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# Investigation of the coupling between pump amplitude noise and differential phase noise in an Er,Yb:Glass two polarization dual frequency solid state laser

Gwennaél Danion, \* Antoine Rolland, François Bondu, Goulch'en Loas, and Mehdi Alouini

*Institut de Physique de Rennes, Département d'Optique et Photonique, UMR 6251 Université Rennes 1—CNRS Campus de Beaulieu, 35042 Rennes cedex, France*

\*Corresponding author: [gwennaél.danion@univ-rennes1.fr](mailto:gwennaél.danion@univ-rennes1.fr)

**We report experimental evidence of the coupling between the pump diode current and the output differential phase in a two-axis two polarization dual-frequency solid state laser. The effect has the same transfer function shape as that for pump current to output power one, suggesting a pump AM/laser PM coupling in the laser medium. We report that the pump amplitude noise is negligible in the laser differential phase noise assuming a linear coupling.**

## 1. INTRODUCTION

Low phase-noise lasers are mandatory in many applications including telecommunications and lidar-radar [1-4]. The laser linewidth of rare-earth doped solid state lasers is known to be smaller than in semiconductor lasers, where it is spoiled by amplitude-to-phase coupling (AM/PM) due to the Henry factor  $\alpha$  [5,6]. Consequently most of the studies dealing with the Henry factor are related to semiconductor lasers. The few reported studies on amplitude to phase coupling in solid state lasers concern microchip lasers [7,8]. Yet, when ultrastable and narrow linewidth are required, the amplitude to phase conversion might become the limiting factor even in solid state lasers. We have been involved during the last years in developing a photonic adjustable ultra-stable sub-millimeter and millimeter wave reference based on a dual frequency laser [9] locked to a single ultralow expansion cavity. In this framework the knowledge of the amplitude to phase coupling coefficient is essential in order to ensure the best possible stability of the beat note between the two optical laser lines [10-13]. Given the extremely low coupling coefficients we are expecting in this kind of solid-state laser, a specific measurement setup has to be designed.

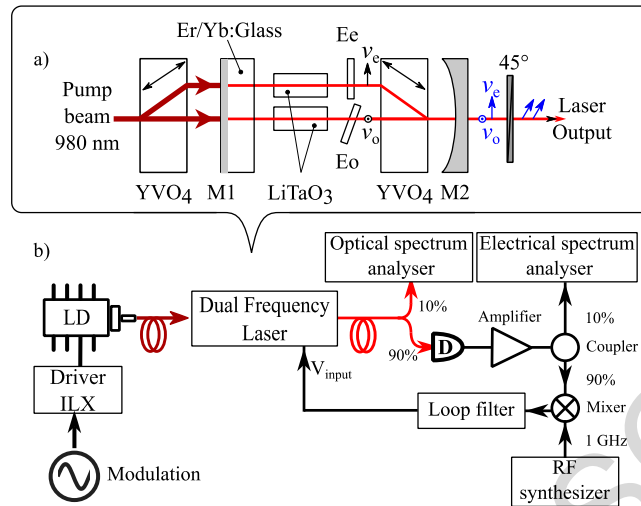
In this paper, we first describe the experimental setup and the protocol used to investigate the AM/PM coupling between the pump and the dual frequency beatnote denoted in the following  $AM_{\text{pump}}/PM_{\text{beat}}$ . We then checked for possible measurement biases. Finally, a thorough analysis is conducted to recover the actual contribution of relative intensity noise of the pump on the differential phase noise of the dual frequency laser.

## 2. EXPERIMENTAL SETUP

The laser under consideration is an Er,Yb:glass laser oscillating at 1550 nm. The optical power of the two optical carriers is 1 mW after injection in the optical fiber [9,13]. The beat-note is tunable over a DC-900 GHz range by rotating the intra cavity etalons [13]. The diode pump is a fiber Bragg grating stabilized longitudinal monomode laser, providing 800 mW at 980 nm. The pump beam is split in two paths using a birefringent YVO4 crystal and orienting the input pump polarization at 45°. Hence, the two optical axes of the laser are pumped with the same pump, that is, with perfectly correlated pump noises, Fig. [1-a].

We seek to measure the  $AM_{\text{pump}}/PM_{\text{beat}}$  coupling in the perturbation regime. As shown in Fig. 2, when the dual frequency laser is operated in the free running regime, the phase noise of its beatnote is relatively high which forbids the measurement of the  $AM_{\text{pump}}/PM_{\text{beat}}$  coupling in the small signal regime. In order to detect small contributions, one has to reduce the beatnote drift by stabilizing the frequencies difference of the laser [12,14,15] as depicted in Fig. 1. This frequency difference is stabilized on a reference provided by a low phase noise electrical synthesizer and a homemade phase locked loop (PLL). The laser frequency difference excursion range being  $\pm 15$  MHz, a PLL is necessary to remove this drift and run the laser in constant conditions over the measurement time. In the experiments described in this paper, we use only one of the two internal LiTaO3 electro-optic crystals (2x2x8 mm3) to servo the frequency difference of the two optical carriers. The output beam is injected into a polarization maintaining 10/90 fibered coupler. Its first arm (10%) is used for optical monitoring purposes while the second arm (90%) is devoted to electrical beat note synthesis. This beatnote is obtained due to a fast InGaAs photodiode (Discovery 16 GHz) in front of which a polarizer oriented at 45° is placed to make the two laser polarizations interfere. The assembly starting from the laser intracavity electro-optic crystal to the photodiode output realizes a voltage controlled oscillator (VCO) synthesizer. In the experiment reported here the frequency beatnote, and thus the phase locked loop, is adjusted to 1 GHz. A directional coupler splits the microwave signal at the output of the photodiode. 10% of its power is directed on a phase noise measurement apparatus described in the following, whereas 90% of the power feeds the PLL. Basically, it is mixed with a microwave reference at 1 GHz provided by a low phase noise synthesizer. The

correction filter has a proportional-integrator shape, so that the open loop unity gain bandwidth is 100 kHz. Finally, the correction signal is applied to the electro-optic crystal inside the laser cavity.

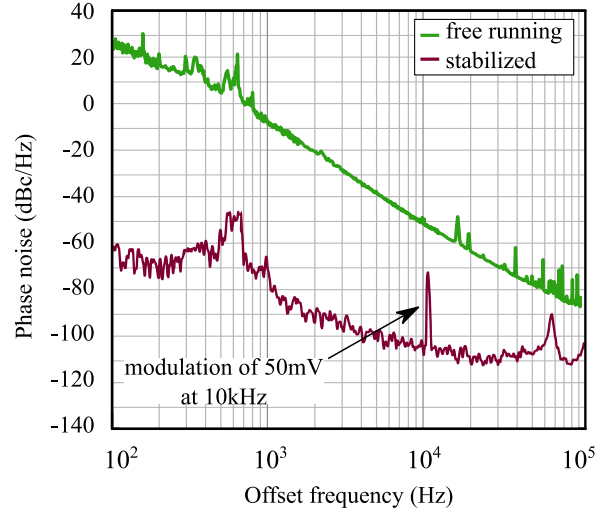


**Fig. 1.** (a) Schematic representation of the two-axis dual frequency laser. (b) Scheme of experimental setup stabilization and first measurement technique: direct measurement

### 3. MEASUREMENT OF THE PUMP DIODE AMPLITUDE NOISE CONTRIBUTION

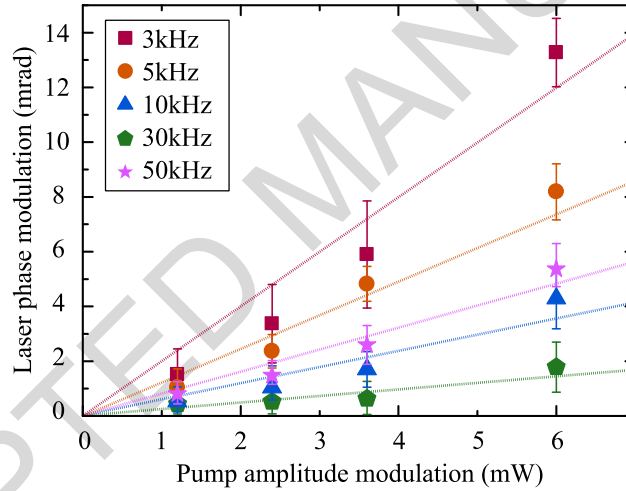
A careful characterization of the optical power modulation of the pump versus the voltage modulation of the driver from 10 to  $10^5$  Hz is performed using a network analyser (Stanford SR780) connected to a high bandwidth photodiode (1 GHz). This allows us to accurately adjust the modulation index of the pumping power.

The microwave phase noise of the beat note delivered by the laser is measured with a 26 GHz Aeroflex electrical spectrum analyser. The experiment is performed in a perturbative regime of low modulation order not to destabilize the laser operation. As shown in Fig. 2, to detect small signals, we need to stabilize the beat note to reduce the noise floor, hence the need for PLL. At 1 GHz, the noise floor is measured to be -80 dBc/Hz at 1 kHz offset frequency. In order to measure the  $AM_{\text{pump}}/PM_{\text{beat}}$  conversion efficiency, we applied a low modulation of the pump power. For example, when we modulate the current of the pump laser driver at 10 kHz in order to obtain 6 mW pump amplitude (0.75% of modulation index), we observe a modulation at the same offset frequency on the phase noise of the optically synthesized frequency. This phase modulation appears as a sharp peak in the phase noise spectrum (see Fig 2). It is worthwhile to notice that the action of the servo loop which reduces the phase noise excursion enabling such a measurement must be taken into account. Indeed, the measured phase noise must be multiplied by the gain of the open loop in order to unfold the effect of the PLL and then recover the actual phase modulation level. This correction factor being frequency dependent, a careful characterization of the open loop gain is performed. Moreover, we checked that the intensity modulation of the beatnote, associated to the intensity modulation of the pump laser, is efficiently filtered out by our I&Q demodulation apparatus. To this aim, we applied to the laser an external amplitude modulation of the same level and in the range 10- $10^5$  Hz and we did not notice after I&Q demodulation any residual peak in the phase noise spectrum.



**Fig. 2.** Phase noise of free running laser (green curve) and phase noise stabilized laser (purple curve) The sharp peak appearing on phase noise spectrum gives access to the  $AM_{\text{pump}}/PM_{\text{beat}}$  coupling induced by the pump power modulation.

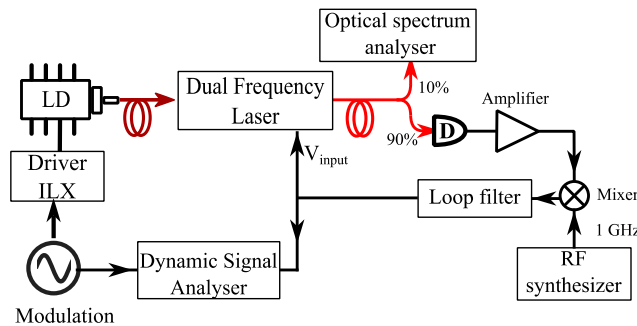
More importantly, we checked that the laser operates, as required, in perturbation regime. To this aim we increase the pump power modulation depth and check that the peak amplitude increases proportionally. We integrate the power fluctuation for frequencies between 900 Hz and 50 kHz and the power fluctuation between 1 mW and 6 mW.



**Fig. 3.** Measure of phase modulation versus amplitude modulation for different frequency of diode pump modulation.

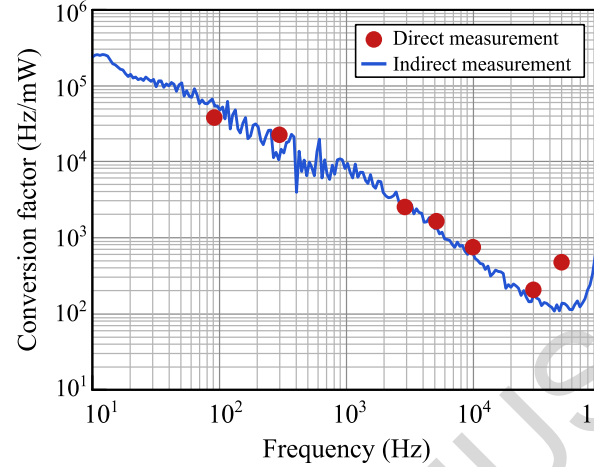
For each modulation frequency the slope of the line giving the phase modulation amplitude versus pump modulation amplitude is extracted using a linear regression as shown in Fig. 3. These slopes are then multiplied by the offset frequency to end up with the magnitude of the transfer function displayed with red dots in Fig. 5.

We then made systematic measurements of the transfer function with a network analyzer (Stanford SR780), Fig. 4. We measure the transfer function between the amplitude modulation and the conversion factor, the blue line on Fig. 5



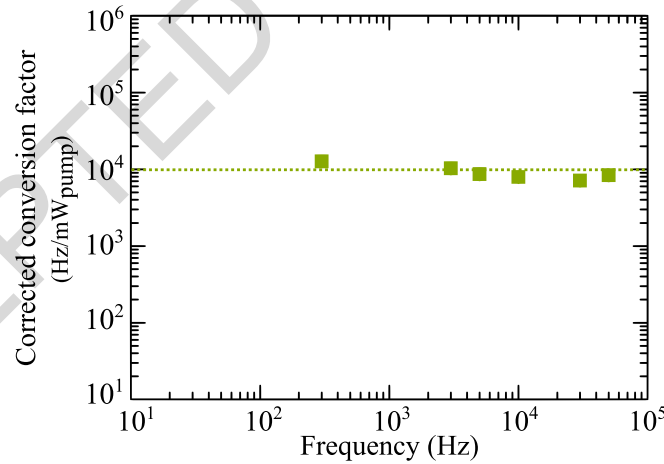
**Fig. 4.** Scheme of experimental setup with a vectorial network: indirect method

To go further and confirm these results we now analyze the transfer function given by the ratio between the amplitude of the correction signal delivered by the PLL and the modulation amplitude of the pump diode current. Indeed, the correction signal, at frequencies smaller than the PLL unity gain bandwidth, is proportional to the laser free running noise weighted by the electro-optic voltage to frequency response. This calibration factor is measured to be constant and equal to 1.1 MHz/V up to a few MHz. The direct (red points) and indirect (blue full line) measurements are in good agreement except for the last point close to the laser relaxation oscillations. At this peculiar frequency, the laser is no more operated in the low signal regime because the output intensity modulation increases by more than 30 dB. Moreover, and because of this increase, the I&Q demodulation setup becomes not efficient enough to filter out the amplitude modulation. Thus, the spectral region around the oscillation relaxations must be avoided for such sensitive measurements.



**Fig. 5.** Conversion factor versus frequency modulation, with phase noise analyzer (dots) and PLL correction signal (plain curve).

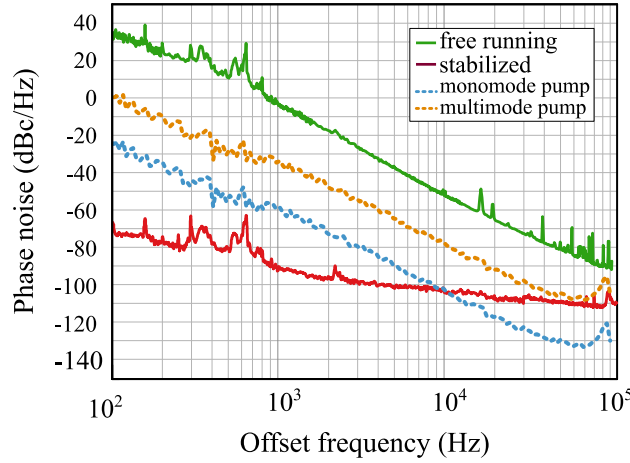
It is worthwhile to notice that the slope of the transfer function does not correspond to the usual  $1/f$  decrease but first to a  $1/f$  decrease up to 1 kHz and then to a  $1/f^2$  decrease between 1 kHz and 30 kHz. This behavior is due to the energy exchange mechanism between Yb and Er in the active medium which has a millisecond time constant leading to an additional first order low-pass filter with 1 kHz pole [16]. The frequency response of the energy exchange mechanism is extracted from low frequency RIN spectrum of the laser (see [13]). When this mechanism is taken into account, it turns out that the  $AM_{\text{pump}}/PM_{\text{beat}}$  coupling coefficient is independent of the modulation frequency as reported in Fig. 6. Moreover, we find that its magnitude is about 10 kHz per mW of pump power.



**Fig. 6.** Conversion factor, between laser output amplitude and output phase modulation, corrected from oscillation relaxations

#### 4. DEDUCTION OF AM/PM FACTOR

This result is of great importance since it will enable us to directly estimate the contribution of the pump noise on the differential phase noise in the dual frequency solid state laser. In particular, one wants to know if the pump diode choice has a detrimental effect on the phase noise of dual frequency laser beatnote.



**Fig. 7.** Estimation of phase noise induced by a multimode pump (orange dotted line) and monomode pump (blue dotted line), and comparison with the on free running and stabilized laser phase noise.

To this aim, we report in Fig. 7, different beatnote phase noise spectra as follows. The green spectrum represents the free running beatnote phase noise of the laser, measured using the correction signal of our PLL when open. The red spectrum represents the stabilized laser beatnote phase noise, i.e., when the PLL is closed. The two remaining dot spectra are deduced from the intensity noise of pump diode weighted by the measured  $AM_{\text{pump}}/PM_{\text{beat}}$  coupling coefficient. Hence, the blue dots spectrum represents the phase noise induced using a single mode fiber coupled pump diode whereas the orange dots spectrum corresponds to the phase noise induced by a multimode fiber coupled laser diode. In both cases, the dual frequency laser is operated in the same conditions, i.e., same pump power, same, threshold and same pump rate.

Fig. 7 clearly evidences that  $AM_{\text{pump}}/PM_{\text{beat}}$  coupling is not the limiting factor for the two pumping schemes since both spectra are below that of the free running laser. The 20 dB phase noise offset between the multimode and monomode pumping schemes corresponds to the measured intensity noise offset between the two pump diodes. Consequently, the beatnote phase noise, although very low in dual frequency solid state lasers, is still limited by another noise source, and probably by intrinsic thermal noise in the active medium.

## 5. CONCLUSION

We highlighted the coupling factor between  $AM_{\text{pump}}/PM_{\text{beat}}$  between the amplitude pump fluctuation and the dual frequency beatnote for a two axis dual frequency solid state laser. We have described the experimental setup and the protocol used to investigate the coupling. To detect the small contribution of this factor, the laser is stabilized with a PLL. Two techniques of measurement, a direct method and an indirect method, allow to determine the coupling factor. We have shown that the slope of the transfer function  $AM_{\text{pump}}/PM_{\text{beat}}$  corresponds to a  $1/f$  decrease up to 1 kHz and then to a  $1/f^2$  decrease between 1 kHz and 30 kHz, which corresponds at a low-pass filter due to energy exchange mechanism between Yb and Er in the active medium which has a millisecond time constant. Correcting the transfer function of this mechanism, the conversion factor is of 10 kHz per mW of pump power. This result, allows to estimate the fluctuation noise contribution of pump diode on the phase noise of the two-axis dual frequency solid state laser. We show that the phase noise induced by the RIN of the diode pump is not the limiting factor of this phase noise laser. One possibility of this limiting the phase noise of beat note is may be caused by intrinsic thermal noise in the active medium.

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