SPONTANEOUS OSCILLATIONS IN A SINGLE MODE CO_2 LASER IN A FABRY-PEROT CAVITY

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Abstract

We show the existence of self-pulsing at two characteristic frequencies in a single mode CO_2 laser for low pump rates. The dynamical behavior of the system as a function of the pump rate, cavity losses and detuning between atomic and cavity frequencies has been investigated. These results can be explained by a recently developed theoretical model which incorporates intensity dependent parameters.

Introduction

Recent advances in nonlinear dynamical systems have stimulated experimental research on instabilities and transition to deterministic chaos in laser devices [1-3]. However, unexpected results have been observed which lack even a qualitative theoretical explanation [4]. In this research, CO_2 lasers have played a major role because they are predominantly homogeneously broadened, can be operated in a single mode, and therefore can be modelled theoretically without excessive complications. In addition, their self-oscillation frequencies usually occur in a range that is easily measured experimentally. Spontaneous oscillations in CO_2 lasers have been observed and reported previously. In the early years of the first CO_2 lasers, this phenomenon was considered uninteresting and was mentioned only in passing [5]. More recently, observations of self-oscillations and even chaos were reported in the study of a bidirectional, single-longitudinal-mode CO_2 ring laser [6]. The interaction between the two waves propagating in opposite directions is mediated by the grating formed in the population inversion and gives rise to oscillations, self-spiking and chaos [6,7]. In this work, we report self-oscillations in a simpler system: a standing wave single mode CO_2 laser, in the absence of any modulation, time perturbation, or multimode interaction. The output intensity of the laser may show small amplitude oscillations superimposed upon a c.w. background or it may be completely stable, depending on the values of the parameters. The region of instability of the laser depends on the excitation discharge current, on the detuning between cavity frequency and optical transition frequency, on the cavity losses and, dramatically, on the temperature of the gas in the discharge. We have studied the behavior of the self-oscillation frequency as a function of control parameters. Our experimental results are in qualitative agreement with a simple theoretical model [9].

Experimental Set-Up

The laser cavity is built in a Fabry-Perot configuration (Fig. 1) with one fully reflecting mirror M (flat) and a grating G (nominal efficiency in the first order: 97%), both gold-coated. The output coupling is provided by a beam splitter (B.S.), a Zn-Se (AR/10%) plate slightly tilted with respect to the optical axis. An electro-optic modulator (EOM) is used to set the level of losses of the cavity at different values and is connected to a high voltage D.C. power supply. The electro-optic crystal is an antireflection-coated Cd-Te crystal for 10 μm, having an aperture of 2 mm in diameter, and a length of 6 cm. Because of the severe restriction on the beam cross section imposed by the crystal aperture (it is not wide enough to allow the development of a lasing mode in the cavity), we have inserted a beam expander, comprised of two lenses L_1 and L_2 (Zn-Se), and leading to a reduction factor of the order of 3. The pinhole P and the small diameter of the tube (6 mm) prevent the laser from working on transverse modes different from the TEM_{00}.

The laser main cooling element is a close loop of circulating water around the discharge tube with a heat exchanger for removal of the excess heat into the general water supply. The lasing medium is a mixture of $He:CO_2:N_2$ in ratios of approximately 8:1:1 at a total pressure of about 17 torr. Flowmeters with high accuracy valves are used to measure and control the partial pressures of each gaseous component. After passing through a mixing chamber, the gas flows through the laser tube. The laser tube is closed at the ends by two

Zn-Se Brewster windows. The D.C. longitudinal discharge is actively current-stabilized to better than .05% [8] in the range 3-20 mA. Variations of the detuning between the cavity and the transition frequency are provided by cavity length adjustments by means of a piezo-electric ceramic mounted on one of the mirrors.

The main function of the grating is to keep the laser running on the P(20) line steadily and to prevent jumps between different transition lines which would produce relaxation oscillations. The output signal is detected using a NERC MPV 11 B60 photovoltaic liquid nitrogen cooled detector. The signal is sent to an oscilloscope, (Tektronix 7904) through a D.C. coupled wideband amplifier, and to an A.C.-coupled real-time spectrum analyzer (Rockland). The spectra shown in the following section are taken under these conditions: full scale frequency 100.0 KHz and resolution .5 KHz. Each spectrum is the result of an average over 256 sample spectra, the scale is linear in the frequency axis and logarithmic in the power.

In order to monitor the molecular transition on which the laser is working, we have aligned outside the cavity an infrared CO_2 laser spectrum analyzer (EG&G); the instrument has a graded scale that reads directly the line on which the laser is working and can be used as a monitor against changes of transition when the position of the mirror is changed. Collinear with the beam under study we have aligned outside the cavity a stabilized CO_2 single mode TEM_{00} commercial laser (Line Lite Laser); we can tune its transition line and its frequency of operation by changing the D.C. voltage applied to the internal cavity piezoelectric crystal. The stability characteristics for this laser are: short term stability (1 minute, typically) better than 100 KHz, long term stability (1 hour) 1 MHz. The output of this laser is mixed on the detector with the output of the laser under study to produce a beat frequency on a fast real time spectrum analyzer (Tektronix 7L12). This serves a double purpose: to check whether the laser is operating in a single mode and to measure the cavity to transition frequency by observing differences from the on-resonance beat frequency. The reference beam is shut off (shutter S) when detecting the output of the laser under study, and allowed to go through after each measurement for stabilization checks.

Experimental Results

When the pump rate is high enough to bring the laser above threshold, we observed periodic pulsations of the output intensity.

In order to determine the origin of this instabily, we first examined carefully the level of noise in the system by taking the power spectrum of the discharge current and comparing it to measurements of spontaneous emission.

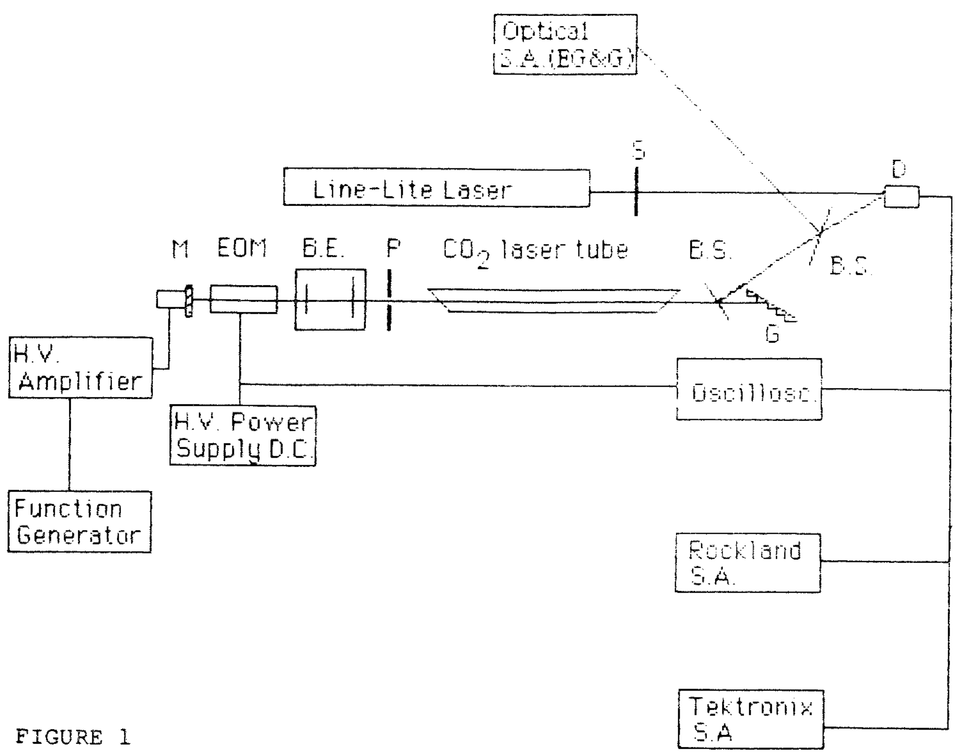


FIGURE 1

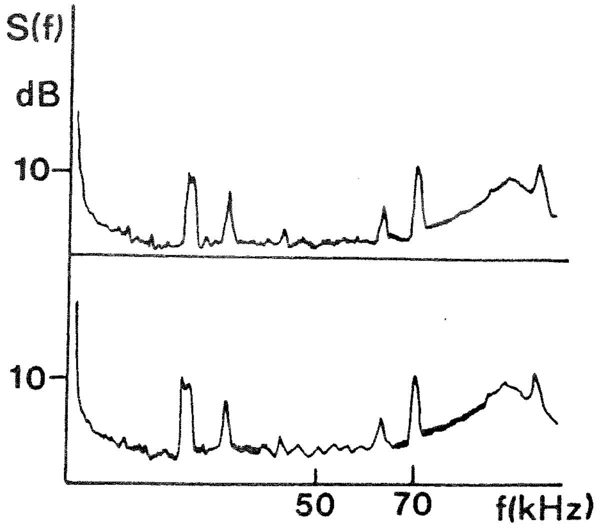


FIGURE 2

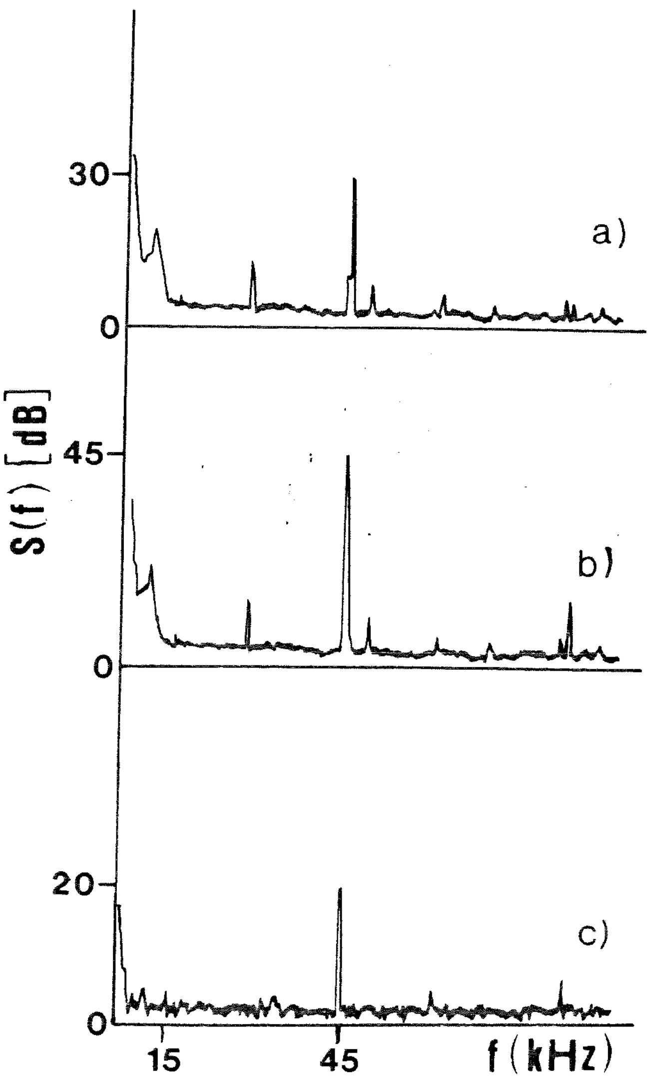


FIGURE 3

The spectra are very similar in relative amplitude and frequency distribution. In fact, the two power spectra shown in Fig. 2 corresponding to the current (upper) and the optical signal (lower) when the cavity is shut off are essentially indistinguishable. This proves that the noise background is only electrical in origin and is very low because of the current controlled power supply [8]. Some frequency peaks remain which are probably due to residual plasma noise. The signal-to-noise ratio can be as high as 70 dB. A comparison between the noise and signal spectra of Fig. 3a indicates that the only two true signal frequency peaks are those marked f_1 at 4.0 KHz and f_2 at 45.0 KHz, with amplitudes 20 dB and 30 dB over the background, respectively. Here the frequency peaks due to the discharge noise have been partly overwhelmed by the background.

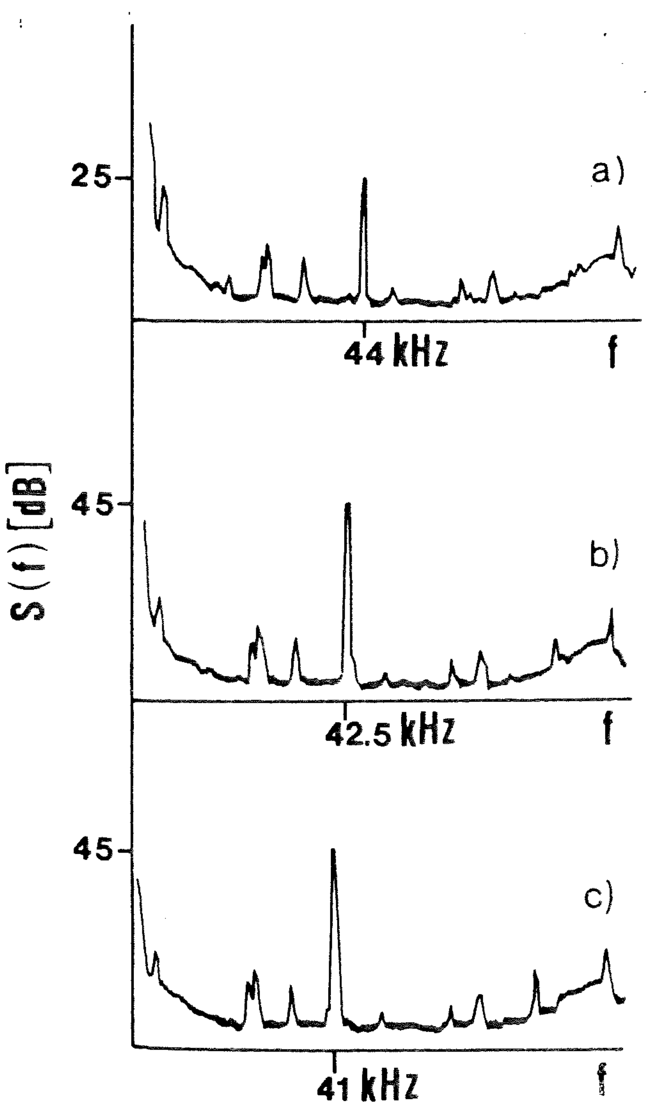
For constant excitation current and detuning parameter, we studied the dependence of the oscillation frequency on the cavity losses; this was achieved by applying different D.C. voltage levels to the electro-optic modulator. The sequence in Fig. 3a-c shows the lack of dependence of the self-oscillation frequencies on the cavity losses, while the amplitude is evidently dependent. When the losses are very high, we do not observe any kind of oscillation; self-oscillations appear at some low loss value and a further decrease in the loss level will produce first an increase (Fig. 3a,b) and then a decrease (Fig. 3b,c) in the amplitude of the oscillation until the output signal becomes stable again.

A similar overall behavior can be obtained by changing the cavity tuning with respect to the center of the transition line by adjusting the cavity length. For large detuning when the laser is barely above threshold, the output is stable; when the cavity and the transition lines approach one another, we observe again self-oscillations that first increase and then decrease in amplitude and disappear at line center if the total gain is high enough. The only influence on the temporal behavior due to the detuning rests on the modification of the actual gain-to-loss ratio. In fact, the values for which these oscillations appear are always the same. The independence of the oscillations on detuning together with the dependence on the losses prove that the instability is of amplitude, rather than of phase [9].

Here we have to stress the fact that the laser is running in a single mode, even when detuned. The experimental technique employed to confirm this statement has already been shown. However, this is not enough to prove the existence of true single mode operation in our laser, because we might be faced with the presence of two different polarization states that oscillate at the same frequency and on the same cavity mode. This could happen if the polarization selection of our cavity were insufficient to suppress completely one of the components, especially because the EOM varies cavity losses by partially rotating the field polarization and using as polarizers the tube's Brewster windows. Two linearly polarized laser fields present in the cavity at the same time and orthogonal to each other could interact in the active medium and give rise to oscillations in the laser output. An experimental check has been performed inserting a polarizer in the cavity parallel to the direction of the laser's Brewster windows. We have seen that this does not affect the oscillation at all, but as soon as we rotate the polarizer itself, even by a very small angle, the intensity drops suddenly to zero and the laser turns itself off. Placing the polarizer in front of the detector, outside the cavity, in order to find whether a beat between different polarizations is generated in the reflection at the B.S., again gives a negative result: when the polarizer has its axis aligned with the polarization of the laser field the oscillations are not affected at all, as soon as we try to rotate it even by a small angle the signal disappears from both spectrum analyzer and oscilloscope.

An important role is also played by the temperature; the amplitude of the oscillations depends strongly on it and a variation as small as 0.1 K in the cooling reservoir can be enough to suppress the self-oscillation. This represents a major inconvenience for our studies because it requires an active temperature stabilization system that is somewhat sophisticated, and unusual for a laser. At the same time, this suggests that internal laser parameters, such as internal relaxation constants among rotational sublevels of each single vibrational state, may be responsible for the pulsations as is discussed in the next section and in Ref. 10.

The behavior of the oscillation frequencies as a function of the discharge current contains more information. As shown in Fig. 4a-c, the peak corresponding to f_2 moves towards smaller values as the current increases, while f_1 moves in the other direction (not visible in this picture because of scale problems). For low values of current, we observe an oscillation at $f_2 = 44.0$ KHz, together with a strong low frequency oscillation at f_1 3.6 KHz [11] both 28 dB over the noise level (Fig. 4a). Increasing the current from 6.5-7.0 mA, we find (Fig. 4b) $f_1 \approx 3.9$ KHz and $f_2 = 42.5$ KHz with amplitudes 18 dB and 40 dB, respectively. Finally, in Fig. 4c, we find $f_1 \approx 4.1$ KHz with amplitudes 16 dB and 40 dB over the background, respectively. The lower frequency f_1 decreases in amplitude and increases in frequency when the current increases, while f_2 initially increases in amplitude, but reaches a maximum, and then decreases again, but it is always decreasing in frequency.



The oscilloscope trace of the signal is rather broad (Fig. 5). This is due mainly to the presence of the other frequency component at about 5 KHz which has nonnegligible amplitude; the optical and detector noise intrinsic in the signal does not play

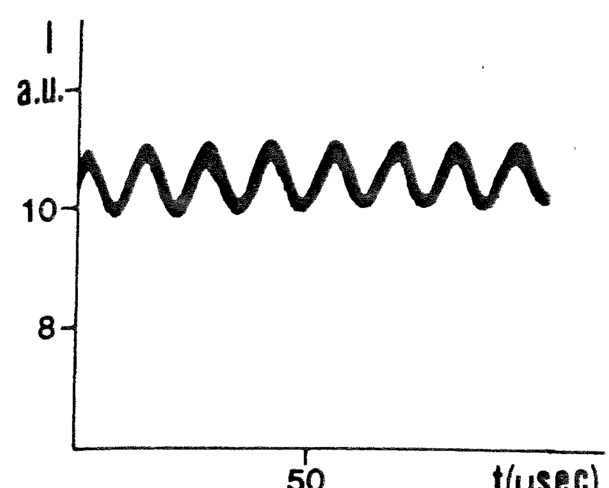
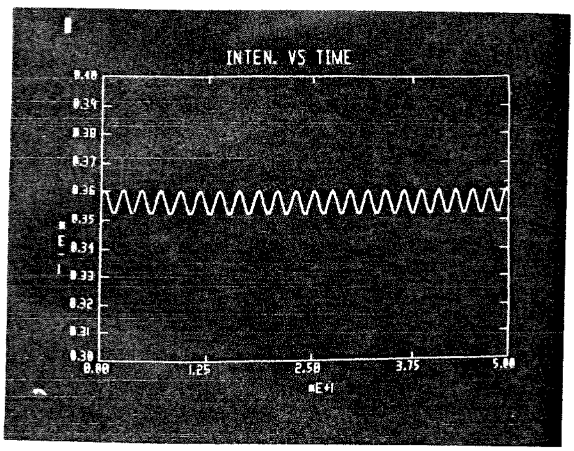


FIGURE 5

any role at all, because it is very small. Another substantial contribution to the thickness of the trace is the noise due to the amplifier. The main oscillation has a frequency $f_2 \simeq$ 38 KHz. The ratio between the amplitude of the intensity oscillation superimposed on the c.w. laser output and the c.w. value itself is about 0.1.

Comparison with Theory

The Maxwell-Bloch equations in the plane wave approximation cannot explain the origin of self-oscillations in the laser intensity in a CO_2 laser, because if one uses the appropriate time constants the equations can only account for damped oscillations [12]. However, a low threshold value for self-oscillations and their disappearance for higher pump rates, just as observed here, have been predicted recently by a theoretical model where the cavity losses are viewed as being dependent on the laser intensity [10]. Using the dynamical equations for a four-level atom as introduced in Ref. 10 and carrying out the calculation for parameter values that are typical of the CO_2 laser, we have obtained oscillations (Fig. 6) which are in good qualitative agreement with our experimental data. In fact, the pump range for which the laser is unstable, and the frequency and amplitude of the oscillations, as well as the change of that frequency as a function of the pump, follows the same pattern in the experiment and in the model. By increasing the pump level in the model, one predicts a reduction in the oscillation frequency after the maximum and then a sudden disappearance of the pulsations for pump values which are nearly 30% above the first laser threshold as was observed experimentally. The region of instability as a function of the gain, and the existence of the instability itself, depend strongly on the ratio between the relaxation rates of the different vibrational-rotational levels; in particular, on the rate at which the rotational level of the upper state of the laser transition is populated from the other rotational levels within the same vibrational level. These rates are strongly dependent on the temperature and this may explain the experimental results described above. The model also predicts that the pulsation can be found for a wide range of cavity losses.



Conclusions

In this paper we have presented the first experimental evidence of instabilities in a CO_2 laser operating on a single longitudinal and transverse mode that cannot be explained by the usual Lorenz model. We found the existence of instabilities to be practically independent of the level of cavity losses, this instability is then observable also in the good cavity limit. The presence of oscillations seems to be highly dependent on the atomic relaxation rates and on the temperature of the gas. We give also the amplitude and frequency dependence of these oscillations as a function of the excitation current and the detuning between cavity and atomic resonant frequencies showing that this instability may be inferred to be of the amplitude type.

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