MODE-LOCKED PULSES IN MULTI-ATMOSPHERE CO_2 LASERS

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The present paper deals with AM mode locking of multiatmosphere CO_2 lasers. We measure the effective linewidth in the laser mixtures and deduce from these data the pulse width. The method is based on determining the maximum frequency shift from the synchronized frequency. The advantage of this method is that the results are not influenced by time constant of detector and display. The results were verified by direct measurements of the pulse widths in mixtures up till three atmospheres. The pulse widths and effective line widths of the P(20) transition are determined for the usual CO_2 laser mixture up till 6 atm. We observe that helium has a large effect on the pulse width. The width decreases with increasing helium percentage at all pressures investigated. We suggest that this has to do with the overlap of a sequence-band transition and that the effect of sequence bands depend ion the helium percentage.

1. Introduction

One of the most important factors that determines the pulse width of mode locked lasers is the width and the shape of the spectral-emission line [1,2]. In the case of a high-pressure CO_2 laser the linewidth has been constructed from the optical cross-sections deduced from absorption measurements in a high-pressure cell containing CO_2 and the usual gas additives. In this way one has obtained an expression for the linewidth that shows a smaller contribution for nitrogen and an even smaller contribution for helium per unit fraction than for carbon dioxide [3,4]. In this way one predicts a line width that decreases and consequently a pulse width that increases with increasing helium percentage. This, however, is not observed experimentally [5].

This discrepancy between the observed line widths of neutral-gas mixtures and those of laser-plasma mixtures has intrigued us to further investigations of the line profile at multi-atmospheric pressures. Not only the interest for the linebroadening mechanism under laser conditions makes this study worthwhile, but even more interesting is the knowledge of the overlap of the individual vibrational-rotation transitions of the CO_2 laser. In the case of overlap of the lasing transitions ultra-short CO_2 pulses and continuously tunable systems over a band width of about 10^{12} Hertz are available. For an overlap it is necessary to use pressures above 10 atm, for which the line structure of the individual rotational transition is expected to disappear [6].

The overlap will not only be caused by the pressure broadening but also by the contributions of the sequence bands [7]. In fact, some sequence lines are so close to strong regular lines that even at a few atmosphere pressure that contribution of a sequence line to a regular line cannot be neglected, e.g. the frequency difference between P(17) of the $00^02{-}10^01$ band and the P(20) of the regular band is about 11 GHz [8]. Due to this effect of the sequence-band transitions it is not realistic to describe the laser-line transitions by lorentzian profiles.

Although the line width is an important parameter determining the pulse width of a mode-locked system, there are always a relatively small number of modes oscillating so that the frequency band width of the pulse is much smaller than the linewidth. This frequency part at the top of the line, which essentially determines the pulse width, can be described by the second derivative of the line at the top. Therefore for our purpose we characterize the effective line width of multi-atmosphere CO_2 lasers by this second derivative. This quantity, as will be shown, can be easily determined by measuring the maximum frequency shift from the modulation frequency ω_m. Further, by using these data the width of mode-locked pulses will be deduced. We also measured the pulse width directly in mixtures with pressures up till 3 atm. The results of both measurements are in a very good agreement. Direct measurements of shorter pulses at higher pressures could not be performed due to insufficiently small time constants of the detection system.

For the present experiments we developed a new type of a multi-atmosphere single discharge TE laser. The construction and operation performance will be discussed. The system has been used for all usual CO_2 laser mixtures at pressures up till 7 atm.

2. Multi-atmosphere single discharge CO_2 laser

The system used is in principle a self-sustained, single discharge TE system of the Blumlein type. The construction is shown schematically in fig. 1. It is somewhat similar to the construction developed by Ernst and Boer for atmospheric mixtures [9]. It consists of two brass uniform field electrodes of 30 cm length and a separation distance of 5 mm, shaped according to the paper of Chang [10]. The metal electrodes are mounted parallel by means of two precisely cut glass blocks, of 4 mm thickness with circular holes for the laser beam, at the ends. Parallel to the axis two mylar indulation plates of 0.5 mm thickness connects the electrodes at two sides of the cavity, as shown in fig. 1. Essential for obtaining a homogeneous glow discharge between the electrodes are the two floating parallel copper sheets covering the two mylar plates. These metal sheets are thus insulated from the electrodes and have the same length as the electrodes. The more detailed technical storage on both sides of the cavity is very compact in order to have low inductance and consequently a fast rise time for the discharge. On one side of the cavity we installed a double row of Spraque capacitors with a total capacity of 10 nF charged at 40 kV. On the other side there is the pressurized air spark gap parallel to a small capacity of 0.3 nF. The whole system is installed into a chamber machined in a 10 cm thick slab of plexiglass. The cavity itself, having Brewster end windows of sodium chloride, can stand 10 atmospheres. The two compartments on both sides of the cavity containing the capacitors are filled with oil.

When the gap fires, the voltage of the electrodes near the gap is reversed within a few nanoseconds and across the electrodes there will be an initial voltage drop of twice the charging voltage. The applied voltage between the electrodes will initially charge the floating copper plates, so that near both the anode and cathode the medium will suffer a very high electric field at the shortest distances between the electrodes and these plates. This electric field and the low impedance give rise to a strong, very fast, short current pulse along the insulation surface. This short current pulse may be compared with a sliding spark and is known to be very effective in producing UV radiation for volume ionization. The ionized medium in turn will take over the current flow. The duration of the

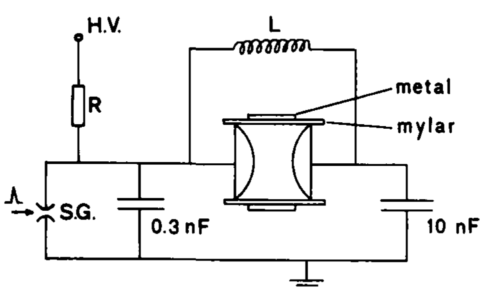

Fig. 1. Schematic diagram of the Blumlein-type laser system.

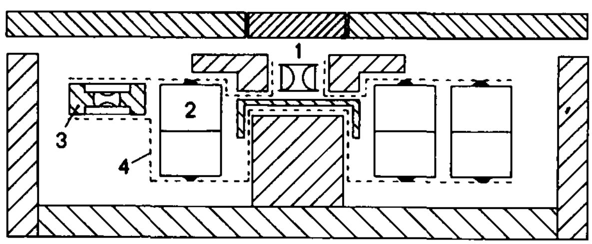

Fig. 2. Schematic diagram of the construction of the Blumlein-type laser system. (1) high-pressure laser chamber, (2) capacitors, (3) spark gap, (4) Cu strips for the electrical current of 30 cm width.

discharge is typical about 200 ns. It is observed visually that in this way a very homogeneous glow discharge is obtained without any streamer. This has been observed at various mixtures and gas pressures up to 10 atm. If the voltage rise is too slow, the sliding electrons along the insulation material will gain less energy and consequently produce insufficient UV for volume ionization. Probably it is also important that initially the left part of the system oscillates with a high frequency (100 MHz) so that there will be no arcing along the insulation surface. The laser system operates perfectly for the usual CO_2 laser mixtures up till 7 atm. We were able to run the system also up till 10 atm for lean CO_2 mixtures, for which the maximum supply voltage of 40 kV was just sufficient. The system yields small-signal gain values as high as 8% per cm.

3. Small-signal gain measurements

The present technique for obtaining the pulse widths as indicated further on relies on known values of the small-signal gain parameter under the relevant conditions. At first glance it looks straightforward to obtain those values. For instance, by just using a low-power stabilized single mode CO_2 laser that irradiates the pulsed system. The transmitted beam will then be focussed on a fast photodiode (HgCdTe). This experimental approach is as simple as unreliable; especially in the case of dealing with high-pressure CO_2 discharges. Although the glow discharge in the high-pressure cavity is visually homogeneous, the gain itself and the propagation constant are not necessarily constant over the small distance of 5 mm between the electrodes. This means that the probe beam will be disturbed and deflected by the medium, so that the spot centre of the focussed beam on the detector area no longer coincides with the most sensitive part of the photodiode. (Similar problems were faced by using a photoconductor as a detector.) We observed that the gain depended very much on the position of the detector in the focal plan of the lens and further that several gain peaks appeared after a shot with a separation distance in the order of a few μsec. The latter is probably related to thermal effects.

Instead, we developed succesfully a variable intracavity loss element for determining the threshold conditions of an oscillating pulsed system. The advantage is not only that the method turns out to be very sensitive and reproducible, but moreover we obtain the data from the region between the electrodes in which we are only interested for deducing the line width. An important condition for the succesful operation of the intracavity loss element is the accuracy of regulating its losses and yielding a minimum of disturbance of field pattern and volume. We have suceeded in this approach by taking advantage of the excellent absorption properties of heated germanium [11]. We developed a special heating and controlling system for the outcoupling germaniun flat. This flat has one antireflection-coated surface near the cavity making a small angle with the uncoated surface used as cavity mirror, so that interference phenomena between these surfaces are eliminated. The main feature is the heating and accurate control. The element and circuit are shown in fig. 3. With this construction a temperature stability of the control unit of less than 0.1°C is assured. The temperature is measured by means of a thermocouple. The calibration is obtained by irradiating the flat with the output beam of a stabilized single mode cw CO_2 laser and measuring the transmissivity as a function of temperature. The measurements are reproducible and can be done accurately within a few percent. The results are shown in fig. 4.

For a particular laser system, keeping the gas composition, partial pressures and total input energy constant the absorption losses of the outcoupling mirror are increased up till the threshold of laser action. Including

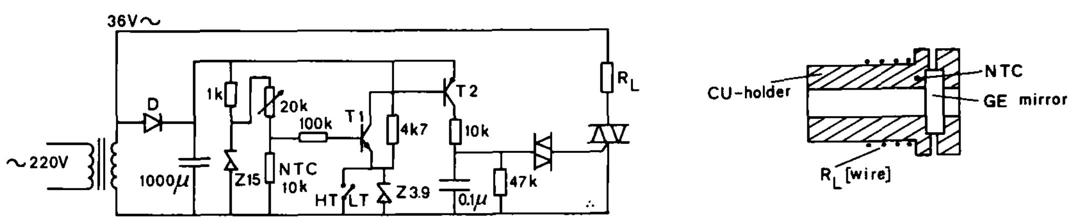

Fig. 3. Scheme of the temperature control unit and heated out coupling mirror holder.

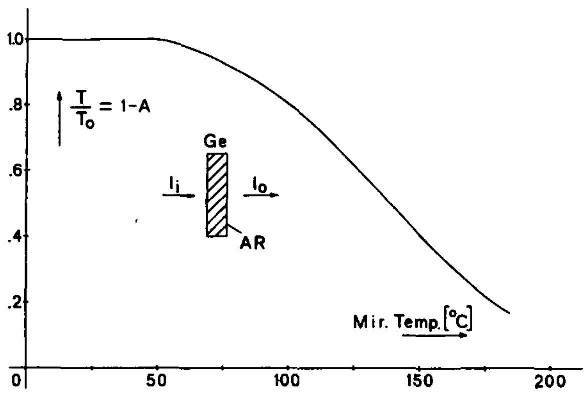

Fig. 4. Transmission of the used germanium flat versus temperature relative to its value at room temperature.

also other cavity losses which are much smaller than that of the outcoupling mirror, we obtain the small-signal gain from the threshold condition. At the outcoupling mirror there is apart from the heating loss a transmission loss of 64%. The losses of the gold-coated end mirror are 2%. The diffraction losses were estimated about 5%. In this way the gain was obtained as a function of temperature. The results are plotted in fig. 5. The gain measurements on our laser system show, as expected, a dependence on gas composition, partial pressures and input energy. In table 1 the gain values and the appropriate system parameters are given. The gain values, given in table 1, are not optimized, because the system was limited by a maximum supply voltage

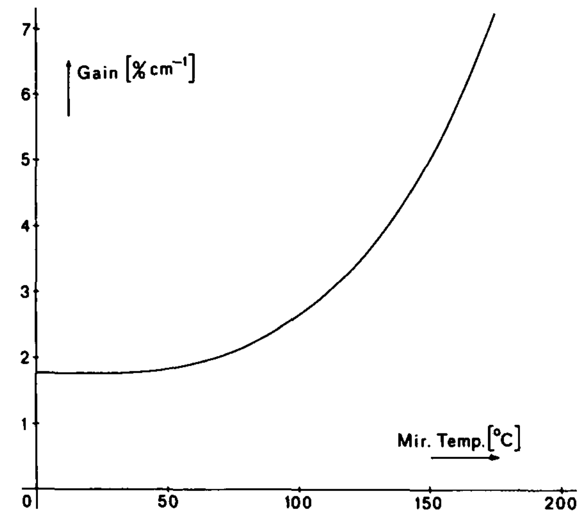

Fig. 5. Small-signal gain versus temperature.

of 40 kV. Nevertheless, we used pressures as high as possible. This is the reason why for some mixtures the small-signal gain does not increase, but even decreases, by increasing the pressure. Remarkable is the high gain measured for low pressures [12].

4. Pulse-width measurements

We observed that the mode-locked pulses near the maximum detuning frequency in nearly all mixtures were oscillating on the P(20) transition. This observation may be understood from the fact the a hot-band and a sequence-band transition are very close to this regular transition, so that the effective gain for the P(20) is favoured as compared with the other ones. We described previously [5] how by detuning an AM mode-locked system information can be obtained on the line profile and the pulse width. The detuning is achieved experimentally by stabilizing the modulation frequency and detuning the cavity mode separation frequency by merely changing the mirror distance. It is shown that the frequency band width of the mode spectrum of such a mode-locked system is less than 10% of the line width [1, 5]. This means that in the frequency region of interest we may to a very good approximation represent the gain and the phase retardation of such a line profile by a quadratic and linear form respectively.

For multi-atmosphere systems the line profile for the laser transition, due to overlap, can no longer be described by a lorentzian profile. However, since the pulse frequency width is much smaller that the line width, we may for our purpose characterize the line profile by determining its second derivative at the top.

The maxium detuning is easily determined because at a certain frequency shift the mode locking and os-

Table 1.
Small-signal gain versus gas composition, pressure and supply voltage

MIXTURE	PRESSURE [atm]									V_{supply}
CO_2 : N_2 : He	2	3	4	5	6	7	8	9	10	[kV atm⁻¹]
	SMALL SIGNAL GAIN [% cm⁻¹]									
5 : 7 : 8	6.4	8.0	8.0							11
1 : 2 : 3	4.3	5.0	6.2							9
1 : 2 : 4	4.9	7.1	7.4	6.2						8
1 : 1 : 4	4.3	4.8	5.7	6.0						8
1 : 1 : 7			2.9	3.5	3.5	3.5				6
1 : 1 : 12							2.6	3.2	3.4	4

cillation disappeared abruptly. Furthermore, it is observed that the maximum positive and negative frequency shift from the synchronized frequency is equal within a few percent. We derived [5] the relation between the maximum detuning x_m and the second derivative G_2 of the line profile, which is given by

$$G_0 - L = -2\pi^2 x_m^2/d^2 G_2 + \alpha_a(1-m), \tag{1}$$

where G_0 and L are respectively the single-pass small-signal gain and the single-pass power loss. The last term on the right-hand side of eq. (1) describes the modulator power loss. In the case of a perfect standing acoustic wave in the modulator $m = 1$. Measuring x_m for several values of α_a it is easy to extrapolate the value of x_m for the case α_a approaches zero. Knowing G_0, x_m, and the modulation frequency ν_m, we find G_2 for several mixtures and gas pressures. From eq. (1) we obtain:

$$(8\nu_m^2 G_0/-G_2)^{1/2} = (c/\pi x_m)\{G_0(G_0 - L)\}^{1/2}, \tag{2}$$

were ν_m = modulation frequency (80 MHz), c = light velocity in vacuum (3×10^8 m/s), m = power-loss parameter of the modulator (0.5), L = single-pass power loss of the cavity (0.4) (including diffraction losses and outcoupling losses).

Eq. (2) is a characteristic quantity of the effective line profile. The results are plotted in fig. 6.

In the case the line can be approximated by a Lorentz profile (low pressure), eq. (2) gives the linewidth because $\Delta\nu_N = (8\nu_m^2 G_0/-G_2)^{1/2}$.

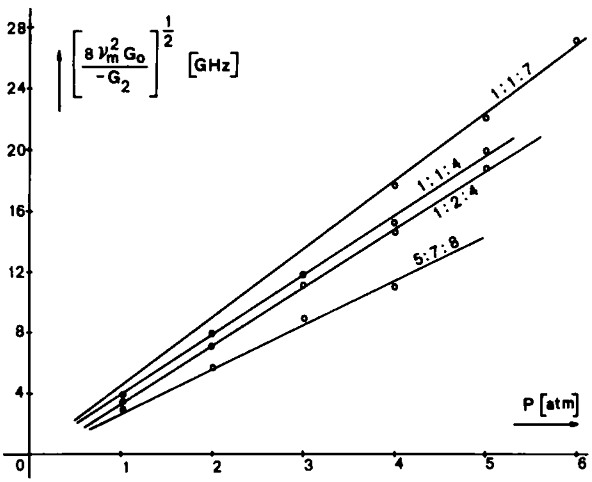

Fig. 6. Effective line width versus pressure, for different gas compositions

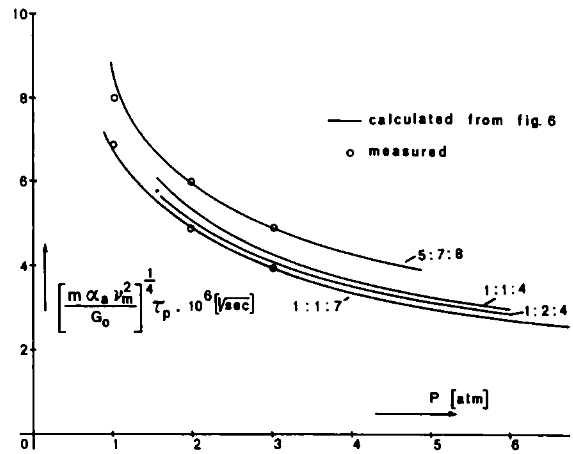

Fig. 7. The solid lines represent the pulse-width measurements deduced from the frequency detuning. The circlets are direct measurements.

The relation between G_2 and the pulse width τ_p can be given by [5]:

$$\tau_p = \{(\ln 2)/\pi^2\nu_m^2\}^{1/2}(-G_2/m\alpha_a)^{1/2}, \tag{3}$$

or

$$\left(\frac{m\alpha_a\nu_m^2}{G_0}\right)^{1/4}\tau_p = 8^{1/4}\left(\frac{\ln 2}{\pi^2}\right)^{1/2}\left(\frac{8\nu_m^2 G_0}{-G_2}\right)^{-1/4} \tag{4}$$

The right-hand side of eq. (4) is measured directly, as

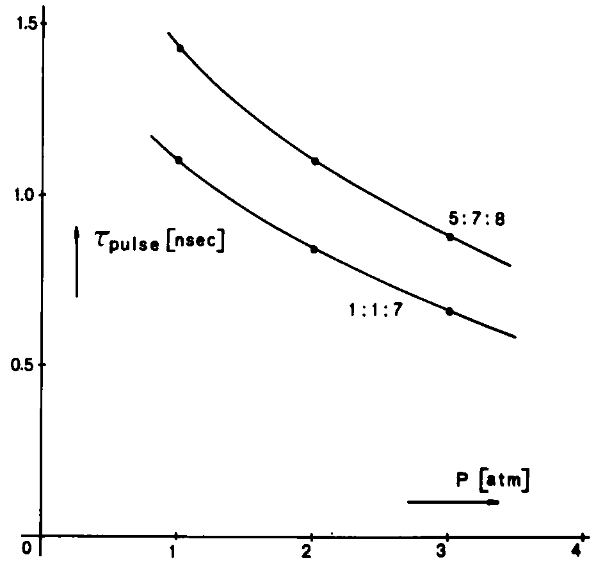

Fig. 8. Measured pulse durations versus pressure for two gas compositions

can be seen by comparing eq. (2). The results are plotted in fig. 7 for several mixtures as a function of pressure.

Up till pressure of 3 atm we measured the pulse width also by means of a hot-hole detector having a rise time of 200 ps and a transient digitizer R 7912 (Tektronix) with a rise time of 0.7 ns. The results of these direct measurements are plotted in fig. 8 for two mixtures. These direct measurements are also plotted in fig. 7 and it is seen that both experimental techniques of measuring are in very good agreement.

5. Discussion

Eq. (2) suggests that the characteristic line width is independent of laser-discharge parameters. This was indeed confirmed by additional experiments. We observed that this quantity was independent of input-energy parameters. Higher energies yield larger frequency shifts but also larger small-signal gains. By deducing the characteristic line width according to eq. (2) both effects just cancel. This is demonstrated in table 2, where some results for a typical CO_2-laser mixture at 3 atm are given. Three different discharge voltages and input energies were used and the characteristic line width is seen to be practically independent of these parameters.

Although due to limited time constants of detection systems we could not check all pulse-width values deduced from the maximum detuning frequency, there is a very good agreement in the lowerpressure range. The experiments clearly indicate that helium has a large effect on the characteristic line profiles and mode-locked pulses. This is on contrast with what can be expected from linewidth measurements on neutral gases but in agreement with our previous observations at atmospheric pressures [5].

The question is still left how this phenomenon can be explained. We suggest that this effect has to do with the overlap of the sequence bands [7, 8]. Describing the occupation of the ν_3-vibrations by a temperature T_3 one can easily show that the ratio of the gain G_2

Table 2
Deduced line-width values for different input energies

$CO_2:N_2:He$ = 5 : 7 : 8	PRESSURE = 3 Atm		
INPUT ENERGY [J]	g_0 [% cm^{-1}]	X_m [mm]	$[-8\nu_m^2 G_0/G_2]^{1/2}$
3.9	6.1	16.5	8.4
5.5	7.0	19.0	8.6
7.2	8.0	22.5	8.5

in the 00^02 sequence band and the gain G_1 in the 00^01 regular band is simply given by

$$G_2/G_1 = 2\exp(-h\nu_3/kT_3)\,. \tag{5}$$

This ratio depends strongly on T_3. It may be possible that T_3 increases with increasing helium percentage, so that this ratio increases with helium.

If this is true, it means that – a line profile being the sum of contributions from nearby rotational lines – helium has a much larger effect on the line broadening at higher pressures than the other constituents.

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