DELAYED BIFURCATIONS IN A CO_2 LASER WITH A SLOWLY SWEPT PUMP

F.T. Arecchi, R. Meucci, and M. Ciofini

Istituto Nazionale di Ottica
Largo E. Fermi, 6, 50125
Firenze, Italy

Theoretical studies of the semiclassical laser equations for two-level atoms predict the appearence of a delayed bifurcation when the pump parameter is swept linearly in time across the threshold region[1]. Recently, such a delayed bifurcation has been observed by Scharpf et al[2]. (2) at the threshold of an Ar^+ laser by varying the cavity losses.

In this paper we report on a delayed bifurcation of a CO_2 laser when the pump parameter is swept across the threshold region.

The experimental data show that the delay of the bifurcation is independent of how far below threshold the laser is brought by a triangular modulation, apart from a sharp transition to zero very near to threshold. We show that numerical results for triangular pump modulation predict the same behavior at the bifurcation, both for two and four level models. However, our data are better described in terms of the four-level model, because this provides a fast damping of the oscillations as experimentally observed.

Our experimental set up[3] consists of a single mode CO_2 laser pumped by means of a direct current stabilized power supply which can be externally modulated around a pre-selected value of the discharge current which is measured on a precision resistor R. The current modulation is monitored directly with an optically coupled isolator in series with the regulator. The laser output intensity is detected by a liquid N_2 cooled HgCdTe detector with a rise time $\tau < 10$ ns. The photodetector signal is sent together with the current modulation signal to an X-Y oscilloscope display and to a digital oscilloscope to monitor the temporal evolution.

In Fig. 1 we report the time evolution of the laser intensity of the corresponding current modulation around a mean value of the discharge current (5.156 ± 0.002) mA and at a modulation frequency of 100 Hz. In Fig. 1b we report an expanded version of the associated X-Y plot, near the threshold region. As can be seen, in the operating range, the laser intensity is not linear as a function of the excitation current, but near threshold the dependence is approximately linear indicating that a linear current sweep near threshold corresponds to a linear sweep of the pump parameter. The stationary threshold current is (3.94 ± 0.02) mA. Calling A(t) the current normalized to the stationary threshold value, we denote

Coherence and Quantum Optics VI
Edited by J. H. Eberly *et al.*
Plenum Press, New York, 1990

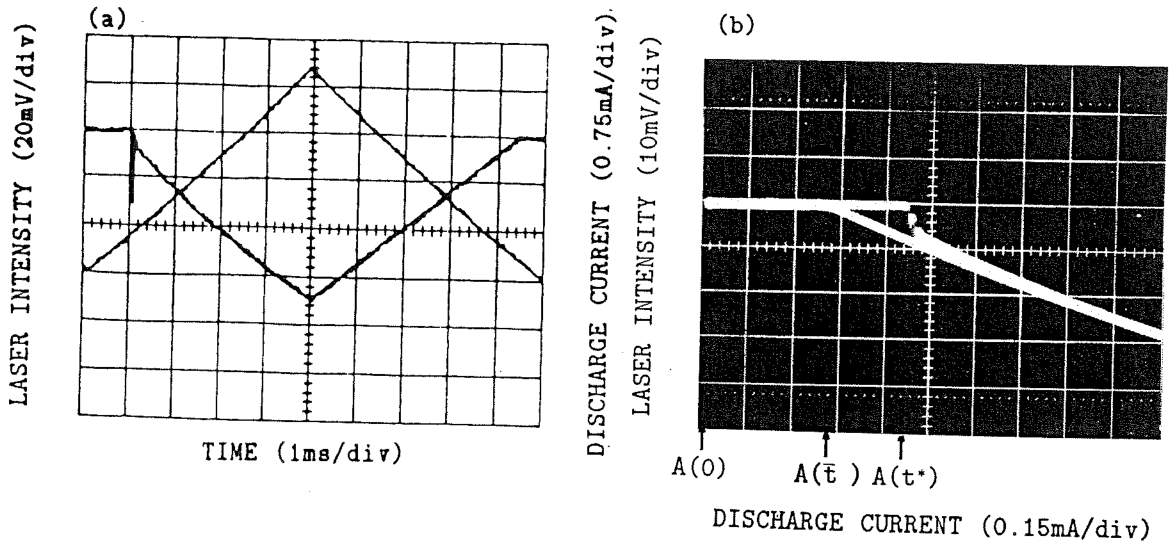

Fig. 1(a) Laser intensity and discharge current versus time. (b) Amplified version of the corresponding X-Y plot near threshold. The width of the bistable region $\Delta A=A(t^*)-A(t)$ is 0.07. $A(0)=0.90$ and $A_{max}=1.7$.

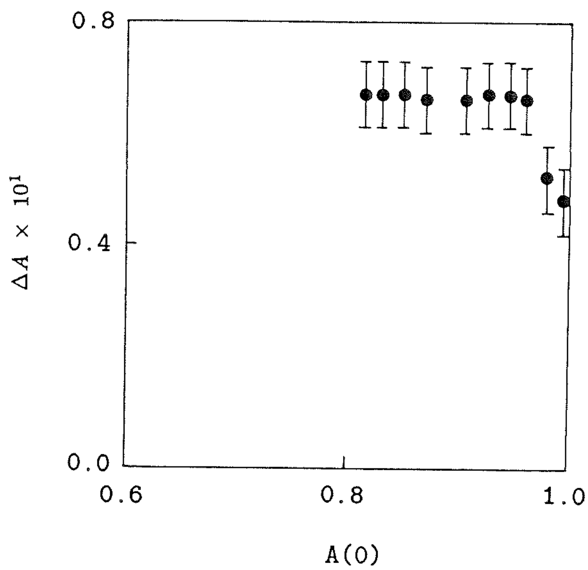

Fig. 2. Pump delay A versus A(0) at fixed modulation frequency (f=100Hz and modulation amplitude $A_{max}-A(0)=0.8$.

by $A(0)$ ($\leqslant 1$) the minimum A value, by $A(t)=1$ the threshold value, by $A(t^*)$ the pump value at which the laser switches-on and by A_{max} the maximum value of $A(t)$. The sweep rate of the pump parameter is given by $2\left[A_{max} - A(0)\right] f$, where is the sweep frequency.
The width of the bistable region defined as $\Delta A=A(t^*)-A(t)$, is unequivocally defined because the switch-on of the laser is characterized by a sharp peak with few damped relaxation oscillations. The independence of ΔA on $A(0)$ at a given sweep frequency and modulator amplitude is shown in Fig. 2.
The reported results can be explained in terms of a four-level molecular model[4,5] in which the two energy levels are coupled to all rotational levels of the same vibrational band. This model consists of three equations describing the intensity (x), the population inversion of the resonant levels (y) and the population inversion of the vibrational band (z) as follows:

$$x = K_0 x(1-y) \tag{1}$$

$$y = (\gamma_R + \gamma_{\parallel})\, y + \gamma'_R z - \mu xy + \eta \gamma_{\parallel} y_0\ (t) \tag{2}$$

$$z = (\gamma'_R + \gamma_{\parallel})\, z + \gamma_R\, y + (Z-1)\, \eta\, \gamma_{\parallel}\, y_0\ (t) \tag{3}$$

where $\mu = \gamma_{\parallel}(\gamma_R + \gamma'_R + \gamma_{\parallel})/(\gamma'_R + \gamma_{\parallel})$ and $=(\gamma_R + \gamma'_R + \gamma_{\parallel})/(\gamma_R + \gamma_{\parallel})$, is the decay rate from the band (v,J) to (v',J') for $v' \neq v$, γ_R and γ'_R are the decay rates from resonant level (v,J) to the vibrational band (v,J') (for all $J' \neq J$) and for the reverse process, respectively. The intensity $x(t)$ is normalized to the saturation intensity $I_s = \mu/2G$, where G is the field-matter coupling constant. Both $y(t)$ and $z(t)$ are normalized to the threshold inversion k_0/G where $k_0 = (c/2\ L)|\ln R|$ for mirror reflectivity R and cavity length L. The last term in each of eqs. (2) and (3) is obtained from Ref. 3 via the equilibrium conditions and assuming that the pump energy is equally distributed among all levels of the vibrational band.
In the numerical calculations we have used $k_0 = 1.2\text{X}10^7\ s^{-1}$, $R=0.75$, $\gamma_R = 1.0\text{X}10^7\ s^{-1}$ $\gamma'_R = \gamma_R/Z$, with $Z = 16$, where $Z + 1$ is an effective multiplicity factor of the vibrational upper band, and the time dependent pump parameter $y_0(t)$ is a linear function of time of the type $A(t) = A(0) + \alpha t(\text{sign} \sin\left[2\pi f t\right])$, with

$$= 2\left[A_{max} - A(0)\right] f.$$

In Fig. 3 we report numerical solutions of the laser intensity versus the pump parameter for increasing values of the sweep frequency (from 20 Hz to 100 Hz) with constant modulation amplitude. Numerical calculations for pump modulation on the two-level model give similar delay, however with long damped oscillations (fig. 3d) never observed in the experiment (see fig. 1). The dependence of the delay time t on $A(0)$ at a given sweep frequency and modulation amplitude is seen in fig. 4. As can be seen, for $A(0) \leqslant 0.97$, t_d is independent of $A(0)$, in agreement with the experimental data of fig. 2.

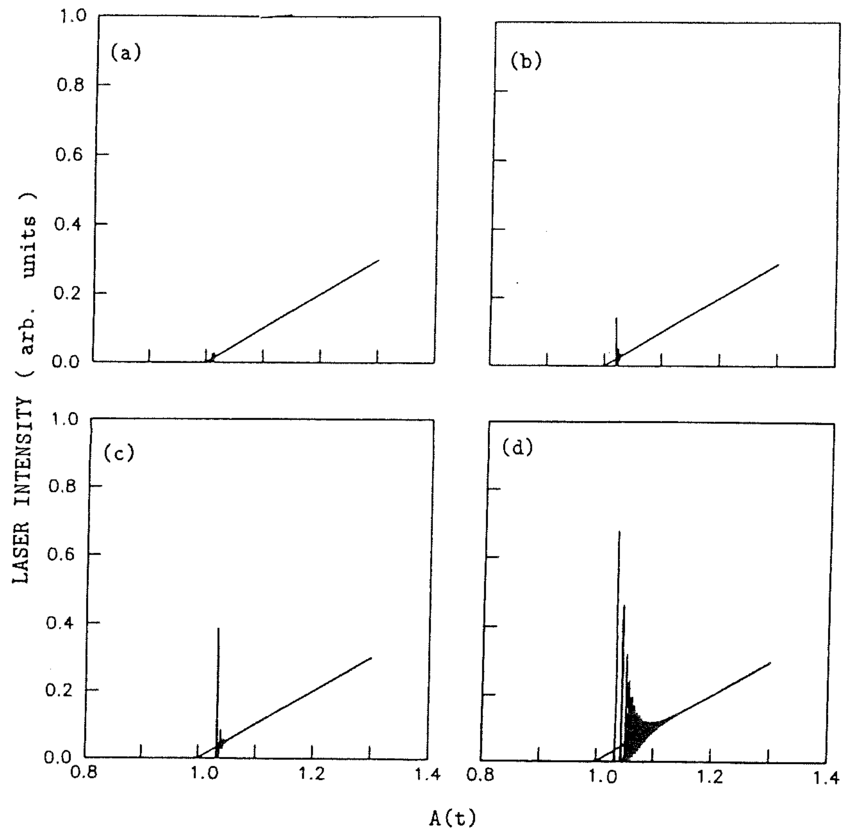

Fig. 3. Numerical results for the four and two level model. (a), (b) and (c), (four level model). Plots of intensity versus A(t) for modulation frequency f=20 Hz, 50Hz and 100 Hz, respectively $\gamma_R=0.5X10^7\ s^{-1}$ and $\gamma_{\parallel} = 1.0X10^4\ s^{-1}$, $k_0=1.5X10^7\ s^{-1}$, T= 0.25. A(0) = 0.80, Z=16, A_{max}-A(0)=0.5 (d) The two-level model with the same parameters as above at f=100 Hz.

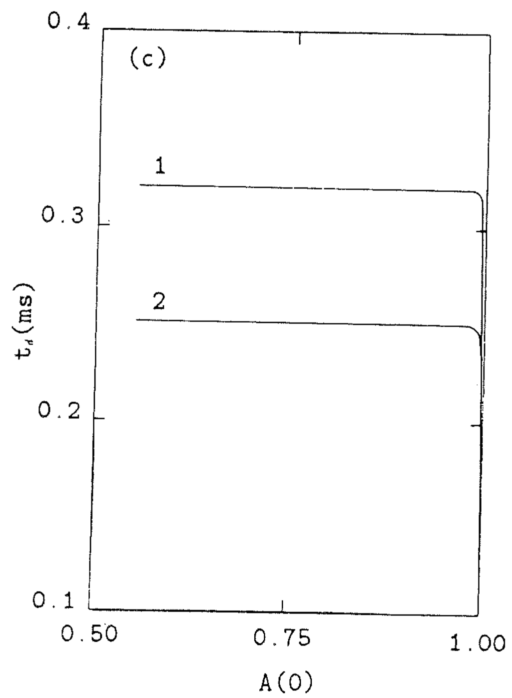

Fig. 4. time delay td versus A(0) for $\gamma_R=10^7\ s^{-1}$, 1 and 2 correspond to f=100 and 200 Hz respectively.

In summary, our experimental results confirm the appearence of a delayed bifurcation when the pump parameter is swept across the threshold region of a CO_2 laser. A preliminary analysis of this bifurcation in terms of first passage time statistics have provided a scaling law for the delay times versus the sweep parameter in agreement with the theoretical model[6].

REFERENCES

1. P. Mandel and T. Erneux, Phys. Rev. Lett. **53** (1984) 1818
   P. Mandel, Optics Comm. **64** (1987) 549.

2. W. Sharpf, M. Squicciarini, D. Bromley, C. Green, J.R. Tredicce and L.M. Narducci, Optics Comm. **63** (1987) 344.

3. F.T. Arecchi, W. Gadomski, R. Meucci, J.A. Roversi, Opt. Comm. **70** (1989) 155.

4. J. Dupré, F. Meyer and C. Meyer, Phys. Rev. Appl. (Paris) **10** (1975) 285.

5. E. Arimondo, F. Casagrande, L.A. Lugiato and P. Glorieux, Appl. Phys. B **30** (1983) 57.

6. M. Ciofini, R. Meucci and F.T. Arecchi, to be published.