Experimental demonstration of a dual-frequency laser free from antiphase noise

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A reduction of more than 20 dB of the intensity noise at the antiphase relaxation oscillation frequency is experimentally demonstrated in a two-polarization dual-frequency solid-state laser without any optical or electronic feedback loop. Such behavior is inherently obtained by aligning the two orthogonally polarized oscillating modes with the crystallographic axes of a (100)-cut neodymium-doped yttrium aluminum garnet active medium. The antiphase noise level is shown to increase as soon as one departs from this peculiar configuration, evidencing the predominant role of the nonlinear coupling constant. This experimental demonstration opens new perspectives on the design and realization of extremely low-noise dual-frequency solid-state lasers. © 2012 Optical Society of America

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Dual-frequency solid-state lasers are attractive for a large number of applications such as microwave photonics [1,2] and metrology [3,4]. In particular, when the two modes are cross-polarized, dual-frequency lasers are shown to be well suited for obtaining large tunability of the frequency difference, voltage controlled tunability as well as compactness [2,5]. In this context, different gain media, either crystals or glasses, may be used to reach different wavelengths [6,7]. While such solid-state lasers are known to exhibit very narrow spectral widths, they suffer from resonant intensity noise at low frequencies, i.e., from a few kilohertz to a few megahertz [1]. 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 antiphase eigenfrequencies of two coupled oscillators [8]. The in-phase noise, which corresponds to the standard relaxation oscillations of the laser, can be reduced either electronically or optically using feedback loops [1,9]. However, the antiphase 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 an 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. The existence of the antiphase noise being by essence due to the fact that the two laser modes share totally or partially the same population inversion, another approach is to separate spatially the two laser modes in the active medium [7,10]. Nevertheless, such a two-axis approach increases the complexity of the laser. Moreover, it reduces the correlation between the frequency jitter of the two modes as compared to a single axis, thus reducing the efficiency of the common mode noise rejection. Besides, another solution consists in using class-A lasers [11], which are free from relaxation oscillations. But this is usually not possible for solid-state lasers. Consequently, 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.

In this Letter, we experimentally demonstrate how the proper design of a two-polarization dual-frequency solid-state laser allows us to get rid of the antiphase 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. The simple two-frequency laser architecture that we chose is schematized in Fig. 1(a). The two-mirror cavity contains a quarter-wave plate (QWP), which defines the orientations of the two eigenpolarizations of the laser. In this case these two eigenpolarizations are linear and aligned along the neutral axes of the QWP. Thus, rotating this QWP is a simple way to rotate the orientation of the eigenpolarizations. The question now is how should we choose our active medium in order to uncouple the two polarization modes, i.e., in order to minimize

![Fig. 1.](Image)

Fig. 1. (Color online) (a) Experimental setup. QWP, quarter-wave plate; HWP, half-wave plate; BS, beam splitter. (b) is the angle between the (100) eigenpolarization direction and the (001) crystallographic axis of the Nd:YAG crystal. (c) Optical spectrum observed with a Fabry–Perot interferometer and showing single longitudinal mode operation for each polarization state. FSR, free spectral range.
cross-saturation effects among our two modes? 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 [12], although more elaborate models suggest more complex descriptions for the spectroscopy of Nd$^{3+}$ ions embedded in YAG matrix [13, 14]. 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. We have thus chosen to use such a crystal here and to observe the evolution of the laser intensity noise spectrum when we rotate the QWP with respect to the crystal axes. As depicted in Fig. 1(a), the laser is based on a 7 cm long planar–concave cavity. The gain medium is a 2 cm long (100)-cut Nd:YAG crystal (FEE GmbH). The crystallographic axes were precisely determined by x-ray diffraction. In order to limit thermally induced birefringence, the crystal is placed inside a copper mount. It is pumped by a cw multimode fiber-coupled low-power laser diode from Opto Power operating at 808 nm and delivering 300 mW. We have checked that the pump beam is thus depolarized, avoiding any pump-induced gain anisotropy. The QWP, which defines the two eigenpolarization directions $x$ and $y$, is mounted on a precise rotation mount in order to control the angle $\alpha$ between the Nd:YAG crystallographic axes and the polarization states [Fig. 1(b)]. A 100 $\mu$m thick intracavity uncoated silica etalon forces the laser to oscillate in a single longitudinal mode for each polarization state. The laser is 1.5 times above threshold, and the total output power is 20 mW. Both modes are continuously analyzed with a Fabry–Perot cavity to check that the laser remains longitudinally monomode for each polarization without any mode hop during data acquisition. The laser intensity is measured using an InGaAs photodiode (Epitaxx Inc, 3.7 MHz bandwidth) and a homemade low-noise amplification setup. A half-wave plate (HWP) followed by an isolator after the laser permits us to project the laser output on any linear polarization state before detection by rotating the HWP. The noise spectrum is recorded with a Rohde & Schwarz electrical spectrum analyzer (ESA) whose frequency range is 10 Hz–3.6 GHz.

Figure 2 reproduces the relative intensity noise (RIN) spectra recorded when only the $x$-polarized mode is detected for two values of $\alpha$ corresponding to the two situations where the eigenpolarizations of the laser are (1) aligned with the crystallographic axes of the active medium ($\alpha = -2^\circ$) or (2) at 45$^\circ$ ($\alpha = 43^\circ$). For $\alpha = -2^\circ$ and $\alpha = 43^\circ$, we observe the existence of the usual in-phase relaxation oscillations peak at around 115 and 120 kHz. It must be noted that the 5 kHz frequency shift of the two peaks in Fig. 2(a) is due to the unavoidable slight change of the intracavity losses when the QWP is rotated. It corresponds to a variation of the pumping rate of 1% only. Now let us focus on the antiphase peak lying at around 50 kHz. When $\alpha$ is set at 43$^\circ$, that is the angle for which the coupling is maximum, the amplitude of the antiphase peak is found to be maximum. Obviously, similar to a (111)-cut Nd:YAG crystal, while the in-phase peak is always there, the antiphase peak can be hidden when one balances the intensities of the two modes on the detector. By contrast, if we now rotate $\alpha$ while detecting only the $x$ polarization and look for the position in which the amplitude of the antiphase peak is minimized, we find $\alpha = -2^\circ$ as shown by the red spectrum of Fig. 2(a). As expected, this orientation corresponds to the situation where the coupling is expected to be minimum [12]. When $\alpha = -2^\circ$, the antiphase peak becomes so small that it disappears below the noise floor. It must be noted that the value $\alpha = -2^\circ$, very close to zero, is within the experimental orientation uncertainty of the active medium in its mount when positioned into the laser cavity. Moreover, it is worthwhile to notice that, in this peculiar case where the two modes are no longer coupled, the term “in-phase” that we use to qualify the peak at the relaxation oscillation frequency is no longer valid. Obviously, this term still applies for all the intermediate situations, namely $-2^\circ < \alpha < 88^\circ$. The evolution of the antiphase peak amplitude versus $\alpha$ is plotted in Fig. 2(b). One can see that this amplitude is maximum (respectively minimum) for $\alpha$ close to $\pm \pi/4$ (respectively 0 or $\pi/2$), i.e., when the coupling is expected to be maximum (respectively minimum). This is consistent with the fact that the laser behaves as if the emitting dipoles were aligned along the crystallographic axes, like in [12]. As shown in the inset of Fig. 2(b), the cross-polarized intensities have been carefully equalized for each orientation of the QWP by fine adjustment of the intracavity etalon.

The principle proposed here of reducing the mode coupling in order to reduce the antiphase noise can be compared from a conceptual point of view to that of [15] in which the stabilization of the output power of a Nd:YAG doubled laser is obtained when the second harmonic generation losses that couple the two polarization modes are reduced. In our case, the coupling mechanism that
is concerned and that we try to reduce is the cross-saturation in the active medium. The QWP that we use is only intended to fix the orientation of the laser polarizations, the active medium being isotropic. Consequently, the amount of retardance created by this wave plate does not play any role unlike in [15].

In the interesting situations corresponding to $\alpha = -2^\circ$ and $\alpha = 88^\circ$ in which the antiphase relaxation oscillation noise peak has been minimized, we expect this peak to be not present for all orientations of the polarization analyzer located after the laser. This is what we check in Fig. 3, which shows the RIN spectra obtained for several orientations $\beta$ between $x$ and the fast axis of the HWP. When the HWP is rotated by $\beta$, the analyzed polarization is rotated by $2\beta$. These experimental spectra show, on one hand, that the RIN behavior remains almost the same for all orientations of the polarization analyzer and, on the other hand, that the antiphase peak is drastically reduced for both polarization modes of the laser.

In summary, we have shown that the noise induced by the antiphase relaxation oscillation resonance in a dual-frequency laser can be almost completely cancelled by a proper choice of the orientation of the laser eigenpolarizations with respect to the orientations of the light emitting dipoles. 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 permits us to cancel this resonance by more than 20 dB. The remaining noise lying at in-phase relaxation oscillation frequency could be easily damped with conventional electronic feedback loop acting on the pump intensity.

This work opens interesting perspectives in several directions. It shows that a properly designed active medium with a careful control of the orientation of the emitting dipoles would permit to solve the same problem at other wavelengths. Finally, it opens new perspectives of applications of dual-frequency solid-state lasers, in domains in which the intensity noises of the two polarization modes play a central role, such as the probing of cesium clocks based on coherent population trapping phenomena.

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