

Experimental evidence of antiphase population dynamics in lasers

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We report a direct experimental observation of antiphase oscillations in population dynamics in lasers. We show that these population oscillations are intrinsically related to the well-known antiphase polarization dynamics, i.e., the antiphase oscillations of two orthogonal polarization laser field states. We have used a class *B* Nd:YAG (yttrium aluminum garnet) laser.

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I. INTRODUCTION

Polarization effects in lasers have been studied from the very beginning of the laser discovery. Periodic or quasiperiodic antiphase oscillations of two orthogonal polarization laser field states have been observed in a large variety of laser systems such as fiber lasers [1–6], Nd:YAG (yttrium aluminum garnet) lasers [7,8], VCSELs [9], CO₂ lasers [10], and Nd-doped microchip glass lasers [11]. The two polarization eigenstate directions may be selected by several symmetry breaking mechanisms depending on the kind of laser. Polarization dynamics and, in particular, antiphase polarization dynamics, has become a very rich field of research due to their potential applications in transmission of encoded information [12,13], heterodyne detection systems [14], Doppler velocimetry [15], and optical microwave systems [16]. A similar behavior can also be seen in multimode lasers [17–19], where antiphase dynamics appears between different axial modes.

In order to measure the antiphase polarization dynamics polarization-resolved experiments are required. Thus, one must separate the two polarizations over two photodetectors linked to the two inputs of a two channel oscilloscope or a similar registration apparatus. In this way, a direct comparison of both signals reveals the antiphase oscillations. However, if the detection is made without polarization discrimination the effect remains unnoticeable. The theoretical interpretation of this phenomenon is based on the presence of two different subsets of population inversions [1,5,7,8,20,21]. Each population inversion is associated to each of the polarization field eigenstates. This is the usual assumption but no direct proof has been reported about this statement. Measuring the antiphase dynamics on the population inversion directly provides an observation of a prediction of these models, confirming their validity as a complete description of the system, and not only as a partial explanation of the phenomenon.

The idea consists of the measurement of the luminiscence emitted at the laser frequency for one of the population inversion subsets. We expect to find the luminiscence modulated at the antiphase oscillation frequency, and with a proper

phase delay with respect to the laser intensity of the same subset, of course, if the inversion subsets really exist. On the contrary, if the population inversion is coupled as a whole to the laser field, no modulation at the antiphase oscillation frequency must be observed.

In a four-level laser the excited state population is only a small fraction of the ground-state population. That means weak luminiscence emission at the laser wavelength. Moreover, in quasistationary laser dynamics the population inversion is strongly locked to the threshold value. Only small fluctuations around the population inversion threshold value can be produced. For these reasons, a weak luminiscence with a weak megacycle modulation is the signal to be measured. On the other hand, as we must take the luminiscence sample from the lasing material, it probably must be buried in the overwhelmingly powerful pumping light. In these conditions, to detect the modulated luminiscence becomes a great challenge.

II. SETUP

A custom made Nd:YAG laser was used in our experiment. The experimental setup is shown in Fig. 1. The laser is an aircooled, low pulse energy (≈ 50 mJ) flash-lamp pumped prototype. The time length of the output laser pulse is of the order of $100 \mu\text{s}$. The lasing medium was a Nd:YAG cylin-

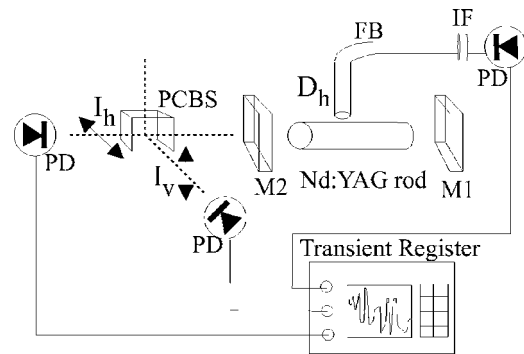


FIG. 1. Experimental setup to measure the laser outputs vertically (I_v) and horizontally polarized (I_h) and the luminiscence generated by the horizontal atomic dipoles (D_h). PD: photodiode, IF: interference filter, FB: fiber bundle, PCBS: polarizing cube beam splitter, M1: concave (10 m radius) total reflector, and M2: plane output coupler (70% reflectivity).

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drical rod (60 mm long \times 6 mm diameter), side pumped by two parallel linear flash lamps. The rod is placed between the two flash lamps and in the same horizontal plane. In this form, the pumping geometry and polarizations break the symmetry between the horizontal and vertical axis. The rod and flash lamps are placed inside a double elliptical gold-plated cylindrical pumping cavity. The lamps were excited by a 100 μ F capacitor allowing a maximum of 1600 V to be applied to the lamps. The 17 cm long laser resonator consists in a concave (10 m radius) total reflector and a plane output couple (70% reflectivity). To collect the luminiscence we use a fiber bundle (3 mm of core diameter), directly in touch with the surface of the laser rod. In this form the proportion of pumping light entering in the fibers is minimized. The fiber bundle is vertically inserted inside the pumping cavity through an aircooling opening. The luminiscence collected with this setup is supposed to be mainly generated by the horizontal atomic dipoles, and these dipoles are the subset coupled to the horizontally polarized laser light. If the concentration of those dipoles is oscillating, the collected luminiscence will be modulated by the oscillation frequency. A narrow band interference filter placed at the end of the fiber bundle and centered at the laser wavelength (1064 nm) suppresses the pumping light before to enter to the detector. The filtered luminiscence is detected by means of an amplified photodiode (rise time 1 ns) linked to a four channel transient register (Tektronix DSA602). With the described setup (see Fig. 1) we have overcome the intrinsic difficulty of measuring the luminiscence emitted during the laser action.

The laser outputs vertically (I_v) and horizontally (I_h) polarized are separated by a polarizing cube beam splitter and detected by two photodiodes. Both detectors are also linked to the transient register. Therefore, the two laser outputs I_v and I_h , and the detected luminiscence signal can be observed simultaneously. The laser works in a single pulse regime to avoid accumulative thermal effects in the laser rod. In order to avoid the stray field produced by the laser excitation circuit, the entire measurement system was placed inside a Faraday cage.

III. EXPERIMENTAL RESULTS AND THEORETICAL DISCUSSION

In agreement with previous studies the polarization-resolved laser outputs exhibit an antiphase dynamics, as shown in Figs. 2(b) and 2(c), where the horizontally and vertically polarized laser outputs are displayed. Each polarization component presents the well-known relaxation oscillations and the low-frequency antiphase oscillations. If the total power is measured, only the usual relaxation oscillations remain, as shown in Fig. 2(a). In this figure, we have set a potential charge of 1200 V which means a pump excitation energy 4 times above the threshold one. In this case the frequency of the relaxation oscillations and the antiphase oscillations are 0.7 and 0.07 MHz, respectively. We have observed that, although these frequency values depend on pumping, the ratio between them remains constant. For a potential charge of 1400 V (pump excitation energy 5.4 times above threshold) we obtain frequency values of 1 and 0.1 MHz.

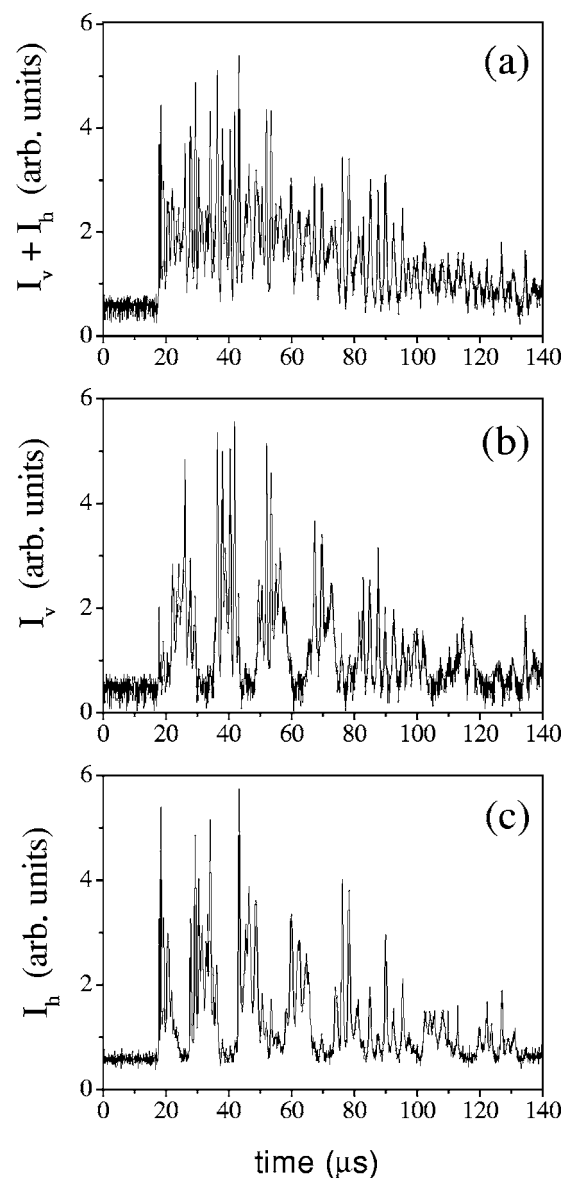


FIG. 2. Temporal evolution of the output laser intensity (a) without polarization discrimination, (b) selecting vertical polarization, and (c) selecting horizontal polarization. The units of the intensity axis are arbitrary.

The antiphase polarization dynamics in lasers has been theoretically explained by a simple phenomenological model that considers the laser as composed of two laser subsystems associated with two orthogonal polarization eigenstates. Therefore, each subsystem is described by its intensity and population inversion. The two subsystems are coupled by cross-saturation phenomena: the intensity of one polarization is amplified by the population inversion associated to the other polarization (cross gain effect) and the stimulated emission in one polarization saturates the population inversion associated to the other polarization. The cross-saturation phenomena, which are due to the angular hole burning (polarization cross saturation), are responsible for the antiphase polarization dynamics. The laser equations can be written in the following form:

$$\frac{dI_v}{dt} = 2\kappa[D_v + \beta D_h - 1]I_v, \quad (1)$$

$$\frac{dI_h}{dt} = 2\kappa[D_h + \beta D_v - 1]I_h, \quad (2)$$

$$\frac{dD_v}{dt} = \gamma_{\parallel}[r - (1 + I_v + \beta I_h)D_v], \quad (3)$$

$$\frac{dD_h}{dt} = \gamma_{\parallel}[r - (1 + I_h + \beta I_v)D_h], \quad (4)$$

where I_v and D_v (I_h and D_h) are the intensity and the population inversion, respectively, associated with the vertical (horizontal) polarization eigenstate. $1/\kappa \approx 6.4$ ns and $1/\gamma_{\parallel} \approx 0.23$ ms are the photon lifetime, and the population inversion lifetime, respectively. r represents the dimensionless pumping parameter. β is the cross-saturation coefficient describing how each laser field is coupled with the population inversion of the other laser subsystem. Bielawski *et al.* [1] and Lacot *et al.* [2] have used this model to explain the antiphase polarization dynamics in fiber lasers. They showed a good agreement between the experiments and the model. More complex models have been used where other effects such as spatial hole burning have been taken into account [5,7,8,21,22].

The linear stability analysis of the stationary solution of Eqs. (1)–(4) shows that the total intensity $I_v + I_h$ and the total population inversion $D_v + D_h$ present the well-known relaxation oscillations of class-B lasers, with a frequency of $f_R^2 = 2\gamma_{\parallel}\kappa[r(1+\beta)-1]/(2\pi)^2$. The linear stability analysis also shows that the difference $I_v - I_h$ and $D_v - D_h$ exhibit slow relaxation oscillations whose frequency is

$$f_L = \frac{1-\beta}{1+\beta}f_R. \quad (5)$$

Therefore, each subsystem presents two damped oscillations: high-frequency oscillations (f_R) which are in phase and slow frequency oscillations (f_L) which are in opposite phase. The slow frequency oscillations destructively interfere to give a total intensity with only the well-known relaxation oscillations. From the experimental results of Fig. 2 and using the expression of the slow frequency given by Eq. (5), we determine an experimental value of the cross-saturation parameter $\beta=0.8$. This large value indicates that a strong coupling between both polarizations takes place. We have checked that the same value of β is obtained for other pump values as it was expected since it only depends on the ratio between both relaxation oscillations. A similar value of β was measured by Poustie in an erbium-doped fiber ring laser [4].

These theoretical results predict that if we measure the population inversion associated to one of the polarization states, a superposition of two oscillations with frequencies f_R and f_L should be observed. Furthermore, we have numerically solved the Eqs. (1)–(4) to show that a phase delay between the population inversion and the laser intensity corresponding to same subsets is obtained. In order to reproduce the experimental pumping conditions, the temporal shape of

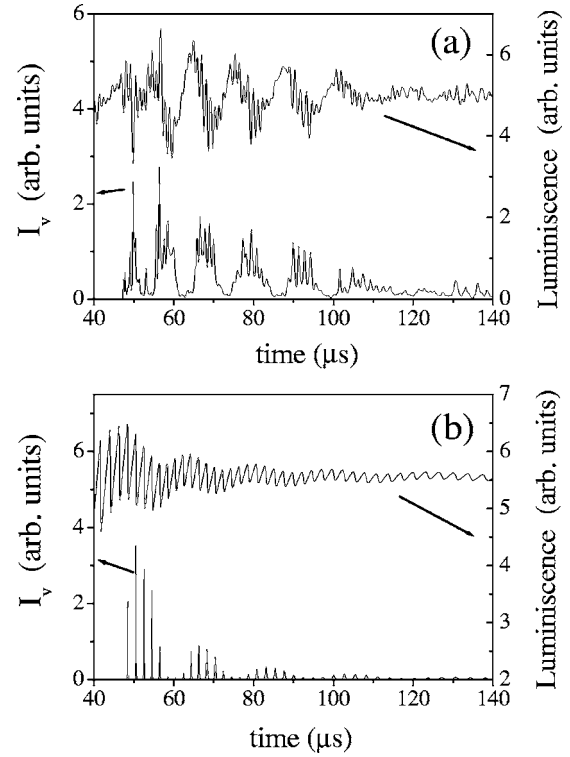


FIG. 3. (a) Luminiscence from horizontal dipoles (upper plot), together with the output intensity in the vertical polarization. Graph (b) shows the results of numerical simulations.

the pumping was simulated by the following function approximating the pulse excitation

$$r = A \left(\frac{t}{t_{\text{peak}}} \right)^3 e^{3(1-t/t_{\text{peak}})} \quad \text{for } t < \frac{5}{3}t_{\text{peak}},$$

$$r = A \left(\frac{5}{3} \right)^5 e^{-2 \left(\frac{t_{\text{peak}}}{t} \right)^2} \quad \text{for } t \geq \frac{5}{3}t_{\text{peak}}, \quad (6)$$

where $t_{\text{peak}}=30$ μs is the time needed for the pump to reach its maximum value. $A=17$ has been chosen in order to obtain a total excitation energy 5.4 times above the threshold one, which corresponds with a potential charge of 1400 V, used in the experiment. Figure 3(b) shows the temporal evolution of the theoretically calculated intensity and luminiscence for one of the polarization eigenstates. Note that both curves exhibit low-frequency oscillations with the same frequency (f_L) but with a small phase-delay of roughly 4 μs between both magnitudes. This phase-delay is completely analogous to the well-known phase delay that appears in the relaxation oscillations between the same magnitudes.

Figure 3(a) compares the oscillations in the measured luminiscence with those in I_v and with the theoretical prediction in Fig. 3(b) using the model presented before. The signal of the luminiscence given by the transient register has been numerically filtered with a band pass filter between 0.05 and 1 MHz in order to show more clearly the searched antiphase dynamics. The two low frequency antiphase oscillations are a little bit out of phase in the same manner as the evolution of the relaxation oscillations in the population inversion and

in the laser intensity. This property allows us to reject the possibility of mistake between the measured luminiscence with any small part of the output intensity in one of the orthogonal polarizations. It must be pointed out that this phase delay has a value of $4 \mu\text{s}$, in agreement with the numerical simulations which supports the validity of the model used.

Comparing the shape of the intensity evolution in Figs. 3(a) and 3(b) a more irregular behavior in the experimental case can be observed. Moreover, the measured intensity does not vanish during the fast relaxation oscillations, in contrast to the numerical case. These differences can be attributed to the large aspect ratio (high Fresnel number) of our laser, which makes transverse dynamics to play a nontrivial role. To check this assumption we have developed numerical simulations including spatial degrees of freedom showing a closer behavior to the experiments. However, they do not give any new effect, and thus, for the purpose of this work, we have chosen to use the simplest model to explain the experimental results.

IV. CONCLUSIONS

In conclusion, we have directly observed antiphase population dynamics in lasers. In order to achieve that, we have measured the luminiscence associated to horizontal atomic dipoles. This luminiscence exhibits the same behavior that the laser intensity of one of those polarization eigenstates, which is clear evidence of the existence of a subset in the population inversion linked to a particular polarization field, as it is assumed in most of the theoretical models used to explain the antiphase polarization dynamics.

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