Polarization competition in a quasi-isotropic CO_2 laser

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We experimentally study the polarization dynamics of a single-mode CO_2 laser during the switch-on transient of the laser intensity. We find a strong competition between two linearly polarized fields, which finally collapse into a single field. As a result of this competition, the two coexisting fields oscillate out of phase by π rad for time intervals much longer than that of the relaxation oscillation. One can control the oscillation frequency of the two polarized fields by varying the intracavity anisotropies. This phenomenon is interpreted in the framework of Maxwell–Bloch equations by addition of nonlinear terms to the polarization equations that allow the fields to compete while they interact with the same population inversion.

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Laser dynamics is commonly studied in light of the fact that the electrical field can be described as a scalar variable because in most of such systems the polarization state is imposed by anisotropies of the cavity. For instance, in gas lasers it is usual to introduce intracavity Brewster windows or diffraction gratings to select the linearly polarized state. However, in perfectly cylindrical laser cavities without any elements to select a preferred polarization, the study of the dynamics includes the necessity to consider the vector nature of the electric field as well as the polarization when material variables enter into the dynamics.

Experimentally, this situation manifests itself in switching between two polarization states or in more-complicated dynamics such as the simultaneous emission and competition of several polarization modes, preferably circularly polarized VCSELs,[1,2] and linearly polarized gas lasers.[3,4]

Several theoretical works have been devoted to the study of the competition dynamics of two simultaneous laser modes in the fundamental transverse state. To explain the observed competition dynamics, models including phase or frequency anisotropies have been used.[1] Lately, in the coupling of two coexisting orthogonal circularly polarized states at magnetic dipole or quadrupole coherence rates[5–7] usually only perfect resonance conditions have been considered in a model for a Zeeman laser with a $J = 1$ upper atomic state and a $J = 0$ lower atomic state, where J is the angular momentum. The main finding of such studies was the determination of an oscillating steady state in both the fields and the total intensity.

Here we present experimental and theoretical results for the polarization dynamics of a quasi-isotropic low-pressure CO_2 laser operating in the fundamental transverse mode. For this experiment we used the unpolarized Fabry–Perot CO_2 laser shown in Fig. 1. The laser cavity is formed by a totally reflective flat mirror and an outcoupling mirror of 3-m radius of curvature with 2.54-cm diameter and reflectivity $R_2 = 0.914$ mounted upon a piezoelectric translator, which allows us to control the emission line ($P20$) and the cavity detuning. The discharge tube is 68 cm long and has an inside diameter of 20 mm. The cavity length is $L = 1.3$ m. The medium is pumped by a dc discharge, which in our experiments is fixed at 6.1 mA. The fundamental TEM_{00} mode is selected by use of an intracavity iris diaphragm located near the beam waist. A mechanical chopper provides the necessary cavity-loss variation to induce transients of the laser field at a repetition frequency of ~120 Hz. Finally, to control the cavity anisotropies, a third ZnSe antireflection-coated window is introduced into the laser cavity.

The polarization state of the total emission of the laser was analyzed with a wire grid polarizer, which has the property of reflecting one polarization of the incident radiation and transmitting the orthogonal polarization. This type of polarizer allows us to analyze both polarization components simultaneously with an extinction ratio of 1:180. The reflected and transmitted parts of the beam are directed to two HgTeCd fast detectors (100-MHz bandwidth), whose sensitive areas ($10^4\ \mu m^2$) are much smaller than the beam size. Both detected local intensities are recorded on a digital signal oscilloscope (LeCroy LT423L) with 500-MHz bandwidth.

We use these measurement to investigate the polarization dynamics of the laser intensity during the switch-on transient induced by the chopper. Static measurements obtained without the chopper show that the fundamental Gaussian mode is always linearly polarized in the vertical or in the horizontal direction. Therefore we take these directions as the

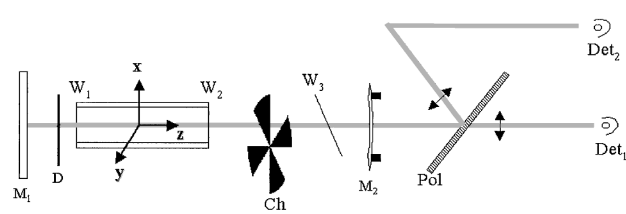

Fig. 1. Experimental setup: M_1, total reflecting flat mirror; D, iris diaphragm; W_1, ZnSe antireflection window; W_2, ZnSe antireflection window; Ch, intracavity chopper; W_3, additional intracavity window; M_2, outcoupler mirror; Pol, polarizer; Det_1, fast detector for the vertical component; Det_2, fast detector for the horizontal component.

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x and y axes, respectively, of our reference frame (Fig. 1). The propagation direction will be the z axis. As was shown previously, in a similar CO_2 laser configuration[4] small residual anisotropies fix the orientation of the final polarization state.

During the transient, if the total laser intensity is analyzed without being separated into two orthogonal polarization states, the laser intensity shows the usual relaxation oscillations before it reaches the steady state [Fig. 2, curve (a)]. In contrast, if we use the polarizer to analyze a single polarization [curve (b)], the laser shows, in addition to relaxation oscillation, another oscillation that is not correlated. By comparing the two components we observe that, apart from the relaxation oscillation, the components oscillate out of phase by π rad [Fig. 2, curve (c)]. To enhance the contrast between the two orthogonal components, the polarizer has to be set at 45° with respect to the x axis.

This phenomenon can be interpreted as a competition between two quasi-orthogonally polarized fields. During the transient, these states lose their initial orthogonality and interact with the same population inversion, giving rise to strong competition. Finally, both states collapse into a single field polarized along the direction preferred by the cavity. Although we consider the fundamental mode TEM_{00} here, this phenomenon is also observed for higher transverse modes, in particular, for the annular mode $TEM_{01}{}^*$.

We can change the frequency and duration of these oscillations by adjusting the laser cavity. In particular, the oscillation frequency depends linearly on the cavity anisotropies, which we can vary by tilting the intracavity window (W_3; Fig. 1). This linear dependence is illustrated in Fig. 3(a). As the competition oscillation can be varied from 20 to 450 kHz, this oscillation proves to be completely independent of the relaxation oscillation, which in our case is fixed at 53 kHz because the pump current is constant.

The duration of this oscillation depends on the cavity detuning, and small variations of this parameter (which are due to the unavoidable frequency chirping at laser switch-on) yield to changes in the time elapsed during the oscillations, as illustrated in Figs. 4(a) and 4(b). Furthermore, we qualitatively observe that the smaller the detuning, the longer the oscillation.

Following our interpretation, the observed dynamics can be reproduced with a model based on the two-level Maxwell–Bloch equations with two linearly polarized fields coupled through the variables in the polarization of matter:

$$\dot{E}_x = \kappa(P_x - E_x)\,, \tag{1}$$

$$\dot{E}_y = \kappa(P_y - E_y)\,, \tag{2}$$

$$\dot{P}_x = -\gamma_\perp[(1 + i\delta)P_x - D(E_x + \varepsilon E_y)]\,, \tag{3}$$

$$\dot{P}_y = -\gamma_\perp[(1 + i\delta)P_y - D(E_y - \varepsilon E_x)]\,, \tag{4}$$

$$\dot{D} = -\gamma_\parallel[D - r + 1/2(E_x P_x{}^* + E_x{}^* P_x + E_y P_y{}^* + E_y{}^* P_y)]\,, \tag{5}$$

where $E_x(t)$ and $E_y(t)$ are the slowly varying electric fields, $P_x(t)$ and $P_y(t)$ are the corresponding polarizations, $D(t)$ is the common population inversion, $r = 2.0$ is the rescaled pump, and $\delta = \omega_a - \omega/\gamma_\perp$ is the rescaled detuning, where ω_a is the frequency of the transition, ω is the frequency of the laser emission and ε is an adimensional coupling parameter. In our low-pressure CO_2 laser, the polarization decay rate can be chosen as $\gamma_\perp = 4.4 \times 10^8\ s^{-1}$ and the inversion decay rate as $\gamma_\parallel = 1.95 \times 10^5\ s^{-1}$. The field transient dynamics was modeled by means of a time-dependent loss coefficient[8]:

$$\kappa(t) = K_1 + (K_2 - K_1)\exp(-t/s)\,, \tag{6}$$

which decreases from the initial value $K_2 = 3.3 \times 10^6\ s^{-1}$ (off state) to the final value $K_1 = -(c/4L)\log(R) = 1.3 \times 10^6\ s^{-1}$, where c is the speed of light, $L = 1.3$ m is the cavity length, and $R = \sqrt{R_1 R_2} = 0.95$ is the reflectivity.

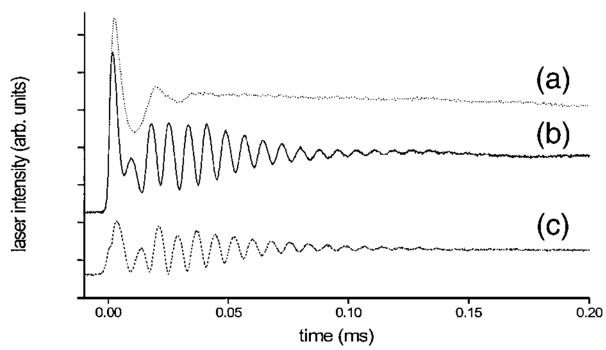

Fig. 2. Experimental measurement of (a) total intensity, (b) the transmitted polarized component when the polarizer in set at 45° with respect to the x axis, and (c) the reflected polarized component when the polarizer in set at 45° with respect to the x axis. The curves are not to scale because of different sensitivities and bias of the photodiodes.

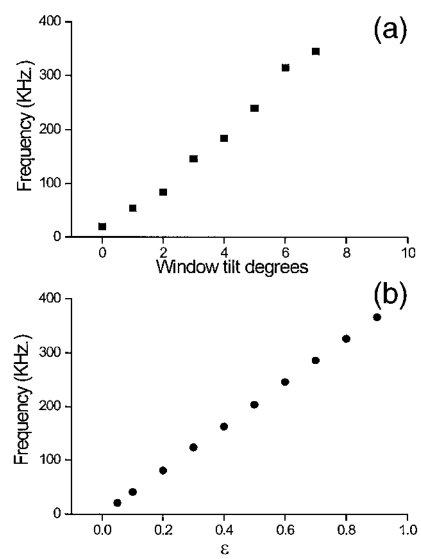

Fig. 3. Linear dependence of the competition oscillation frequency: (a) experimental, as a function of the tilt of window W_3; (b) numerical, as a function of coupling parameter ε.

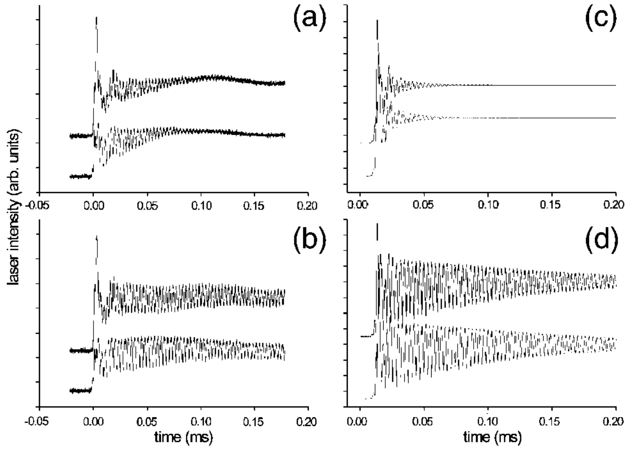

Fig. 4. Experimental samples with different competition frequency durations. Equivalent numerical results obtained for (a) $\delta = 0.005$, $\varepsilon = 0.8$, and $\nu = 330$ kHz and (b) $\delta = 0.05$, $\varepsilon = 0.8$, and $\nu = 330$ kHz.

It has to be noted that the coupling parametric terms are not symmetric in both polarization equations (3) and (4). This asymmetry proves to be fundamental for obtaining the out-of-phase oscillation of the fields, as was observed in the experiment. In this model, each field affects the other through the projection on its polarization, because the two fields are not orthogonal. This coupling resembles that proposed in Refs. 5 and 6 in accounting for the quadropole coherence terms, which does not apply to non-Zeeman lasers such as CO_2. Once the appropriate coupling terms are introduced, and considering that $\gamma_\perp \gg \gamma_\|$, polarization matter equations (3) and (4) can be adiabatically eliminated, yielding a simplified class-B laser model without losing the peculiar features of the oscillation.

The numerical results obtained with this model agree with the observations. As in the experiment, the frequency of the oscillation depends linearly on the coupling strength ε [Fig. 3(b)], which allows us to assimilate this phenomenological coupling parameter to the intracavity window tilt. This equivalence suggests a practical method for generating intensity-modulated light with an arbitrary frequency, which can be of important practical use.

As is shown in Figs. 4(a) and 4(b), in the experimental observation the oscillation is usually damped after a time that varies from 0.1 to 0.5 ms, depending on the cavity detuning. This phenomenon can also be interpreted in our model, whereas, in previous models, only resonant conditions were considered. In Figs. 4(c) and (d) two values of detuning δ are shown and compared with the previously mentioned experimental values. The model predicts stable oscillation for perfect resonance. However, it is difficult to fulfill this condition experimentally during a transient, and as a consequence damped oscillation is always observed.

In conclusion, we have characterized the polarization competition dynamics in a quasi-isotropic CO_2 laser. A model based on the competition of two fields is able to reproduce the observed oscillations.

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