Dual-polarization mode-locked Nd:YAG laser

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A mode-locked solid-state laser containing a birefringent element is shown to emit synchronously two frequency combs associated to the two polarization eigenstates of the cavity. An analytical model predicts the polarization evolution of the pulse train which is determined by the adjustable intracavity birefringence. Experiments realized with a Nd:YAG laser passively mode-locked by a semiconductor saturable absorber mirror (SESAM) are in perfect agreement with the model. Locking between the two combs arises for particular values of their frequency difference, e.g. half the repetition rate, and the pulse train polarization sequence is then governed by the relative overall phase offset of the two combs. © 2012 Optical Society of America

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The polarization state of mode-locked lasers is usually fixed by strong loss anisotropies such as Brewster windows or gain dichroism in crystalline media. Dynamics of such lasers are well-described by scalar models [1]. In mode-locked vectorial lasers, the role of polarization has been evidenced namely in semiconductor and fiber lasers. In semiconductor lasers, external cavities containing a phase anisotropy leads to polarization switching [2, 3]. In fiber lasers, polarization dynamics have been studied in detail since the nonlinear polarization rotation can lead to short pulse formation [4]. In particular, vector soliton fiber lasers have shown peculiar dynamics such as freely varying pulse polarization states, or locked polarization states for certain anisotropy ranges [5,6]. However, the polarization of bulk mode-locked lasers, where discrete anisotropies can be precisely controlled, has received scarce attention. Notably, Yang has modeled an actively loss-modulated laser containing a single quarter-wave plate, predicting a pulse train with alternate polarizations [7], reminiscent of polarization self-modulated semiconductor lasers [2, 8]. Since bulk rare-earth doped solids are well suited for dual-polarization oscillation, as well in *cw* [9, 10] as in *Q*-switched regimes [11], one may wonder whether mode-locking would result in pulsed polarization sequences. Indeed, semiconductor saturable absorber mirrors (SESAM) are well known to mode-lock diode-pumped solid state lasers passively [12]. The aim of this letter is consequently to show that a Nd:YAG mode-locked by a SESAM can emit synchronously two frequency combs associated to the two polarization eigenstates. A twisted-mode cavity [13] offers adjustable and stable polarization states, and permits to compare experimental results with a cold-cavity modal analysis.

The laser under consideration is described in Fig. 1(a). The L=554 mm-long cavity contains a 5 mm-long Nd:YAG crystal, and two quarter-wave plates (QWPs). The input mirror is directly coated on the active medium while the output coupler is a SESAM from BATOP GmbH (5% modulation depth and 1% transmission). Two lenses, of focal lengths 25 mm and 15 mm, provide focusing in the active medium and in the SESAM, where the waists are estimated at 25 μm and 5 μm, respectively. The cavity design takes into account the thermal lens in the active medium, induced by the 5 W pump beam at 808 nm. The laser oscillates at 1064 nm on a 60 GHz-wide spectrum. The pulse width is shorter than 20 ps and the output power is about 100 mW.

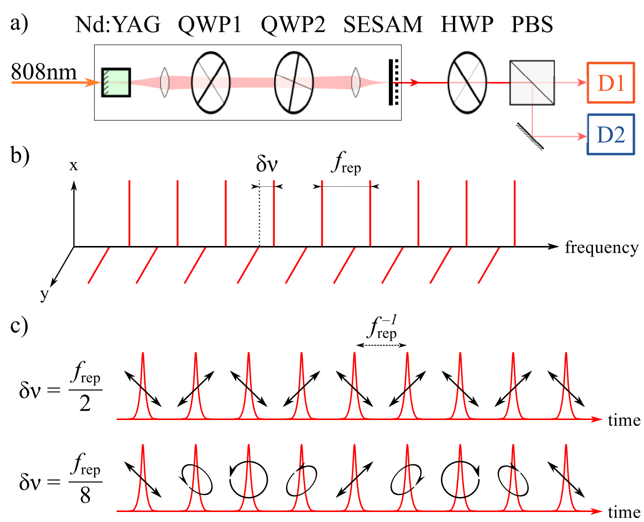

Fig. 1. (a) Experimental laser and detection setup. (b) Schematic frequency combs. (c) Schematic polarization sequences emitted when $\delta\nu = f_{rep}/2$ and $\delta\nu = f_{rep}/8$.

Since all intracavity interfaces are taken at normal incidence, the eigenpolarizations are determined by the two QWPs and the residual birefringence in the active medium. The neutral axes of QWP1 are aligned with the neutral axes of the residual birefringence of the YAG crystal. QWP2's axes are rotated by an angle α with respect to QWP1's axes. The eigenstates, determined by a single round-trip resonance condition including Jones matrices [14], are (i) linearly polarized in the Nd:YAG at $\pm 45°$ from QWP1's axes, (ii) left and right helicoidally polarized between QWPs, and (iii) linearly polarized at $\pm 45°$ from QWP2's axes at the laser output. The round-trip phase anisotropy induced by the QWPs is equal to 4α.

Assuming that the laser oscillates on two frequency combs associated to the two eigenpolarizations, these combs are expected to be shifted by $\delta\nu = 2\alpha/\pi \times c/2L$ with respect to one another, as schematized in Fig. 1(b). The output electric field then writes, in the output eigenpolarization frame $(\hat{x}, \hat{y})$,

$$\begin{bmatrix} E_x(t) \\ E_y(t) \end{bmatrix} = e^{i2\pi\nu_x t} \begin{bmatrix} 1 \\ e^{i(2\pi\delta\nu t+\psi)} \end{bmatrix} \sum_p A(t - p/f_{rep}). \quad (1)$$

Here ν_x is the optical frequency of the $\hat{x}$-comb. ψ is the relative overall phase offset. $A(t)$ is the pulse envelope and $f_{rep} = c/2L$ is the repetition rate. From eq. (1), the Jones vector $\vec{J}_p$ of the p-th pulse of the train, at $t = p/f_{rep}$, is given by

$$\vec{J}_p = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ \exp\left(i\left(2\pi p \frac{\delta\nu}{f_{rep}} + \psi\right)\right) \end{bmatrix}. \quad (2)$$

Eq. 2 indicates that the polarization state varies from one pulse to another, forming polarization sequences depending on $\delta\nu$ and ψ. Without loss of generality, we assume first that $\psi = 0$. Two examples are depicted in Fig. 1(c). For the case $\delta\nu = f_{rep}/2$, that will be discussed in detail below, one gets at the laser output alternate linearly polarized pulses oriented successively at $\pm 45°$ with respect to $\hat{x}$ and $\hat{y}$. For $\delta\nu = f_{rep}/8$, the pulse train consists in elliptically polarized pulses whose ellipticity varies gradually from one pulse to another, illustrating how the pulse train samples the polarization evolution. Obviously, the period of the polarization evolution is given by the beatnote period $1/\delta\nu$.

In order to verify these predictions, we monitor the laser output for different relative orientations α of the QWPs, using the detection scheme shown in Fig. 1(a). The combination of a half-wave plate (HWP) and a polarization beam splitter (PBS), followed by two 2 GHz-bandwidth InGaAs photodiodes D1 and D2, permits to monitor simultaneously either the intensities of the two eigenstates $\|E_x\|^2$ and $\|E_y\|^2$, or of their beats $\|E_x \pm E_y\|^2$. In the time series depicted in Fig. 2, we reproduce the beats $\|E_x + E_y\|^2$ (upper trace), and $\|E_x - E_y\|^2$ (lower trace) for three increasing values of $\delta\nu$. On Fig. 2(a), $\alpha \approx 0$ leading to $\delta\nu \approx 0$: in this case, the polarization of the pulse train is constant, with the pulse repetition rate $f_{rep} = 271$ MHz ($f_{rep}^{-1} = 3.7$ ns). On Fig. 2(b), we set $\alpha = \pi/8$, that is $\delta\nu = f_{rep}/4$: the pulse train is a sequence of linear and circular polarizations (linear at $+45°$, left circular, linear at $-45°$, right circular). Finally, we set $\alpha = 7/30 \times \pi$, i.e. $\delta\nu = 7/15 \times f_{rep}$. As $\delta\nu$ is close to $f_{rep}/2$, the pulses polarization ellipticity slowly evolves as shown on Fig. 2(c). All the chronograms are in perfect agreement with eqs. (1–2). We verify experimentally, when D1 and D2 monitor $\|E_x\|^2$ and $\|E_y\|^2$ separately, the two eigenstates are emitted synchronously whatever the value of $\delta\nu$, despite their optical lengths difference. This effect can be attributed to the SESAM which compensates for the group velocity mismatch.

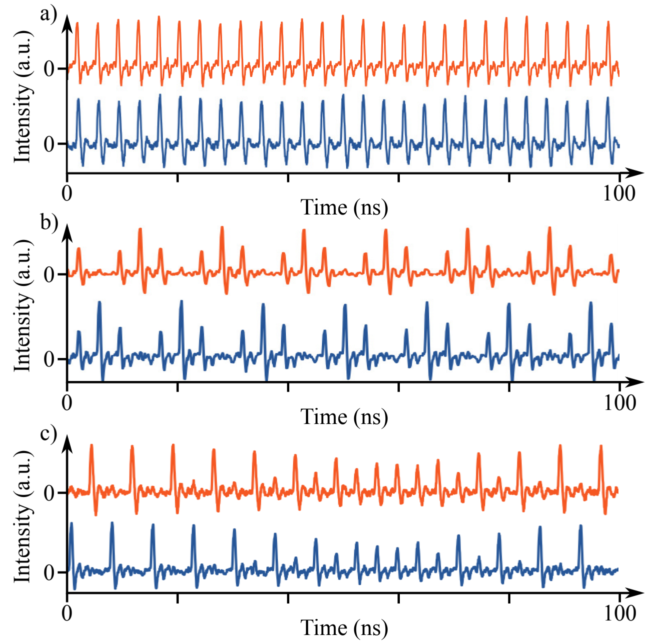

Fig. 2. Experimental eigenstates beats $||E_x+E_y||^2$ (red), and $||E_x - E_y||^2$ (blue), for (a) $\delta\nu \approx 0$, (b) $\delta\nu = f_{rep}/4$, and (c) $\delta\nu = 7/15\ f_{rep}$.

We now investigate the peculiar case $\delta\nu \approx f_{rep}/2$. A stable phase locking effect is observed for values of $\delta\nu$ within $f_{rep}/2 \pm 30$ kHz. To evidence this behavior, we monitor the electrical spectrum of the beat $\|E_x + E_y\|^2$ reported in Fig. (3). There is a double peak around $f_{rep}/2$ when $\delta\nu$ is outside the locking range (see Fig. 3(a) with a 2 MHz span). When $\delta\nu$ enters the locking range, these two peaks merge into one (Fig. 3(b)). Then a wider span (2 GHz) shows a comb with a perfect periodicity of $f_{rep}/2$ (Fig. 3(c)). Peaks whose frequencies are equal to $nf_{rep}, n \in \mathbb{N}$, are the well-known beat-note frequencies between different modes of one eigenstate or the other. On the contrary, peaks whose frequencies are equal to $(n + 1/2)f_{rep}$ are beats between modes from the two eigenstates. The stability of the whole spectrum confirms the dual-comb locking. It is worthwhile to note that the linewidth of the peak at $f_{rep}/2$ is measured to be 10 Hz, as narrow as the peak at f_{rep}. We suspect the phase-locking at $\delta\nu = f_{rep}/2$ to be due to nonlinear coupling through four-wave-mixing, as already observed in dual-polarization *cw* multimode lasers [15]. Note that similar phase-locking behavior is also observed at $\delta\nu = f_{rep}/3$ but with a smaller locking range (≤ 10 kHz).

We finally focus on an interesting feature of this locking range in relation with the relative phase ψ. When $\delta\nu = f_{rep}/2$, eq. 2 becomes

$$\vec{J}_p = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ (-1)^p \exp(i\psi) \end{bmatrix}. \quad (3)$$

We find in this equation that ψ governs the polarization

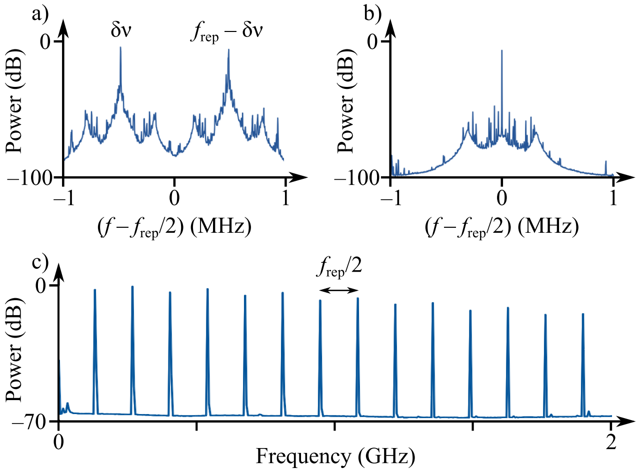

Fig. 3. Experimental FFT spectrum of the laser output, when $\delta\nu \approx f_{rep}/2$. (a) $\delta\nu$ outside the locking range. (b) $\delta\nu$ inside the locking range, and (c) resulting $f_{rep}/2$-periodic spectrum.

evolution of the pulse train. For example, when $\psi = 0$, one gets alternate $\pm 45°$ linearly polarized pulses as in Fig. 1(c). If $\psi = \pi/2$, one gets left and right circularly polarized pulses. Experimentally, we find that ψ can be modified in a reproducible way by slightly translating the SESAM along the propagation axis (a few microns). Fig. 4 shows eigenstate beat-note time series for $\delta\nu$ locked at $f_{rep}/2$, for two values of ψ. Using eq. (3), ψ can be measured experimentally from the modulation depth. Fig. 4(a) and (b) correspond respectively to $\psi = 0$ and $\psi = 0.39$ rad. For all the values of ψ, we check that the spectrum remains the same as depicted in Fig. 3(c). Furthermore, we verify that two successive pulses always hold orthogonal polarizations, i.e. $E_p \cdot E^*_{p+1} = 0$ in agreement with Eq. (3). This emphasizes the fact that this phase locking is different from soliton polarization locking in fiber lasers that leads to a constant pulse polarization state [16].

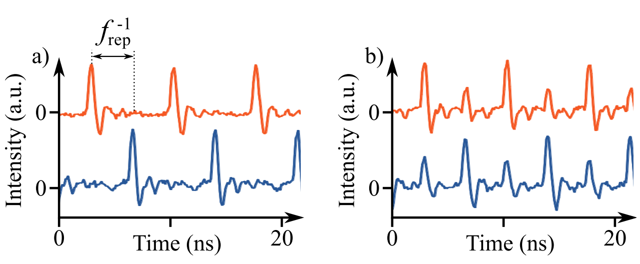

Fig. 4. Experimental eigenstate beats $||E_x + E_y||^2$ (red), and $||E_x - E_y||^2$ (blue), when the combs frequency shift $\delta\nu$ is locked at $f_{rep}/2$. (a) $\Psi = 0$ and (b) $\Psi = 0.39$ *rad*.

In conclusion, we have demonstrated a dual-polarization pulsed passively mode-locked solid-state laser. This laser embeds two independant combs, held by two orthogonal polarization eigenstates. The output pulse train forms controllable polarization sequences that result from interferences between the two orthogonally polarized combs. The usual polarization evolution of a dual-polarization laser is here sampled by the mode-locked pulse train. It is interesting to note that, adding a QWP at the laser output, one could find a sequence of linearly polarized pulses whose orientation varies from one pulse to another. The experimental results are well supported by a simple cold cavity modal analysis. We observe a phase-locked regime when the two combs are shifted by $f_{rep}/2$ with respect to one another. In this regime, the role of the relative overall phase offset has been isolated.

Perspectives of this dual-polarization mode-locked regime include the extension to femtosecond lasers, and applications like, for example, transient birefringence [17] and light/heavy holes quantum dynamics analysis [18], or the optical control of chiral molecular motors [19].

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