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Acoustic mapping of the back-scattering interferometer signal in a CO_2 laser

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It is shown that a microphone placed in the laser plasma can be used for detection and observation of the optical phenomenon such as an optical feedback in a continuous wave regime of the laser operation. To observe the effect, a periodically moved external mirror has been used. The periodical changes of the optical beam intensity in the laser cavity generated changes in frequency and amplitude of the acoustic signal. In conclusion, the acoustic wave gives information about optical effects created in a waveguide CO_2 laser.

Keywords: CO_2 laser, self-mixing, optical feedback, back-scattering, interferometer, photoacoustics.

1. Introduction

As is known, an acoustic wave is a perturbation of the medium density and pressure propagated as a longitudinal wave. A possible medium for the propagation of an acoustic wave is obviously air, in other words, gas. We consider in the paper a specific effect possible to observe in lasers (in our case, in a gas, molecular carbon dioxide laser), so called a back-scattering effect [1]. In some cases, the output laser beam can return to the laser chamber because of a partial or total reflection. The result of the interference of a returning beam and internal optical field is the change in frequency and power of the output laser beam. Usually, the effect is parasitic for many laser measuring devices; sometimes it can be used as a method of the distance measurements [2, 3]. The effect is weakly related to a photoacoustic spectroscopy, where the laser radiation reacts in a resonance way with narrow spectroscopic lines of the medium investigated [4, 5]. The goal of the paper is the use of an acoustic device (a microphone) to detect and reconstruct the back-scattering signal in a cw CO_2 laser. (The pulse regime of the laser will not be considered here because of the dramatic changes of the laser plasma density which can be "jammed" by the signal investigated [6]). The back-scattering signal is chaotic (related with so called "laser chaos" [7]). To make the back-scattering signal quasi-ordered, it is enough to move periodically a reflecting object (the third mirror in our experiment).

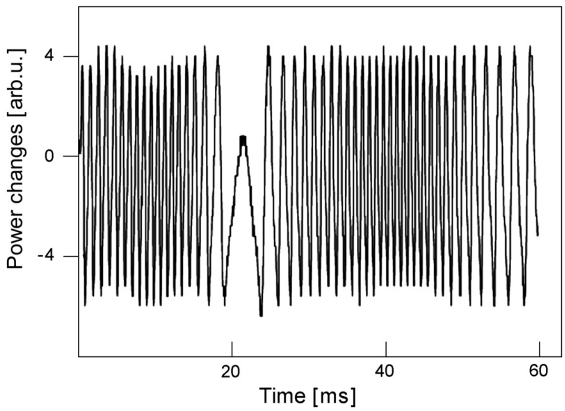

Fig. 1. A typical experimental shape of sawtooth-shaped changes of the optical power for a sine displacement of an external reflecting surface.

During the laser tuning or movement of an external reflecting surface, the laser output power changes are sawtooth-shaped. The slope of a sawtooth-shaped optical signal depends on direction of the moving object (see a typical experimental result in Fig. 1). In this case, the frequency Doppler shift is:

$$\nu_D = \frac{2\upsilon\cos\theta}{\lambda} \tag{1}$$

where: ν_D – Doppler shifted beam frequency, υ – velocity of the moving object, θ – angle between the optical axis of laser resonator and velocity direction of moving object, λ – laser beam wavelength.

The effect is utilized in the laser Doppler velocimetry [2, 3]. The first to describe the back-scattering effect (self-mixing) was KING [8]. In 1968, Born presented theoretical description of the optical feedback [9]. The model is based on a three-mirror structure of a Fabry–Perot resonator. The outside reflecting surface is represented by a mirror M_3 with a reflection coefficient R_3.

Mirrors M_2 and M_3 can be represented together with an output laser mirror by a substitute-mirror of a complex reflection coefficient R_z (Fig. 2). The complex coefficient includes reflection coefficient of an object, reflection coefficient of

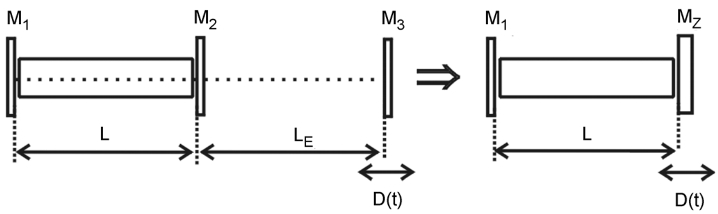

Fig. 2. A substitute model of the three-mirror structure. M_1, M_2, M_3 – mirrors, L, L_E – optical paths, $D(t)$ – mirror displacement in time, M_Z – substitute mirror.

the output laser mirror and the time of light wave propagation in the external resonator (created by mirrors M_1 and M_3, Fig. 2) [9]:

$$R_z = \frac{R_2 + R_3 \exp(2jkL_E)}{1 + R_2 R_3 \exp(2jkL_E)} \tag{2}$$

where: R_2, R_3 – reflectivity of the output laser mirror and third (target) mirror, respectively, k – wave number vector, L_E – distance between the second and the third mirror.

The complex coefficient can also be written as [10]:

$$R_z(\nu) = R_2 + \left(1 - |R_2|^2\right) R_3 \exp(-j\,2\pi\nu\,\tau_F) \tag{3}$$

where $\tau_F = 2L_E/c$ – time of light wave propagation in external resonator.

The reflection factor of the substitute-mirror can be changed depending on the object position. When the optical feedback appears, the output laser beam frequency starts to fluctuate (it becomes time-dependent). The conditions of the laser action make this behavior stronger [11, 12]. The optical wavelength changes can be determined by solving the phase equation [13]:

$$x_0(t) = x_F(t) + C\sin\left[x_F(t) + \operatorname{atan}(\alpha)\right] \tag{4}$$

where: $x_F(t)$ and $x_0(t)$ are phase signals (functions of the laser wave frequency $\lambda_F(t)$ and λ_0, respectively), and can be written as:

$$\begin{aligned} x_F(t) &= 2\pi\nu_F(t)\,\tau(t) \\ x_0(t) &= 2\pi\nu_0(t)\,\tau(t) \end{aligned} \tag{5}$$

where: $\tau(t) = 2D(t)/c$, $D(t)$ – displacement of the reflecting surface in relation to the initial position.

The feedback coefficient C in (4) has a big influence on the shape of output laser power changes. The coefficient C depends mainly on an external surface reflection coefficient and the distance between an external surface and a laser chamber:

$$C = \frac{\tau_F}{\tau_L}\,\kappa_E\sqrt{1 + \alpha^2} \tag{6}$$

where $\tau_L = 2Ln/c$ – light propagation time in an internal resonator, α – ratio of real to imaginary part of a reflection coefficient, usually 3–7 [13, 14], coefficient κ_E is equal to:

$$\kappa_E = \frac{\left(1 - |R_2|^2\right) R_3}{R_2}$$

The reflection coefficient of the third mirror is decisive for an amplitude and shape of optical beam power changes. For values C less than 1 the signal is sinusoidal, for values C much higher than 1 ($C \gg 1$) the output power exhibits leaped changes. The laser operation is highly unstable and sometimes is called a "chaos" [15–17]. Usually in measurement applications the feedback factor is in the range of 0.1–4.6 [18].

The optical feedback causes power changes of an optical beam intensity. In plasma thermodynamics the changes are manifested by temperature and pressure changes. Thus, it can be expected that appearance of optical feedback would generate an acoustic wave.

2. Experiments

The experiments are performed in a configuration shown in Fig. 3. The vibration exciter is controlled by voltage of fractions of hertz. The characteristic changes of an output power laser beam are observed as a consequence of a periodic movement of mirror M_3 (mounted on the vibration exciter) (Fig. 1).

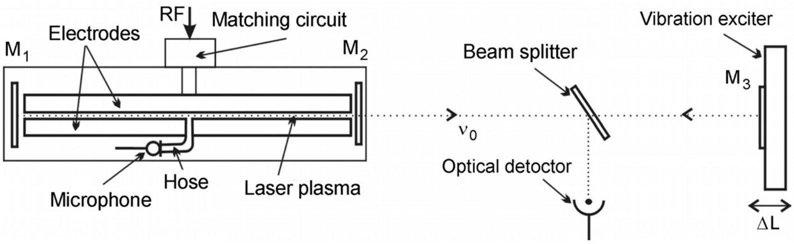

Fig. 3. An experimental setup for acoustic signal measurements in a three-mirror structure.

For the feedback coefficient C less than 1, the changes are sinusoidal. Taking relations (4), (5) and (6) the phase changes of the laser beam after a transition through the resonator can be described as:

$$\Delta\phi = 2\pi m = 2\pi\tau_0(\nu_F - \nu_0) + \kappa_E\sqrt{1+\alpha^2}\,\sin\left[2\pi\nu_F\tau_F + \operatorname{atan}(\alpha)\right] \tag{7}$$

where: $\Delta\phi$ – phase change of a beam after transition through the resonator, m – integer, ν_F – real frequency of laser action, ν_0 – frequency of laser action without feedback, τ_0, τ_F – light propagation time, in internal and external resonator, respectively, α – ratio of real to imaginary part of reflection coefficient, $\kappa_E = (1 - |R_2|^2)R_3/R_2$, R_2 – reflection index of mirror M_2 (Fig. 3), R_3 – reflection index of mirror M_3 (Fig. 3). In this case, equation (6) has one solution regarding ν_F, and fluctuations of a gain coefficient can be determined as follows:

$$g_F - g_0 = -\frac{\kappa_E}{L}\cos(2\pi\nu_F\tau_F)$$

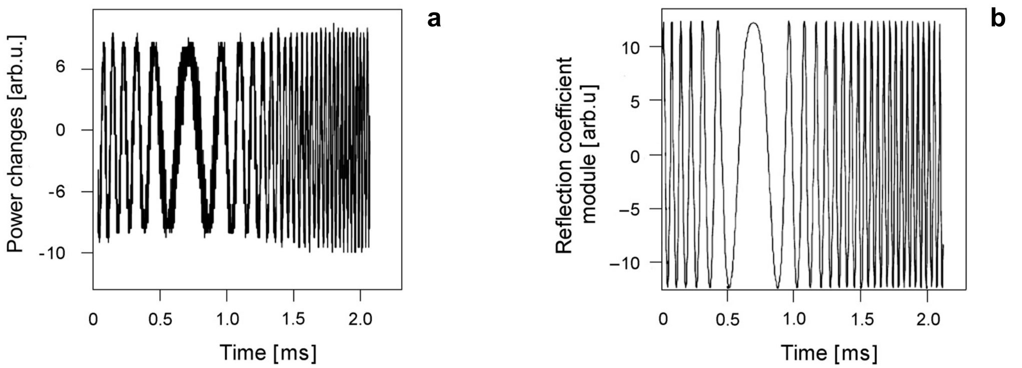

Fig. 4. Changes in an output laser beam signal caused by an optical feedback: **a** – experimental data for $C < 1$, **b** – calculated reflection coefficient module from relation (2) for $R_2 = 0.92$, $R_3 = 0.1$, $L_E = 1$ m ($C < 1$).

where: g_F – gain coefficient during laser operation with optical feedback, g_0 – gain coefficient during laser operation without optical feedback, L – optical resonator length, ν_F – frequency of laser action during laser operation with optical feedback, τ_F – light propagation time in external resonator.

Figure 4**a** shows the curve of output laser power obtained experimentally. In Fig. 4**b**, the module of calculated refractive index of substitute-mirror (M_Z – Fig. 2) from formula (2) is presented. The feedback ratio C assumed in calculations is less than 1. The module of the complex refractive index is proportional to the laser output power. As seen, experimental and simulated data are proportional.

The optical feedback caused by a periodical movement of the external mirror creates an acoustic wave of a changeable amplitude and frequency (Fig. 5).

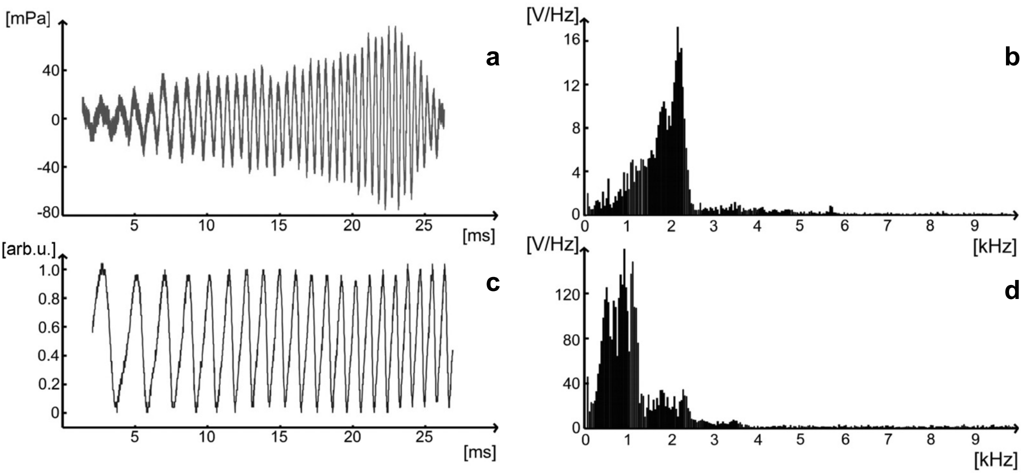

Fig. 5. Signals generated by an optical feedback; **a** – acoustic signal; **b** – frequency spectrum of an acoustic signal; **c** – optical signal; **d** – frequency spectrum of an optical signal.

A condenser microphone with the band 20−20 000 Hz was used in the experiment. The amplitude of the measured (with a microphone) signal rises with frequency (see Fig. 5, top) – compare with an optical signal at the bottom of Fig. 5. Moreover, a frequency of the acoustic signal seems to be two times higher compared to the optical signal.

There are a few reasons for the behavior of the acoustic signal shape. One of them is an acoustic characteristic of the laser reservoir used. Figure 6 shows an acoustic spectrum of the reservoir. As one can see, in our arrangement it contains strong maxima around 1850 Hz, 2650 Hz, and 3650 Hz. The resonances indicated make strong deformation of the acoustic signal shape.

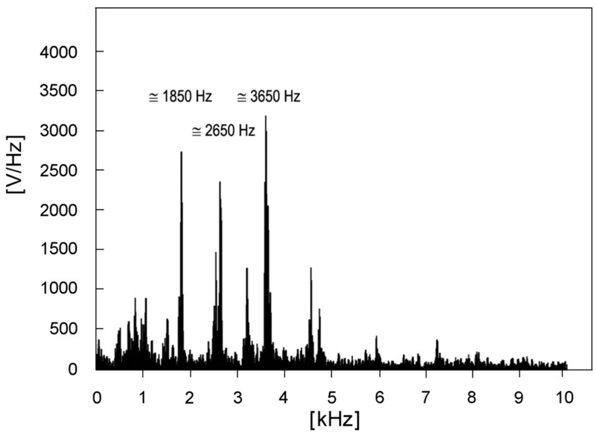

Fig. 6. An acoustic spectrum of the laser reservoir. The strongest resonances are indicated.

Careful investigation of the microphone equipped with a plastic hose (which guides an acoustic wave created in the laser plasma to the microphone, see Fig. 4) gives an acoustic spectrum of the microphone−hose setup, as seen in Fig. 7. The measurements were performed in an anechoic chamber, and measured using the white-noise signal. It can be seen that the microphone characteristic is more or less smooth in the region of interest (1000−4000 Hz), but the characteristic of the microphone equipped with the hose exhibits a group of resonances. Different positions of the hose, and different shapes of the bended hose have not changed the picture (see Fig. 8).

Comparing Figs. 6, 7, and 8, it is visible that the laser reservoir architecture, and the microphone−hose setup can influence a measured acoustic signal created by a back-scattering effect under investigation. The influence is clearly visible in Fig. 5, left. As already mentioned, the frequency of the acoustic signal seems to be twice as high as that of the optical one. The Fourier transform of both signals gives the explanation of the effect. Harmonic components of the optical signal are lower and lower for higher frequencies. As seen in Fig. 5**b**, a spectrum of the acoustic signal is

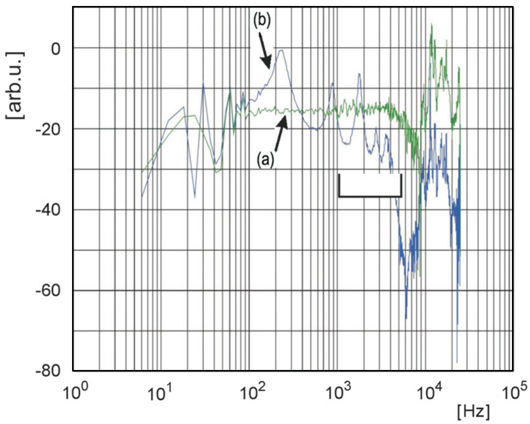

Fig. 7. An acoustic characteristic of the microphone without hose (*a*) and with the hose bended in a way suitable for measurements (*b*). Significant resonances are indicated.

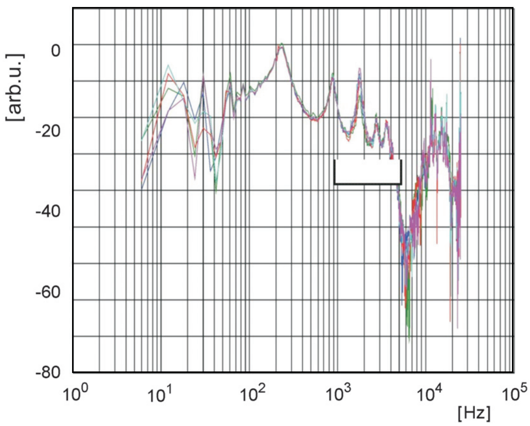

Fig. 8. An acoustic characteristic of the microphone with the hose bended in different ways. A group of the significant resonances are indicated.

shifted to the higher frequencies compared to the optical signal spectrum (Fig. 5**d**). That is why the acoustic signal in Fig. 5**a**, shows higher frequency than the optical signal (Fig. 5**c**). Another effect observed is the difference in the amplitude for lower and higher frequencies comparing optical and acoustic signals. A low efficiency of the microphone used for lower frequencies can play here a significant role.

The effects are illustrated in other figures. The results presented in Fig. 9 are similar those of Fig. 5: an amplitude of the acoustic signal is higher for higher frequencies, and an acoustic spectrum is shifted to higher frequencies, compared to an optical signal. The moment the third, external (Fig. 3) mirror has stopped is visible at the beginning of the oscillogram in Fig. 9**c**. After that the frequency rises according

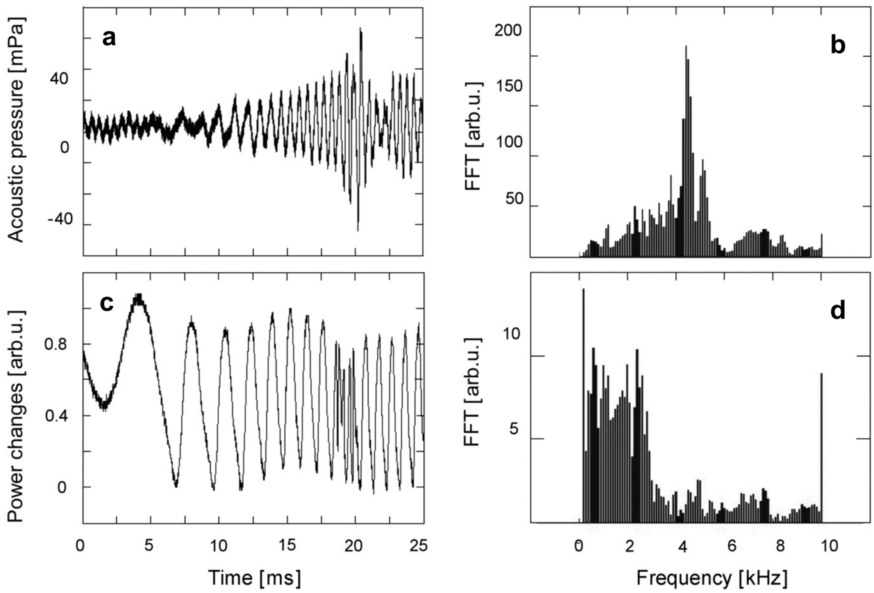

Fig. 9. Another example: **a** – acoustic signal; **b** – frequency spectrum of the acoustic signal; **c** – optical signal; **d** – frequency spectrum of the optical signal.

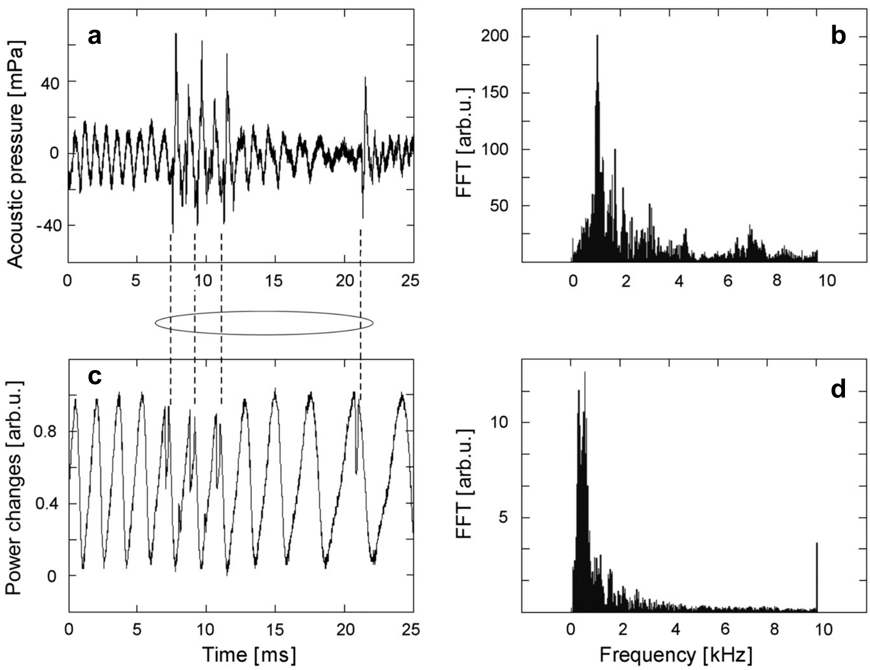

Fig. 10. Another example: **a** – acoustic signal; **b** – frequency spectrum of the acoustic signal; **c** – optical signal; **d** – frequency spectrum of the optical signal. The group of "cracks" is indicated with an ellipse.

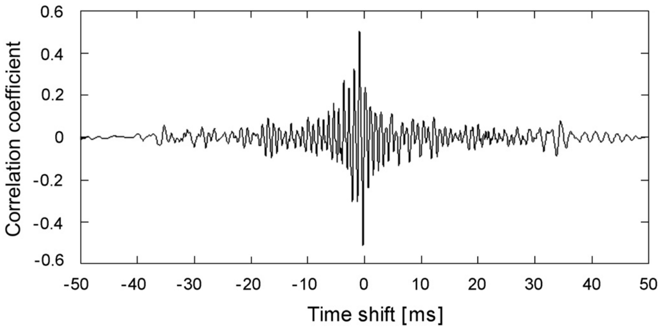

Fig. 11. A correlation coefficient of optical to acoustic signals.

to the sinusoidal signal put on the vibration exciter. It is clearly visible how an amplitude of the acoustic signal rises with modulation frequency of the optical signal.

Other results are presented in Fig. 10. The acoustic signal is still higher for higher frequencies, the acoustic signal spectrum is still shifted to the region of higher frequencies. Additionally, we can observe a strong reaction of the microphone for short perturbation of the optical signal. The perturbations are caused by a temporary higher-mode operation of the laser (see Fig. 10**c**). As seen in Fig. 10**a**, a reaction of the microphone dominates the reaction of the optical detector. Optical perturbations introduced to the laser operation are immediately detected by the microphone.

The correlation coefficient of optical and acoustic signals is determined to obtain a convergence between these two signals. An example result for 2500 samples and sample frequency 50 kHz is shown in Fig. 11 (the time interval between samples is 20 μs). As one can see, the correlation coefficient is on the level of 0.5.

3. Conclusions

The results obtained show that the microphone application in "listening in" the laser plasma can be used for detection and observation of the optical phenomenon such as an optical feedback (self-mixing or back-scattering) in a continuous wave regime. The monitoring of the acoustic wave in the laser chamber is able to give information about optical effects created in a waveguide CO_2 laser. As is known, the intensity changes of the optical beam cause changes of the laser plasma thermodynamic parameters. A shown above, they are visible in the acoustic signal. The amplitude of the generated acoustic signal depends on laser beam power and level of optical power changes. The periodical changes of the optical beam generate changes in frequency and amplitude of the acoustic signal. It was pointed out that the microphone used here as a detector of the laser beam intensity changes is very "sensitive" to any disturbances of an optical feedback signal. All disturbances of the optical signal "self-mixing" are visible in the acoustic signal as "cracks" (sudden, momentary changes of pressure). It is necessary to emphasize that measurement results given by a microphone provide rather a quality picture of the back-scattering phenomenon. The acoustic signal is distorted by resonances of the laser chamber used and by the characteristics of the acoustic waveguide, in other words, by an architecture of the laser chamber and a mechanical measurement system. A value of the correlation between optical and acoustic signals equal to approximately 0.5 is rather low. A microphone, as a substitute of the optical detector can be used rather carefully. On the other hand, a big advantage of the microphone is the possibility of putting it inside the laser chamber. In this way, we can easily get a simple internal system of the optical phenomena monitoring closed in the laser reservoir.

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