dramatically. In the initial phase of the pulse, the increase in temperature and pressure is observed. The changes in pressure (acoustic pressure) can be directly measured by a microphone. In the applied measurement system there is some signal delay of the acoustic pulse, as a result of the hose application. That is why all acoustic signals are shifted in time. In Figure 5, the circles indicate the electric signals generated in the moment when the input pulse is turned on and off.

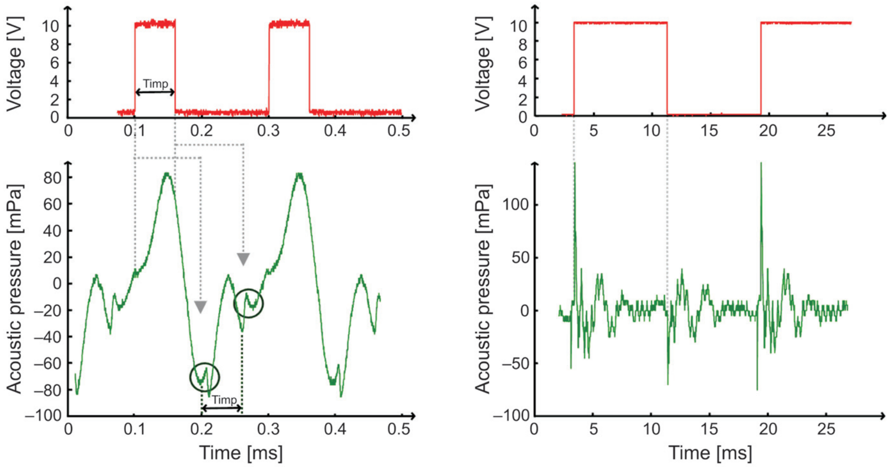

Fig. 5. Changes in laser plasma during the pulse developing; for a pulse duration 60 μs (left) and 8 ms (right). Top signals show a voltage controlling the power signal of a generator supplying the laser.

These signals are not delayed in relation to the input power pulse, so they are not acoustic signals and they would not be considered in this paper. The beginning and the end of the input power pulse is a source of acoustic wave decayed with time (Fig. 5) [6]. In the time range of 40–50 μs from the moment of the system excitation, the increase in plasma pressure is observed. After that, when the maximum value is reached (value dependent on input power), plasma pressure decreases and starts to "stabilize". The decay of the acoustic signal is observed (compare to simulations in Fig. 3).

For pulses longer than 150 μs two acoustic signals are observed: one caused by pulse initiation (the initial signal) and the second caused by plasma turn off (the ending signal). The amplitude of the ending signal is much lower than the initial pulse signal. It indicates that the changes in plasma parameters generated during turning off the plasma are not so dramatic as at the pulse beginning. The change in the pressure amplitude caused by this process is lower (12 dB) than in a pulse initial phase. The dynamics of plasma thermodynamic parameters is lower than the one due to plasma excitation. In both cases, the amplitude of the acoustic signal depends on input power.

For relatively short pulses (*e.g.*, 150 μs and shorter) the ending signal is created before the initial signal decays. In this case, both waves propagate simultaneously. Because of a much stronger initial signal, the weaker, ending signal is "jammed". The ending signal is hardly visible in the registered acoustic pulse shape (see Fig. 6).

The CO_2 laser is an optical device, where we can observe some specific spectral phenomena, when the laser is tuned (when the length of the optical resonator is changed). A first thing easy to observe is the so-called "line hoppings" phenomenon [7]. When we tune the laser, its frequency is changed (what is obvious for each laser), but in the case of the carbon dioxide laser, it "jumps" from line to line, changing the frequency dramatically. During the pulse operation, the change in the laser plasma pressure means the change in the laser medium density, which means the change in the medium refractive index, that is the change in the optical path, and finally the laser is tuned. These changes lead to fluctuations in the optical resonator frequency or, in other words, changes in the output laser frequency. The simulation results in Figs. 2 and 3 explain a "line hoppings" effect caused by changes in the laser plasma density.

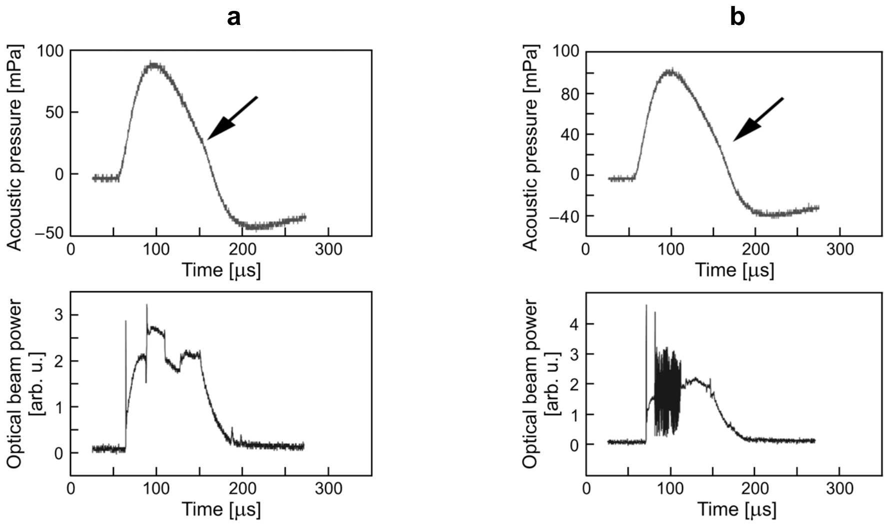

Fig. 6. An acoustic signal (top), output laser pulse with the "line hoppings" effect (bottom) – **a**; An acoustic signal (top), high order laser mode beating (bottom) – **b**. (The end of the laser pulse is indicated at the acoustic pulse profile).

Sometimes, for the wrong adjusted laser, it is possible to observe a high order mode effect (or the so-called "hooting" modes in the case of the waveguide laser like in our experiment [8]) at the profile of the output laser power. We can see two cases in Fig. 6 (**a** – bottom and **b** – bottom): (**a**) the output laser profile disturbed by the "line hoppings" effect (as seen, we have the laser operating on three emission lines, line by line), (**b**) during the laser operation on the second in time emission line we observe a high order laser mode beating effect. When we compare bottom signals (laser output) and top signals (acoustic response), there are not any visible changes in the acoustic signals. Summing up, the thermodynamic parameters "do not follow up" laser power changes, like laser tuning, hooting modes, high order modes. So weak spectral phenomena do not influence the acoustic signal shape because of the high speed appearance.

5.2. Loudspeaker

We also investigated "inverted" process during the pulse operation, *e.g.*, the influence of the acoustic wave on the laser plasma density or, in other words, possibility to tune the laser frequency via changing the refractive index of the plasma at the presence of the acoustic wave generated from the loudspeaker. As seen in Fig. 4, the loudspeaker was inserted into the laser reservoir. The operation of the loudspeaker is problematic in relatively so low pressure, but we checked experimentally that the microphone was able to detect the sound from the loudspeaker to 10 torr of the laser gas mixture pressure. In the experiment, the laser operation was performed at the pressure around 50 torr. It results from our calculations that the pressure created by an acoustic wave generated by the loudspeaker at approximately 50 torr was not higher than 20 mPa. For such low value of the pressure any spectral effects like "line hoppings" were not observed in cw regime. But, it was possible to observe the influence of "lighting" the laser gas medium with the acoustic wave in a pulse regime of the laser. Figure 7**a** shows that the laser output power pulse is disturbed with "line hoppings" effect. As seen in Fig. 7**b**, it is possible to "clean" the laser operation during the pulse developing from parasitic spectral perturbations.

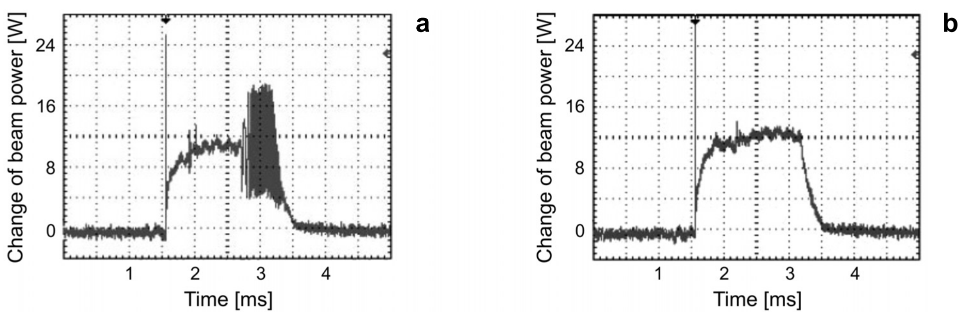

Fig. 7. Changes in output laser power without the influence of an acoustic wave on plasma (**a**); changes in output laser power measured during the emission of an acoustic wave of 1.3 m length into a laser reservoir (**b**).

6. Conclusions

Acoustic processes in CO_2 laser plasma during the pulse regime were considered. The distribution of the acoustic wave intensity in the laser cavity was predicted theoretically, and the velocity of the acoustic wave was calculated. The acoustic measurements were performed to investigate spectral behavior of the laser during the laser pulse developing. As it was pointed out, the beginning of the laser pulse and the end of the pulse, as well, result in acoustic waves propagating in the laser chamber. The specific echo is easy observed during the pulse regime of the laser. It was shown that higher mode operation and spectral phenomena, like "line hoppings", so specific for the CO_2 laser, are not observed in an acoustic signal. On the other hand, it was shown that the acoustic wave can influence the laser operation during the pulse regime, and it can improve the spectral purity of the output laser pulse.

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