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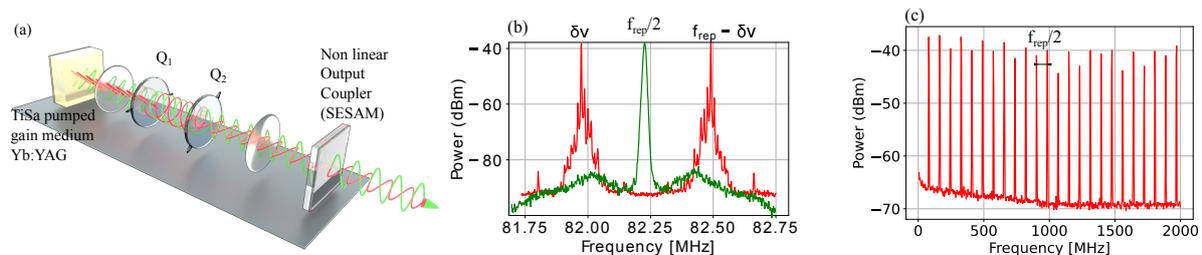
# Phase-locked dual polarization frequency combs in Yb:YAG

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Mode-locked lasers polarization states are typically fixed by gain dichroism in crystalline media. However, dual-polarization oscillation and pulse-to-pulse polarization control in bulk isotropic active media have attracted attention recently [1,2]. Apart from using extra-cavity polarization devices, one can wonder whether an oscillator can generate directly adjustable polarization sequences. Here, we demonstrate how phase locking of two orthogonal polarization eigenstates can occur in a passively mode-locked Yb:YAG laser using two quarter-wave plates.

The laser used is described in Fig.1(a). The cavity contains a 2 mm-thick, <111>-cut, 5% at.-doped, Yb:YAG crystal, and two quarter-wave plates ( $Q_1$  and  $Q_2$ ). The pump mirror  $M_1$  is dichroic (high-reflection at 1030 nm, high-transmission at 940 nm). The active medium is anti-reflection coated. It is pumped at 940 nm by a continuous-wave Ti:Al<sub>2</sub>O<sub>3</sub> laser, which is focused to a spot radius of 17  $\mu\text{m}$  in the active medium. The output coupler is a semiconductor saturable absorber mirror (SESAM) from BATOP (1.2% modulation depth and 3% transmission). Two lenses, with focal lengths of 25.4 and 15 mm, provide focusing in the active medium and in the SESAM where the waist is 20  $\mu\text{m}$ . The cavity design takes into account the thermal lens in the Yb:YAG crystal, induced by the 2.8 W pump beam at 940 nm. The laser oscillates at 1030 nm on a roughly 400 GHz-wide spectrum. The pulse full width at half-maximum is 2.5 ps, the output power is 90 mW, the pulse repetition rate is  $f_{rep} = 164$  MHz.



**Fig. 1** (a) Illustration of the Yb:YAG mode-locked laser experimental setup. (b) Beat frequency spectrum around  $f_{rep}/2$ ,  $\delta\nu$  outside locking range (in red) and inside the locking range (in green). (c)  $f_{rep}/2$  periodic spectrum.

Since all intracavity interfaces are taken at normal incidence (see Fig.1(a)), the eigenpolarizations are determined by  $Q_1$ ,  $Q_2$  and the residual birefringence in the Yb:YAG crystal. The neutral axes of  $Q_1$  are aligned with the residual birefringence of the active medium. The neutral axes of  $Q_2$  are rotated by an angle  $\alpha$  with respect to the axes of  $Q_1$ . The eigenstates are determined by a single round-trip resonance condition including Jones matrices [1]. They are linearly polarized in the gain medium at  $45^\circ$  from the axes, right and left helicoidally polarized between  $Q_1$  and  $Q_2$  and linearly polarized at  $45^\circ$  from  $Q_2$  axes at the laser output. The laser oscillates on two frequency combs associated to the two eigenpolarizations and the output pulse train is made of a controllable polarization sequence. These two combs are shifted by  $\delta\nu = \frac{2\alpha}{\pi} \times \frac{c}{2L}$  with respect to one another leading to polarization sequences in the pulse train as in [1]. When  $\delta\nu$  enters the locking range, i.e.  $f_{rep}/2 \pm 25$  kHz, the two peaks in red (see Fig.1(b)) at frequencies  $\delta\nu$  and  $f_{rep} - \delta\nu$  merge into one peak leading to phase locking. A wider span over 2 GHz shows a comb with a perfect periodicity of  $f_{rep}/2$  (see Fig.1(c)). The stability of the whole spectrum confirms the dual-comb locking.

It is important to note that in this current experimental setup the two orthogonally polarized combs share the same repetition frequency at 164 MHz while the optical frequency combs are offset by  $\delta\nu$ . Ongoing work concerns the spatial separation of the two orthogonal polarizations on the SESAM using additional beam displacers inside the cavity [2,3], and the use of the pump polarization orientation [4]. The principles of this dual-comb polarization dynamics can be extended to other isotropic gain media such as Yb:CaF<sub>2</sub>.

## References

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