Optica Applicata, Vol. XXXV, No. 2, 2005

Thermodynamic and optical parameters of the RF pulse excited slab-waveguide CO_2 laser

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In the paper, changes of the optical and thermodynamic parameters, such as a refractive index, pressure, and temperature are investigated on an RF pulsed CO_2 slab-waveguide laser. Changes of the refractive index, and pressure are measured with a Mach–Zehnder interferometer, and microphone, respectively. A Gladstone–Dale formula is applied to calculate the changes of the temperature. It is shown how an acoustic wave in the laser cavity modifies the pressure of the laser medium in the course of the pulse duration. The results of measurements allow explaining a line hopping effect observed during the laser plasma pulse evolution.

Keywords: CO_2 laser, slab-waveguide, RF excitation, pulse operation, acoustic wave, line hoppings.

1. Introduction

The spectrum of CO_2 molecule consists of a number of emission lines grouped in many bands and branches [1]. When the laser resonator is tuned, then different resonant frequencies of the optical resonator can be in coincidence with some frequencies of the emission lines of CO_2 laser medium. Of course, each line being in coincidence with that resonant can take part in laser action. Theoretically, the laser can operate on many emission lines simultaneously. Fortunately, a strong competition exists between different rotational levels in the CO_2 medium, and consequently, the laser usually operates only on one chosen line [2], specifically, on the line whose central frequency is the closest to the resonant frequency of the resonator. When the resonator is tuned, then we can expect “jumps” from line to line (a line hopping effect). The observed picture of the output laser power is called a laser signature [3]. The signature is reproducible with each half-wavelength of the tuning. The laser signature is stable, and easy to calculate for the chosen length of the optical resonator [4, 5]. In a pulse operation of the laser, dramatic thermodynamic and optical phenomena can be observed in the laser medium. Changes in pressure, temperature, and refractive index of the laser medium occur during the development of plasma pulse. When the pulse of the input power is delivered to the laser cavity, then the laser gas expands from the space between electrodes. The pressure and temperature rise at the beginning of the input pulse delivered. After that, the gas expands, the pressure drops, and the refractive index becomes lower. In such a way, the optical length of resonator is changed during the pulse development; in other words, the laser is tuned. Taking into account the above, a line hopping phenomenon is expected, too. Some part of the laser signature is mapped onto the profile of the laser output pulse. It is correct if all thermodynamic and optical parameter changes are measured to control or at least to monitor the phenomenon. The changes of the refractive index can be easily measured with an interferometer. As a result of the change in pressure an acoustic wave is directly created in the laser cavity, which (by definition) modulates the local pressure of the gas medium. The methodology of the investigation is based on a known formula given by Gladstone and Dale, linking the refractive index of the fluid, density (or pressure), and temperature of the medium [6]. The refractive index and pressure are investigated experimentally. The main goal of the work is to give a clear picture of the optical and thermodynamic processes which occur during the pulse operation of the RF excited CO_2 waveguide laser.

2. Background

The relation between thermodynamic and optical quantities is described by the Gladstone–Dale equation of ideal gas defining the gas refractive index n as a density function N [m^{-3}]. It can be written:

$$\frac{n-1}{N} = \gamma \tag{1}$$

where γ [m^3] is Gladstone–Dale constant.

On the other hand, changes of the laser gas density N are the result of changes of both pressure p and temperature T, according to the equation of state of an ideal gas:

$$N = \frac{p}{kT} \tag{2}$$

where k – Boltzmann constant. Thus,

$$n-1 = \gamma \frac{p}{kT}. \tag{3}$$

The refractive indexes for the three kinds of gas used here, *i.e.*, CO_2, N_2, He, are known to be the following [7]:

$$\begin{aligned} (n-1)^{CO_2} &= 450\times10^{-6}, \\ (n-1)^{N_2} &= 300\times10^{-6}, \\ (n-1)^{He} &= 36\times10^{-6}. \end{aligned} \tag{4}$$

Taking into account fractions of the gas mixture, a refractive index can be readily calculated from the formula [8]:

$$n - 1 = \left(450 f_{CO_2} + 300 f_{N_2} + 36 f_{He}\right) 10^{-6} \tag{5}$$

where: f_{CO_2}, f_{N_2}, f_{He} – fractions of CO_2, N_2, and He, respectively,

The temperature and pressure dependent formula can be easily recalculated from Eq. (5) taking into account Eqs. (1) and (2):

$$n - 1 = \left(450 f_{CO_2} + 300 f_{N_2} + 36 f_{He}\right) \frac{p}{p_0} \frac{T_0}{T} 10^{-6}. \tag{6}$$

For $T_0 = 273.16$ K and $p_0 = 760$ torr:

$$n - 1 = 3.59\left(450 f_{CO_2} + 300 f_{N_2} + 36 f_{He}\right) \frac{p}{p_0} 10^{-7}. \tag{7}$$

For the laser gas mixture used in the experiment – $CO_2 : N_2 : He = 1 : 1 : 3$

$$450 f_{CO_2} + 300 f_{N_2} + 36 f_{He} = 450 \times 0.2 + 300 \times 0.2 + 36 \times 0.6 = 176.1. \tag{8}$$

The final equation is [9]:

$$n - 1 = 6.17 \frac{p}{T} 10^{-5} \tag{9}$$

where p is expressed in torr, and T in K.

Comparing (3) and (9) a Gladstone–Dale coefficient γ can be calculated for the gas mixture, and conditions applied in the experiment. In Eq. (9) the dependence of the refractive index on the wavelength is neglected [9]. In dynamic conditions, pressure $p(x, y, z, t)$ and temperature $T(x, y, z, t)$ in Eq. (9) should be considered as time and space dependent. Assuming a homogeneous excitation of the laser slab the space dependence can be neglected, and Eq. (9) can be rewritten as:

$$n(t) = 1 + 6.17 \frac{p(t)}{T(t)} 10^{-5} \tag{10}$$

where: $n(t)$, $p(t)$, and $T(t)$ are only time dependent functions averaged over the active area of the discharge channel.

The medium refractive index can be evaluated from interferograms (interferometric fringes) given in the Mach–Zehnder interferometer, for example. The difference of optical path length against the reference medium $\Delta o(x, y)$ at linear propagation of rays by a three-dimensional non-homogeneity of the length L in the direction z is given in the Mach–Zehnder interferometer by the relation:

$$\Delta o(x, y) = \int_0^L \left[n(x, y, z) - n_i \right] \mathrm{d}z = \lambda \Delta S(x, y) \tag{11}$$

where n_i and $n(x, y, z)$ are refractive indexes in ambient medium and at the point (x, y, z), λ is a wavelength of light and $\Delta S(x, y)$ is a change in interference order in the plane xy caused by a subject measured.

3. Auxiliary calculations

In the experiment, the refractive index is measured using a Mach–Zehnder interferometer, where the CO_2 laser medium (the laser cavity without mirrors) is put into one of the legs of the interferometer. A He-Ne laser is used as a source. In practice, formula (11) leads to the relation between changes of the refractive index Δn and the number of fringes as follows:

$$\Delta n = \frac{\lambda}{L} \tag{12}$$

where: L – length of the optical resonator (380 mm in our experiment), λ – wavelength (0.63 μm for He-Ne laser).

Taking into account the data as above we have:

$$\Delta n = 1.64\times10^{-6} \text{ per fringe.} \tag{13}$$

4. Experimental

The RF excited laser mechanical structure shown in Fig. 1 consists of water cooled aluminum electrodes with an area of 380×20 mm (top), and 400×110 mm (bottom), spaced 2 mm apart. The laser head is supplied with an RF generator up to 2 kW power via a matching circuit [10]. A positive branch unstable resonator with a rear mirror M_R = 5800 mm and output mirror M_O = 5000 mm is applied. The mirror spacing, defined by a low expansion invar bar, is L = 402 mm for approximately confocal operation of the resonator. The electrodes and laser mirrors are placed in a vacuum reservoir. The cross-section of the laser and vacuum reservoir is shown in the figure. A known technique of the parallel resonance is used to fit the laser head resonant frequency to the output of the power generator [11]. The optimum 70 torr pressure with a typical $He:N_2:CO_2 = 3:1:1$ gas mixture is applied.

5. Investigations

In order to check how the refractive index changes during the pulse evolution the setup shown in Fig. 2 was arranged. The laser cavity was placed, along its axis of symmetry, into one leg of the Mach–Zehnder interferometer working with a He-Ne 0.63 μm laser [12]. During the pulse excitation in the laser cavity interference fringes were observed.

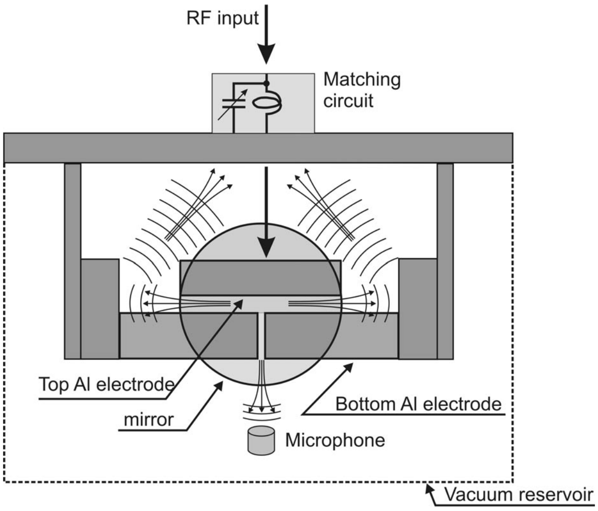

Fig. 1. Cross-section of the laser structure used in the experiment. A typical Γ-kind matching circuit is marked in the figure. The laser cavity with mirrors is put into the vacuum reservoir to increase the volume of the laser mixture. The laser beam leaves the laser cavity via a transparent AR-AR coated ZnSe window mounted in the front wall of the reservoir. There is a channel of 1 mm in diameter drilled in the bottom electrode to measure an acoustic wave created by a pulsed laser plasma. Possible propagation of acoustic waves inside the laser reservoir is shown.

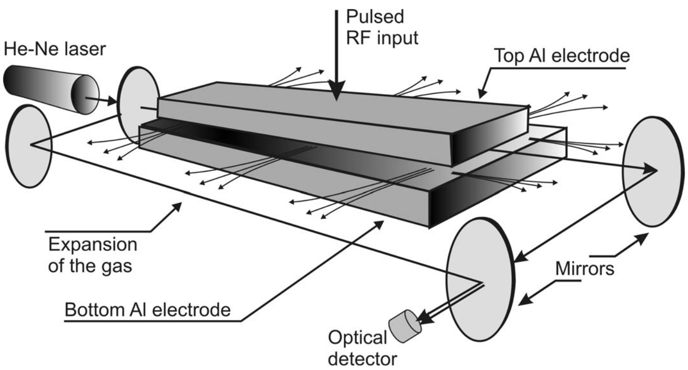

Fig. 2. Laser cavity (without laser mirrors) put into one leg of the Mach–Zehnder interferometer to measure changes of the refractive index during a pulse operation of the plasma. The plasma is excited with a radio-frequency (RF) current. HgCdTe detector is used.

The results of measurements with a Mach–Zehnder interferometer are shown in Fig. 3. As one can see, the density of the fringes is higher at the beginning of the input signal, and much lower when the input signal is turned-off. It is clear that at the beginning of the input pulse the plasma glowing is forced. On the contrary, when the forcing electrical field disappears, a relaxation process in the plasma occurs, and all changes are lesser.

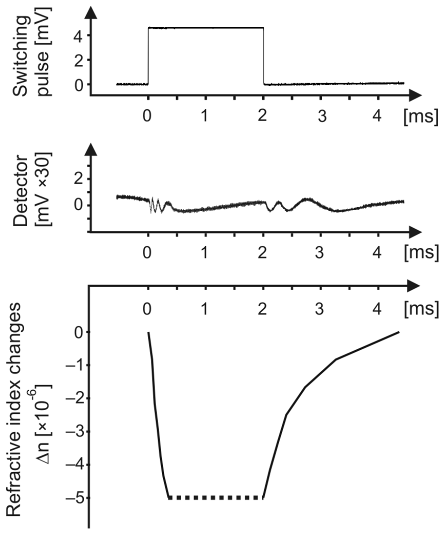

Fig. 3. Refractive index Δn of CO_2 laser medium *vs.* laser pulse development time estimated from the interferometric signal. The beginning of the laser pulse is indicated (switching pulse), and the response of the microphone. The refractive index is calculated from Eq. (13).

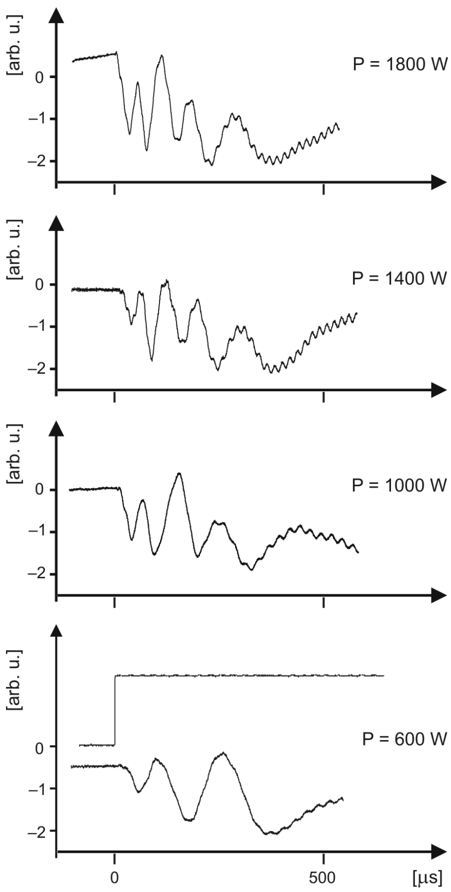

Fig. 4. Interferometric signals for the rising edge of the laser pulse for different input powers, at the laser mixture pressure of 70 torr.

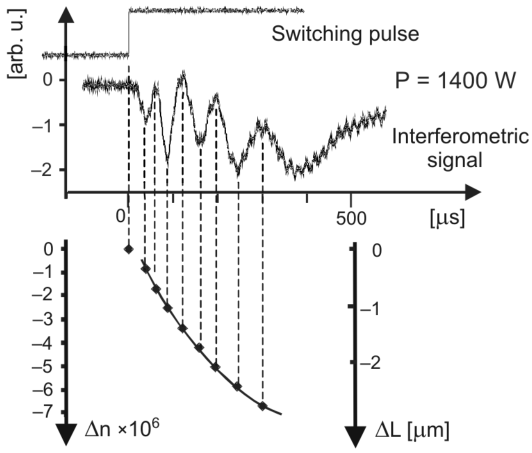

Fig. 5. Illustration of the method for calculation of the refractive index changes. The number of fringes is calculated to determine changes of both refractive index, and of optical length of the laser cavity. The changes Δn of the refractive index are estimated from (13). The changes ΔL of the laser resonator optical length are calculated from $\Delta n = \Delta L/L$ (L = 380 mm – active length of the laser cavity).

Figure 4 shows a series of interferometric signals for the rising edge of the laser pulse for different input powers, at the laser mixture pressure of 70 torr. The number of interferometric fringes rises with the level of input power. This is due to the fact of the temperature being higher for higher input power.

Figure 5 illustrates the method of calculating changes of the refractive index taking a fringe signal. The number of fringes was calculated to determine the changes of both refractive index, and of optical length of the laser cavity. The changes Δn of the refractive index are estimated from (13). The changes of the optical length are calculated according to the relation $\Delta n = \Delta L/L$ (L = 380 mm – active length of the laser cavity). The temperature of the laser mixture can be estimated from Eq. (10) recalculated into:

$$\Delta n = 6.17 p(t)\left[\frac{1}{T(t)} - \frac{1}{T_0}\right]10^{-5} \tag{14}$$

where: T_0 = 288 K (temperature of the electrodes), Δn – changes of the refractive index.

Figure 6 shows collected characteristics of an output laser pulse, pressure $p(t)$ changes inside the laser cavity, interferometric fringes calculated to determine the changes of both refractive index $n(t)$, and of temperature $T(t)$ during the plasma pulse development using the Gladstone–Dale formula.

As the experiment shows, a pulsed laser plasma is the source of an acoustic wave. A mechanical structure of the laser creates an acoustic resonator, where an acoustic wave can be formed in a more or less complicated way (see Fig. 1). Propagation of the acoustic wave along the laser cavity can be disturbed by the walls of the laser

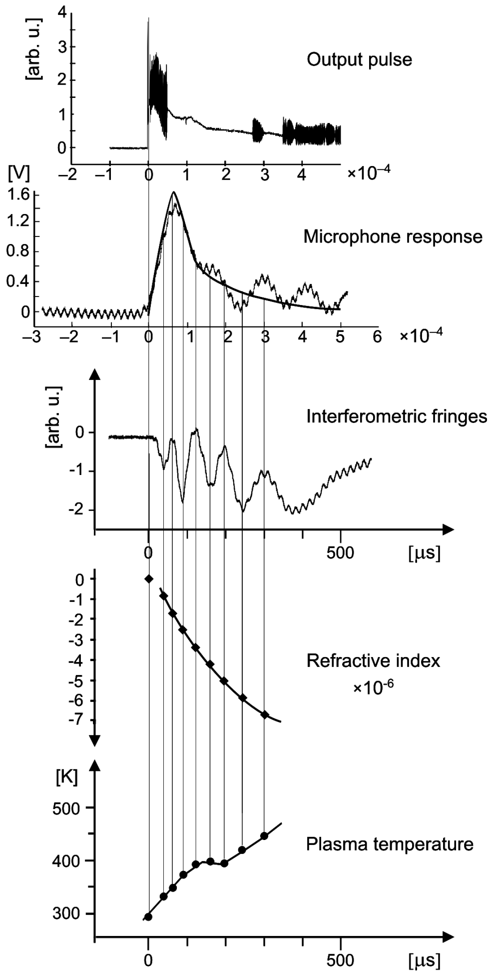

Fig. 6. Full set of measured and calculated characteristics: output, pressure, fringes, refractive index, and temperature *vs.* the output pulse development time.

mechanical structure giving many echoes. The wave penetrates the discharge area, and it can be measured through the small, drilled channel in a bottom electrode, as shown in Fig. 1. Results of the measurements are shown in Fig. 7. The upper signal is a typical laser output. As seen from Fig. 5, the laser is tuned to a few micrometers, almost a half-wavelength. Visible perturbations along the pulse profile are the evidence of laser tuning. This means that the laser "jumps" a few times from one emission line to another one – a line hopping effect. In other words, the laser is tuned over the pulse duration. This is due to changes of the density (pressure) of the laser medium, which involves changes of the refractive index. In this way, part of the laser signature (see Introduction) is mapped along the laser output pulse profile [13].

The acoustic signal (lower trace in Fig. 7) is delayed for the time $\Delta\tau_A$ in relation to the laser pulse beginning. It is easy to show that the acoustic waveguide is responsible for the delay, taking into account the sound speed in the laser media.

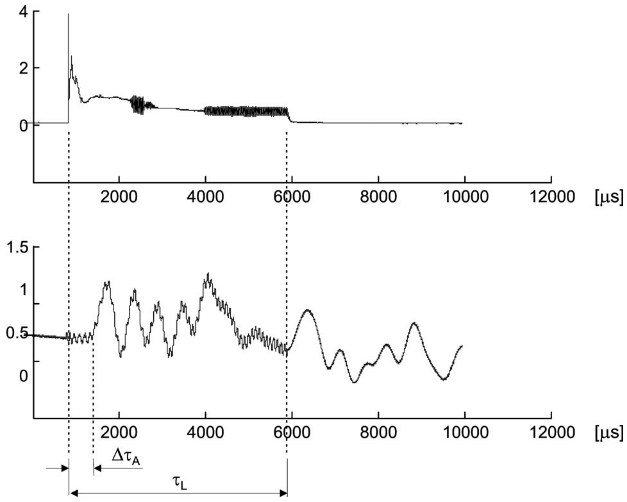

Fig. 7. Results of the measurements. An upper signal is a typical laser output. The response of the microphone (lower trace) shows how the pressure of the laser medium is modified by an acoustic wave.

As already mentioned, the refractive index $n(t)$ and changes of pressure $p(t)$ are measured experimentally. In this way changes of the temperature $T(t)$ in the laser cavity over the pulse duration can be easily determined from (14).

6. Conclusions

The investigation shows that it is possible to monitor the behaviour of plasma during pulse excitation, that is, changes of the laser plasma refractive index, laser media temperature, and pressure can be easily measured. An input laser pulse is the source of an acoustic wave, which modifies pressure inside the laser cavity. A line hopping effect, visible as perturbations along the output laser pulse shape, is a result of the laser tuning during the input power delivery. It is due to temperature and pressure changes, and consequently plasma density and refractive index changes. It changes the optical length of the laser resonator – the laser is tuned, and changes several times the operation frequency during the pulse duration. The pulsed CO_2 laser is not a single-frequency device, and it can create serious obstacles in some technological applications. In the laser material processing the process can be ineffective for some media. This happens in the case of such materials as some organic polymers as PET (polyethylene terephthalate) or PP (polypropylene) [14]. Those media exhibit relatively narrow absorption bands, and only a part of the delivered energy can be effectively absorbed during the time a singular laser pulse is being developed. The PET absorption spectrum exhibits strong dip for a R20 9.6 μm CO_2 laser line (1078.57 cm^{-1}), and the PP spectrum for a R18 10.6 μm CO_2 laser line (974.61 cm^{-1}). Increasing the pulse repetition frequency leads to a quasi cw laser operation, but even in this case a line hopping effect can be observed due to temperature drifts of the laser resonator, or low repeatability of excitation plasma conditions with each pulse. Reassuming, the results of the experiments give a clear picture of the CO_2 laser plasma behaviour during the pulse operation, and in consequence, explain a line hopping phenomenon observed in the pulsed CO_2 laser.

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Received September 22, 2004