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# Solid-state dual-frequency laser free from anti-phase noise

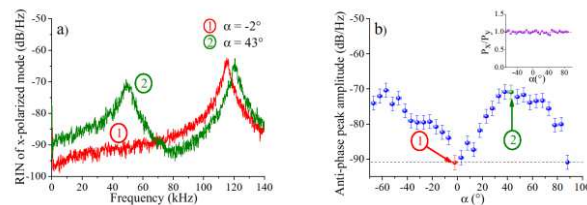
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Dual-frequency solid-state lasers are attractive for a large number of applications such as microwave photonics, spectroscopy, and metrology. As far as dual-frequency lasers are considered, the intensity noise spectrum of each eigenmode exhibits two peaks lying at the well-known in-phase and anti-phase eigen-frequencies of two coupled oscillators. The in-phase noise, which corresponds to the standard relaxation oscillations of the laser, can be reduced either electronically or optically using feedback loops [1]. However, the anti-phase noise, which is related to a resonant exchange of energy between the two laser modes, is very difficult to circumvent [2] because the reduction of this noise would require additional servo-loop acting on the difference of the intensities of the two modes or two servo-loops acting independently on the intensity of each mode. An optimal dual-frequency laser in terms of intensity noise and beat frequency stability would be a single axis laser in which the population inversions related to each mode are independent. We experimentally demonstrate how the proper design of a two polarization dual-frequency solid-state laser allows to get rid of the anti-phase noise in the simplest possible architecture and without using any electronic or optical feedback loop. This design is based on an appropriate choice of the active medium cut and orientation in order to assign two almost independent families of active atoms to the two laser modes.



**Fig. 1** RIN spectra for the x-polarized mode only for different values of  $\alpha$ . b) Evolution of the amplitude of the anti-phase peak versus  $\alpha$ . Dashed line: noise floor level below which the anti-phase peak is no longer measurable. The inset shows the evolution of the intensity ratio of two orthogonal modes versus  $\alpha$ .

Besides, it has recently been shown that, in Nd:YAG, the emitting dipoles behave as if they were aligned along the crystallographic axes of the matrix [3]. In particular, by choosing a (100)-cut Nd:YAG crystal instead of the more common (111) cut, it was shown that almost complete decoupling of two perpendicularly polarized modes could be obtained by aligning them with the (010) and (001) crystallographic axes. One then expect the antiphase noise to vanish using a properly oriented (100)-cut Nd:YAG crystal. In order to adjust the angle,  $\alpha$ , between the laser polarization eigen-states and the crystallographic axes of the active medium, we insert into the two-mirror cavity a birefringent plate (BP) whose neutral axes define the two crossed and linear polarizations of the laser. Fig. 1(a) reproduces the relative intensity noise (RIN) spectra recorded when only the x-polarized mode is detected for two values of angle  $\alpha$  corresponding to the two situations where the eigen-polarizations of the laser are (1) aligned with the crystallographic axes of the active medium ( $\alpha=-2^\circ$ ) or (2) at  $45^\circ$  ( $\alpha=43^\circ$ ). We observe the existence of the usual in-phase relaxation oscillations peak at about 115 kHz and 120 kHz. When  $\alpha$  is set at  $43^\circ$ , that is the angle for which the coupling is maximum, the amplitude of the anti-phase peak is found to be maximum. By contrast, if we now rotate  $\alpha$  and look for the position in which the amplitude of the anti-phase peak is minimized, we find  $\alpha=-2^\circ$  as shown by the red spectrum of Fig. 1(a). The evolution of the anti-phase peak amplitude versus  $\alpha$  is plotted in Fig. 1 (b). Consequently, we show that the noise induced by the anti-phase relaxation oscillations resonance in a dual-frequency laser can be almost completely cancelled by a proper choice of the active medium and design of the cavity. This has been illustrated in the case of a Nd:YAG crystal in which the choice of a (100)-cut crystal together with the proper orientation of the polarizations of the laser modes permit to cancel this resonance by more than 20 dB [4].

## References

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