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Polarization selection by optical feedback

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Abstract

We present experimental and numerical evidence of polarization selection in an isotropic CO_2 laser achieved by means of an unpolarized optical feedback. This mechanism can be applied in situations where the direction of polarization plays a crucial role, including polarization coding.

Keywords: Polarization; Control; Information coding

1. Introduction

Laser dynamics is commonly studied considering the electric field as a scalar variable, since in most systems the polarization state is imposed by anisotropies of the cavity. However, in perfectly cylindrical laser cavities without any elements to select a preferred polarization, the study of the dynamics includes the necessity of considering the vector nature of the electric field.

The polarization dynamics of the quasi-isotropic laser have been dealt with several theoretical works, pointing out the important role played by the material variables in the selection of the polarization state [1]. In particular, the degeneracy of the angular momentum states of the laser transition sublevels has been considered as the coupling source between different polarization states. Dynamical models have been developed to explore the role of the anisotropy due to the laser medium [1–8]. These models show how the final polarization state depends on the value of the total angular momentum of the lasing levels, and the relative magnitudes of the magnetic dipole and electric quadrupole relaxation rates of the sublevels.

Although these models have been developed for the simplest transition ($J = 1 \rightarrow J = 0$), our group has extended the study to more complicated level structures [9] and has considered spatial degrees of freedom [10].

Intensive research has been developed on polarization dynamics of solid state lasers [11], due to their great interest in applications. In particular, the interesting possibility of coding information in the polarization state of these lasers has been numerically [12] and experimentally [13] studied.

The extremely fast dynamics of semiconductor lasers however cause experimental difficulties in these experiments. In the study of polarization dynamics, gas lasers present some experimental advantages over semiconductor lasers because of their relatively slow dynamics and the accessibility of the cavity parameters. In this paper, we show experimentally and numerically a feedback method to control the polarization state of an isotropic laser. We use this technique for coding information in the polarization, without modifying the total laser intensity.

2. Experimental results

The transient polarization dynamics of a quasi-isotropic CO_2 laser shows a competition between two distinct orthogonal polarization modes. The competition dynamics

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and the final steady state is related to residual anisotropies of the laser cavity. In the particular case where the laser is in perfect resonant condition, none of the polarization modes is favored by anisotropy and the system remains in a bistable condition, with spontaneous flips between both competing polarization states [9].

In the present experiments, we first prove that in this condition, stabilization of the polarization emission is possible by using an optical feedback. Taking advantage of this possibility, we demonstrate controlled fast switching between two polarization states.

The experimental setup is illustrated in Fig. 1. It consists of an unpolarized Fabry–Perot cavity, feedback mirror, polarization monitoring and detection unit. The laser cavity length is 1 m, implying a free-space mode separation of about 150 MHz. A total reflective flat mirror (M_1, reflectivity $R_1 = 1$) and an output coupler mirror (M_2) with a reflectivity $R_2 = 0.914$ define the optical resonator. The total reflective mirror is mounted on a PZT transducer in order to control the laser detuning.

The active medium is a mixture of 82% He, 13.5% N_2, and 4.5% CO_2 gases. The laser tube is 0.75 m long and it is terminated with two antireflection coated ZnSe windows 0.5″ of diameter. Particular attention has been devoted to the insertion of two identical electrodes in order to preserve the cylindrical geometry of the applied discharge. The medium is pumped by a DC discharge current fixed at 7 mA, where the threshold current is about 2 mA. A mechanical chopper (C) is inserted inside the laser cavity in order to repeatedly change the cavity losses from below to above threshold and therefore obtain a pulsed operation. The output laser beam is splitted into two beams by means of a 80/20 ZnSe unpolarized beam splitter (BS). The first beam (part) is directed toward the totally reflecting feedback mirror (FM), while the other beam is directed toward a detection unit (D) via a 100 mm focal length ZnSe lens. A linear polarizer (P, wire grid polarizer) has been inserted between the beam splitter and the detection unit to analyze the laser output polarization state. The detection apparatus including a MCT detector (D) with a 10^4 μm sensitive area and a 500 MHz bandwidth digital oscilloscope (S) is appropriate for the dynamics of the system.

As the system is in resonant condition, during the pulsed operation with the intracavity chopper the laser shows two possible linear polarization directions which are orthogonal as far as we can measure. These two linear polarization states spontaneously change each to other in successive pulses as shown in the first part of the temporal evolution of the laser output intensity (see Fig. 2a and b). The presence of a moderate polarization insensitive optical feedback, estimated to be less than 1% of the total output intensity, is sufficient to select one of the two competing polarization states. The feedback strength can be varied by means of micrometric adjustments of the feedback mirror. The selection of the two polarization states can be observed in the final parts of Fig. 2a and b when the intracavity chopper is set at 8 Hz.

Once we can select one of the polarized states, this result opens the possibility to exploit polarization encoding. For this experiment, we slightly modify the laser detuning in order to fix the polarization state to one of the states. Therefore, the system is now very close to bistable condition, but is not able to flip the polarization spontaneously. Then, we insert another mechanical chopper in the optical feedback branch responsible for polarization selection. The feedback mirror is adjusted to select the orthogonal component of the polarization. The chopper in the feedback loop, at a frequency lower than of the intracavity one, allows perfect encoding using the two polarization states. The experimental results are shown in Fig. 3, where the chopper frequencies are chosen in the 1:7 ratio.

In the previous tentative method, the coding is paced by the external feedback chopper. However, faster coding can be obtained in continuous lasing regime, only by using the external optical feedback. For this part of the experiment, the intracavity chopper C is removed to avoid the frequency limitation to the polarization switching. As in the

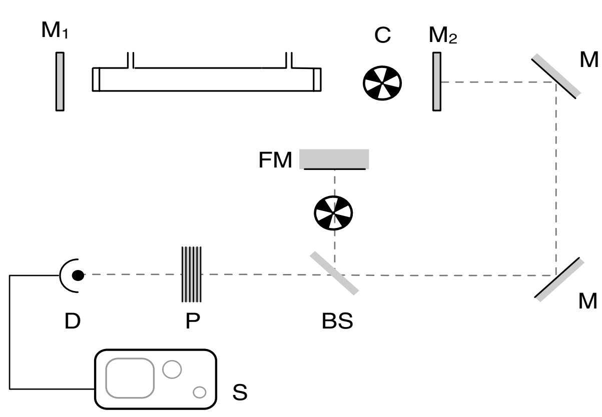

Fig. 1. Experimental setup: M_1 total mirror, M_2, partial mirror, C intracavity chopper, BS beam splitter, FM, feedback mirror, P polarizer, D detector, S digital data processor.

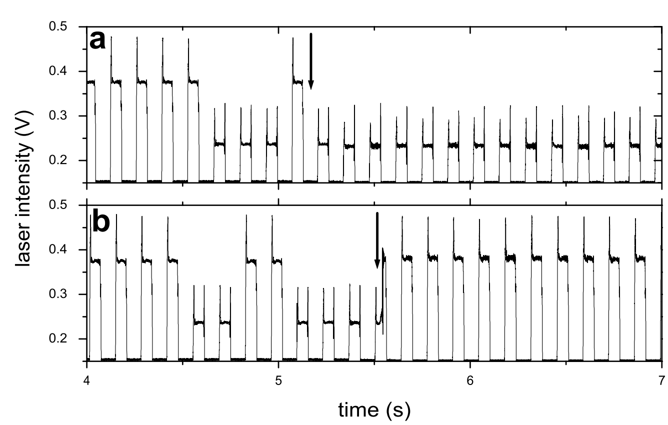

Fig. 2. Transition of spontaneous polarization into: (a) vertical and (b) horizontal polarization, induced by the feedback mirror. The time of insertion of the feedback is pointed by an arrow. The frequency of the intracavity chopper is set at 8 Hz.

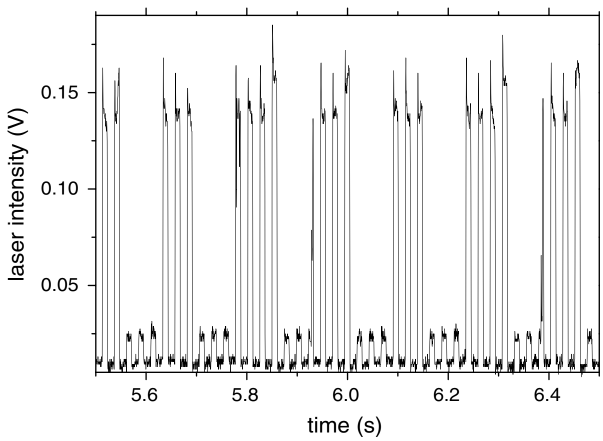

Fig. 3. Polarization coding with intracavity and extracavity choppers.

previous case, the laser is slightly detuned in order to fix the polarization state to one of the states.

Then, by means of the external chopper and the feedback mirror adjusted to impose the opposite state, we obtain fast switching between the two states as shown in Fig. 4. The alternation between the two states occurs at a rate which is about two orders of magnitude higher as compared with the intracavity chopping condition shown in Fig. 3. Such a rate could be further increased using other modulation techniques like opto-acoustic modulators in the feedback arm. The modulator should introduce the minimal loss perturbation able to change the state of polarization. The advantage of this last method is that the laser itself is kept operating in a stable polarized regime. Therefore, the modulation rate is not limited by the appearing of transient effects as the initial high intensity spike followed by relaxation oscillations or polarization competition antiphase oscillations [9]. It can be seen that such effects are not present when the intracavity chopper is removed as shown in Fig. 4 compared with Figs. 2 and 3.

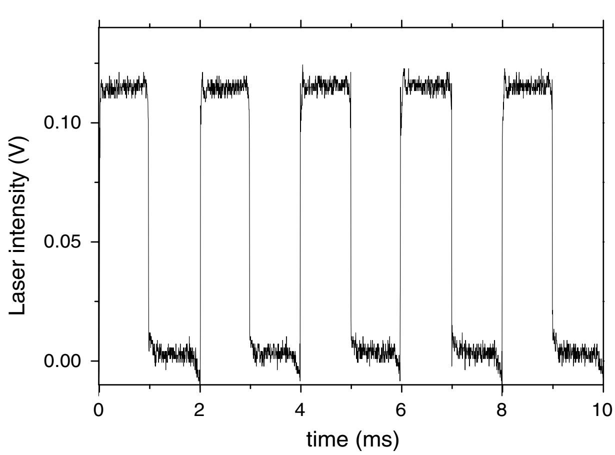

Fig. 4. Switching between the two linear polarized states imposed by the modulated optical feedback. The frequency of the external chopper is set at 500 Hz. The axis of the wire grid polarizer is oriented along one the polarization states.

3. Model and numerical results

Our theoretical approach is based on the theory of the isotropic laser developed in Ref. [2] where the optical coherences between upper levels are considered. In spite of the fact that this theory was developed for the simplest case ($J=1 \to J=0$), it has also been used to predict the behavior of lasers with a more complex level structure as our laser ($J=19 \to J=20$), as shown in Ref. [9], where an effective value of the coherence decay rate was deduced for this case. Since only first order coherences ($\Delta m = \pm 1$) will be considered, there are only two kinds of possible transitions, and then the population splits in two ensembles, in such a way that an anisotropy is induced in the active medium [5]. Therefore, the laser field can also be decomposed (here in a circularly polarized basis), each component evolving separately but interacting through the coherences between upper sublevels. Additionally, the observed spontaneous flips between the competing polarization states are reproduced by considering residual linear anisotropies in the cavity. Finally the model reads [1,9]:

$$
\begin{aligned}
\dot{E_{\mathrm{R}}} &= \kappa(P_{\mathrm{R}} - E_{\mathrm{R}}) + \mathrm{i}\delta E_{\mathrm{R}} - \alpha E_{\mathrm{L}} + g(E_{\mathrm{R}} + \Delta E_{\mathrm{L}}),\\
\dot{E_{\mathrm{L}}} &= \kappa(P_{\mathrm{L}} - E_{\mathrm{L}}) + \mathrm{i}\delta E_{\mathrm{L}} - \alpha E_{\mathrm{R}} + g(E_{\mathrm{L}} + \Delta E_{\mathrm{R}}),\\
\dot{P_{\mathrm{R}}} &= -\gamma_{\perp}[P_{\mathrm{R}} - D_{\mathrm{R}}E_{\mathrm{R}} - E_{\mathrm{L}}C],\\
\dot{P_{\mathrm{L}}} &= -\gamma_{\perp}[P_{\mathrm{L}} - D_{\mathrm{L}}E_{\mathrm{L}} - E_{\mathrm{R}}C^{*}],\\
\dot{C} &= -\gamma_{c}C - \frac{\gamma_{\parallel}}{4}(E_{\mathrm{L}}^{*}P_{\mathrm{R}} + E_{\mathrm{R}}P_{\mathrm{L}}^{*}),\\
\dot{D_{\mathrm{R}}} &= -\gamma_{\parallel}\left[D_{\mathrm{R}} - r + \frac{1}{2}(E_{\mathrm{R}}P_{\mathrm{R}}^{*} + E_{\mathrm{R}}^{*}P_{\mathrm{R}}) + \frac{1}{4}(E_{\mathrm{L}}P_{\mathrm{L}}^{*} + E_{L}^{*}P_{\mathrm{L}})\right],\\
\dot{D_{\mathrm{L}}} &= -\gamma_{\parallel}\left[D_{\mathrm{L}} - r + \frac{1}{2}(E_{\mathrm{L}}P_{\mathrm{L}}^{*} + E_{\mathrm{L}}^{*}P_{\mathrm{L}}) + \frac{1}{4}(E_{\mathrm{R}}P_{\mathrm{R}}^{*} + E_{\mathrm{R}}^{*}P_{\mathrm{R}})\right],
\end{aligned}
\tag{1}
$$

where $E_{\mathrm{R}}(t)$, $E_{\mathrm{L}}(t)$ are the slowly varying electric fields, $P_{\mathrm{R}}(t)$, $P_{\mathrm{L}}(t)$ stand for the matter polarization fields, $D_{\mathrm{R}}(t)$ and $D_{\mathrm{L}}(t)$ are the respective population inversions and $C(t)$ is the coherence field. The losses are $\kappa = -c\log(R_1R_2)/4L = 6.74 \times 10^{6}\ \mathrm{s}^{-1}$. In our low pressure CO_2 laser, the polarization decay is $\gamma_{\perp} = 4.4 \times 10^{8}\ \mathrm{s}^{-1}$ and the inversion decay rate is $\gamma_{\parallel} = 1.95 \times 10^{5}\ \mathrm{s}^{-1}$ [9]. The parameter $r(t)$ stands for the pump strength normalized to its threshold value, and its value is periodically varied from 1.1 to 0.9 to reproduce the intracavity chopper effect. The parameter δ represents the detuning between the cavity and the atomic transition frequencies, and in our numerical study is set to zero, then the laser remains in resonant condition. The parameter α represents the linear anisotropies in the losses with respect to the cavity H–V axes (in the following, X–Y axes). In our case the laser is mostly isotropic, therefore this parameter is reduced to the residual anisotropies that induce the polarization state spontaneously flip between polarizations. Then, we write this parameter as $\alpha = \kappa\alpha_{o}\epsilon(t)$, where parameter α_{o} is a small perturbation and ϵ is a dichotomic noise varying between 1 and -1 with a characteristic time fitted to the observed experimental polarization flips.

The feedback loop is modelized in the equations for the fields by means of the terms $g(E_{R(L)} + \Delta E_{L(R)})$, where g is the main feedback strength and Δ stands for the feedback anisotropy that in the experiment allows to choose one of the polarizations. Note that in the orthogonal basis this feedback term takes the form $g(1 + \Delta E_{x(y)})$, therefore a positive (negative) Δ value will make predominate the $x(y)$ polarization, playing the same role as the feedback mirror tilt does in the experiment. For a better comparison with the experiment, in the figures the fields are presented in the orthogonal basis, $E_x = (E_L + E_R)/\sqrt{2}$, $E_y = i(E_L - E_R)/\sqrt{2}$, corresponding to the eigendirections in the laser.

The numerical results are presented in Fig. 5, where we plot the total intensity (Fig. 5a) and both polarized components (Fig. 5b and c) when $g = 0.03\kappa$. The feedback is introduced a bit earlier than $t = 3$ ms. As in the experimental counterparts showed in the previous section, a small feedback strength is enough to control the laser polarization. In order to show the possibilities as a communication scheme, in this numerical example the value of Δ is randomly varied from 0.5 to -0.5 to generate a binary code with a bit duration of 0.27 ms. The value of g (enlarged for a better observation) is plotted in Fig. 5c together with the Y polarization component.

In order to study the rate of this simple communication scheme we have carried out a set of computer experiments for different values of the bit period. Fig. 6 shows the error probability attained by the system for several values of the bit duration. We can see that for a bit period of 0.133 ms the error probability is already below 5×10^{-5}.

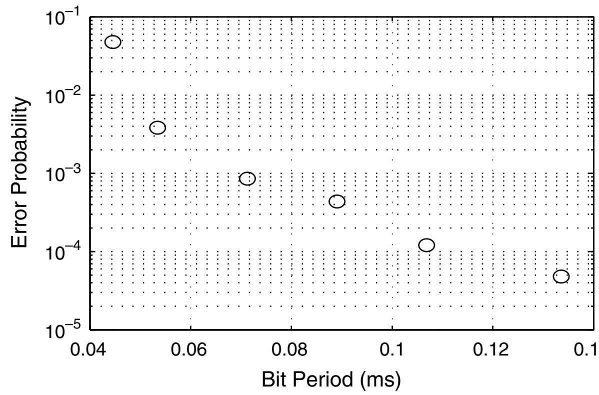

Fig. 6. Error probability for several values of the bit period.

4. Discussion and conclusions

An optical feedback insensitive to polarization is able to control the polarization state of a CO_2 laser. As discussed above, this kind of control can be useful in communication, but also in industrial applications. For instance, the switching between the two polarization directions could be used in laser cutting processes. These processes and other laser operations critically depend on the kerf width or cross sec-

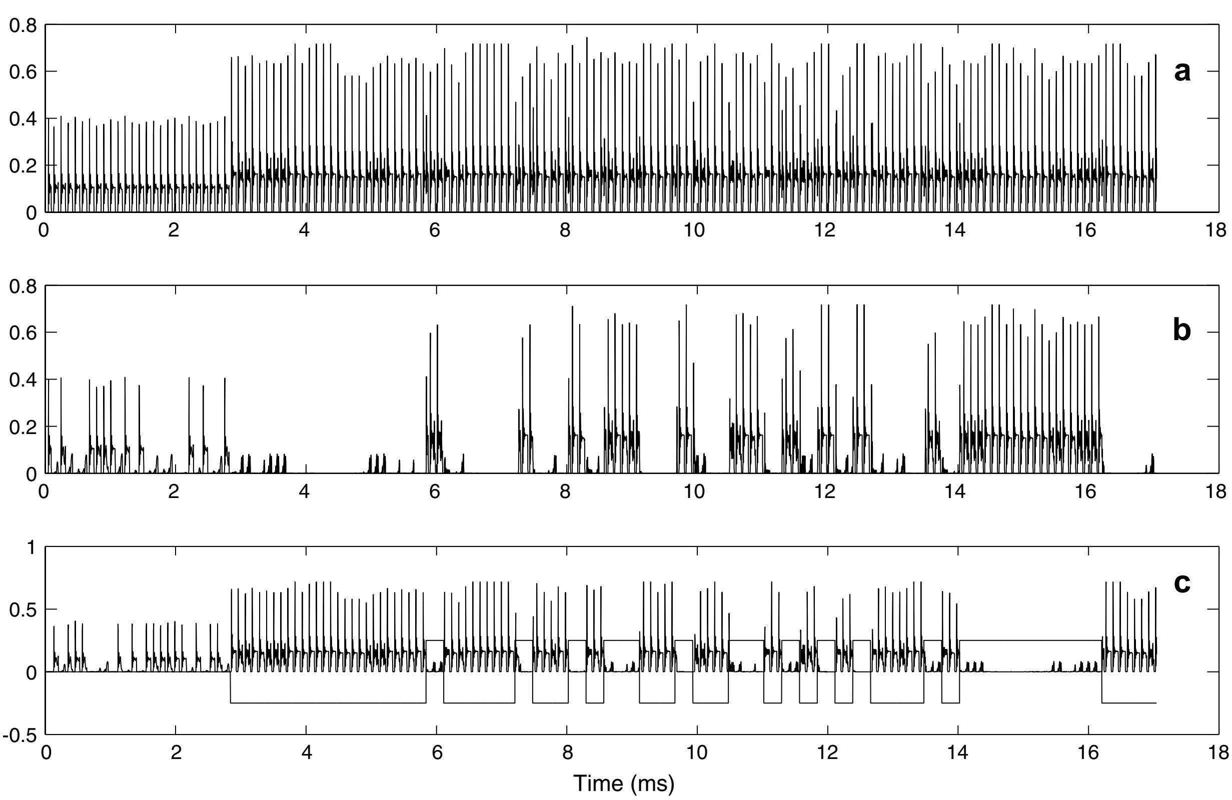

Fig. 5. Numerically generated intensities for the case of feedback with message coding, with $\alpha_o = 0.002\kappa$ and $g = 0.03\kappa$: (a) total intensity, (b) X polarized component, and (c) Y polarized component and feedback strength (enlarged) representing the desired binary message.

tion of the cut. The optimal kerf is obtained when the beam polarization is oriented to the direction in which the cut is traveling. An improvement of the cutting process is currently obtained by using circular polarized laser light by means of a reflective phase retarder introduced into the beam delivery path. In our configuration using a laser with the optical feedback it is possible to select the proper linear polarization or achieve fast switching between the two polarization directions which is equivalent to using circular polarized light.

In optical schemes, fast switching between two orthogonal polarization states is normally achieved by introducing a nonlinear crystal between a crossed polarizer analyzer pair [14,15]. If the applied voltage corresponds to the half-wave voltage the device is equivalent to a half wave plate and a vertical linear polarization is completely converted to the horizontal one. Operating with CO_2 lasers requires the use of CdTe crystals driven by high voltages (the half-wave voltage is of the order of several kilovolts). Furthermore, in order to prevent the heating damage threshold, the laser power is limited to low values. These limitations are not present when the linear polarization direction is controlled by an optical feedback.

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References

[1] N.B. Abraham, M.D. Matlin, R.S. Gioggia, Phys. Rev. A 53 (1996) 3514.
[2] G.C. Puccioni, M.V. Trantnik, J.E. Sipe, G.L. Oppo, Opt. Lett. 12 (1987) 242.
[3] G.C. Puccioni, G.L. Lippi, N.B. Abraham, Opt. Commun. 72 (1989) 361.
[4] N.B. Abraham, E. Arimondo, M. San Miguel, Opt. Commun. 117 (1995) 344.
[5] (For a review see) G.M. Stephan, A.D. May, Quantum Semicl. Opt. 10 (1998) 19.
[6] Yu.V. Loiko, A.M. Kulminskii, A.P. Voitovich, Opt. Commun. 210 (2000) 121.
[7] M.D. Matlin, R.S. Gioggia, N.B. Abraham, P. Glorieux, T. Crawford, Opt. Commun. 120 (1995) 204.
[8] J. Redondo, G.J. de Varcárcel, E. Roldán, Phys. Rev. A 56 (1997) 648.
[9] I. Leyva, E. Allaria, R. Meucci, Opt. Commun. 217 (2003) 335.
[10] I. Leyva, E. Allaria, R. Meucci, Phys. Rev. A 68 (2003) 053806.
[11] (See, for instance:) M. San Miguel, Q. Feng, J.V. Moloney, Phys. Rev. A 52 (1995) 1728;
O. Hess, T. Kuhn, Phys. Rev. A 54 (1996) 3347;
G. Giacomelli, F. Marin, I. Rabbiosi, Phys. Rev. Lett. 82 (1999) 675;
Yanhua Hong, Paul S. Spencer, K. Alan Shore, Opt. Lett. 29 (2004) 2151.
[12] A. Sciré, J. Mulet, C.R. Mirasso, J. Danckaert, M. San Miguel, Phys. Rev. Lett. 90 (2003) 1139O1.
[13] G.D. VanWiggeren, R. Roy, Phys. Rev. Lett. 88 (2002) 097903.
[14] A. Yariv, Optical Electronics, Holt, Rinehold and Winston, New York, 1985.
[15] Christopher C. Davis, Lasers and Electro-Optics, Fundamentals and Engineering, Cambridge University Press, 1996.