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### ► To cite this version:

M. Guionie, Ludovic Frein, Anthony Carré, Goulc'Hen Loas, François Bondu, et al.. Beat note stabilization in dual-polarization DFB fiber lasers by an optical phase-locked loop. *Optics Express*, 2018, 26 (3), pp.3483-3488. 10.1364/OE.26.003483 . hal-01716235

**HAL Id: hal-01716235**

**<https://hal.science/hal-01716235v1>**

Submitted on 23 Feb 2018

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# Beat note stabilization in dual-polarization DFB fiber lasers by an optical phase-locked loop

M. GUIONIE,<sup>1</sup> L. FREIN,<sup>1</sup> A. CARRÉ,<sup>1</sup> G. LOAS,<sup>1</sup> F. BONDU,<sup>1</sup> E. PINSARD,<sup>2</sup>  
L. LABLONDE,<sup>2</sup> B. CADIER,<sup>2</sup> M. ALOUINI,<sup>1</sup> M. ROMANELLI,<sup>1</sup> M. VALLET,<sup>1</sup>  
AND M. BRUNEL<sup>1,\*</sup>

<sup>1</sup>Univ Rennes, CNRS, Institut FOTON - UMR 6082, F-35000 Rennes, France

<sup>2</sup>iXblue Photonics, rue Paul Sabatier, 22300 Lannion, France

\*[marc.brunel@univ-rennes1.fr](mailto:marc.brunel@univ-rennes1.fr)

**Abstract:** A fully fibered microwave-optical source at 1.5  $\mu\text{m}$  is studied experimentally. It is shown that the beat note between two orthogonally polarized modes of a distributed-feedback fiber laser can be efficiently stabilized using an optical phase-locked loop. The pump-power-induced birefringence serves as the actuator. Beat notes at 1 GHz and 10 GHz are successfully stabilized to a reference synthesizer, passing from the 3 kHz free-running linewidth to a stabilized sub-Hz linewidth, with a phase noise as low as -75 dBc/Hz at 100 Hz offset from the carrier. Such dual-frequency stabilized lasers could provide compact integrated components for RF and microwave photonics applications.

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**OCIS codes:** (060.3510) Lasers, fiber; (060.5625) Radio frequency photonics; (140.3425) Laser stabilization.

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## 1. Introduction

Short fiber lasers are appealing sources for a wide variety of applications because of their compactness, ruggedness, and ease of integration [1]. Distributed-feedback (DFB) fiber lasers are usually designed to be single frequency. Nevertheless, it has long been shown that these structures are capable of sustaining the oscillation of two orthogonal polarizations at different frequencies [2–4]. Such dual-frequency DFB fiber lasers were foreseen as efficient sensors [5], and may be promising as heterodyne sources in the field of microwave photonics [6–9]. However, in the context of optical distribution of local oscillators for instance, stabilization of the beat frequency against a reference is mandatory. At variance with common solid-state lasers, where additional optical components can be inserted into the laser cavity, new techniques have here to be imagined in order to ensure, on the one hand, simultaneous and stable oscillation of the two polarizations and, on the other hand, possible phase locking of the beat note. Elasto-optical effects (torsion [7] or compression [8]) have already been tested to control the beat frequency of dual-polarization fiber lasers, but phase-locked stabilization to a reference oscillator has never been performed. Besides, optical feedback on a DBR laser also leads to efficient noise reduction [9]. In this work, we investigate an optical phase-locked loop where the DFB fiber laser acts as a voltage-controlled oscillator (VCO) driven by the laser pump power.

Pump-induced thermal effects may become useful for noise reduction or locking in the case of diode-pumped short-cavity solid-state lasers. For example, phase-locking microchip lasers was demonstrated with a feedback on the pump-power of one laser with respect to the other [10]. Besides, simultaneous intensity and frequency noise reduction was obtained in a non-planar ring oscillator [11]. Also, locking a single-frequency erbium microchip laser to a molecular line was realized by a simple modulation-demodulation technique through the pump power [12]. In all these examples, small temperature variations leads to important frequency shifts due to the thermo-optical effect in the short cavity. The low dimensions also leads to reasonable kHz lock-in bandwidths [10,12]. While in [13] the role of pump-induced thermal effects on the frequency switching in ytterbium-doped DBR fiber lasers was demonstrated theoretically and experimentally, the pump-induced beat tuning effect has not been exploited previously in fiber lasers. Here we focus on erbium-doped DFB fiber lasers emitting in the 1.5  $\mu\text{m}$  wavelength region. We find experimentally that minute differential refractive index changes provided by the pump power offer a satisfactory VCO effect, in both amplitude and bandwidth, which in turn permit to build a robust servo-locking loop.

We first detail in Section II the experimental set-up and laser characteristics, with emphasis on the beat note study, of a laser operating with a 1 GHz frequency difference. Section III is then devoted to the optical phase-locked loop based on pump-power control. In Section IV we extend the same principle to a laser emitting a 10 GHz beat note. Conclusions are given in Section V.

## 2. Dual-polarization DFB fiber lasers

The experimental set-up is shown in Fig. 1. We have investigated different samples of erbium-doped silica fiber lasers, all being made with a distributed-feedback (DFB) structure. The Bragg gratings are photo-induced using the phase-mask technique with a pulsed, unpolarized, UV laser. The dual-polarization lasers studied here bear different grating profiles

that are detailed below. In particular we will show results obtained with samples emitting beat notes at around 1 GHz (labeled 1G) and at 10 GHz (labeled 10G). The lasers are spliced to single-mode fibers (cut-off 900 nm) on both sides. The lasers are pumped at 980 nm on the output coupler side through a 980/1550 wavelength-division multiplexer. The laser output is transmitted through an isolator, a polarization controller (PC), and a polarizer, to the analysis instruments. The system is entirely single-mode (non PM) fibered. In the following, we concentrate our analysis on the dual-frequency performance of the DFB lasers, in order to define a suitable phase-locked loop for beat note stabilization, either at 1 GHz or at 10 GHz.

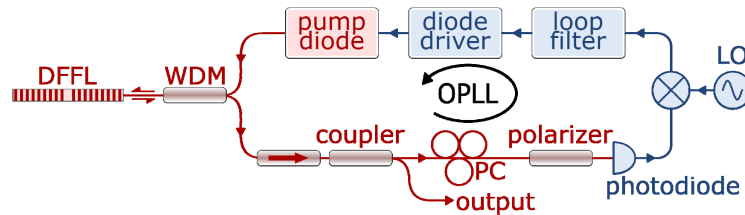


Fig. 1. Optical phase-locked loop (OPLL) experimental set-up. DFFL: dual-frequency fiber laser; WDM, pump-signal coupler; PC, polarization controller; LO, local oscillator.

Let us detail the characteristics of sample 1G. The active medium is made with a 35 mm-long erbium-doped fiber, whose cladding diameter is 80  $\mu\text{m}$ , and whose absorption is 11.3 dB/m at 1530 nm (the concentration is low enough to prevent any self-pulsing operation). The FBG is photo-induced at 193 nm, its central wavelength is  $\lambda_B = 1547.3$  nm, its length is  $L_B = 30.5$  mm, and its strength is  $\kappa = 390$   $\text{m}^{-1}$ . The resulting calculated effective length is  $L_{\text{eff}} = 2.6$  mm. A  $\pi$  phase-shift is made at 18 mm from the beginning of the grating, leading to mirror intensity transmissions of  $-57$  dB and  $-34$  dB. Due to the photo-induced birefringence of the fiber, the phase-shifted grating sustains two polarization-resolved resonances at the center of the stop band. This is verified experimentally by characterizing the spectral transmission of the component without pumping, using a high-resolution optical spectrum analyzer (OSA) containing a built-in tunable laser source. As can be seen in Fig. 2(a), the polarization-mode wavelength difference is 8 pm (1 GHz), while the width of the stop band is 200 pm (25 GHz). Note that the weakness of the two resonances is here due to absorption of the tunable probe by the un-pumped erbium ions. The wavelength difference  $\Delta\lambda$  can be directly linked to the birefringence  $\Delta n$  by  $\Delta\lambda/\lambda_B = \Delta n/n$ . We can thus deduce  $\Delta n = 7.5 \cdot 10^{-6}$ . This value is typical of DFB fiber lasers based on standard, i.e. non-PM, fiber, in agreement with the typical residual anisotropy induced by the photo-inscription process [14].

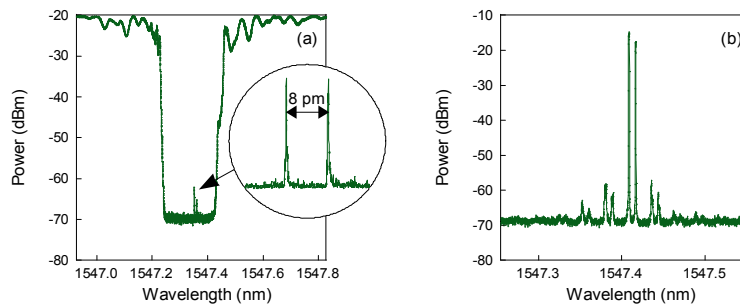


Fig. 2. Optical spectra of sample 1G. (a) Unpumped DFB transmission spectrum. Insert: zoom on the dual-mode structure (linear scale). (b) Laser spectrum showing the two frequencies with a 1 GHz (8 pm) difference; pump power 59 mW (130 mA).

The fiber laser is pumped by a laser diode emitting 145 mW at 980 nm. The pump power at laser threshold is 3 mW and the laser emits at 1547 nm a total output power of 100  $\mu\text{W}$  at

120 mW pumping power. The emitted optical spectrum corresponds to the dual-resonance bands of the FBG, and the frequency difference is measured to be 1.02 GHz at room temperature (Fig. 2(b)). We verify that the two orthogonally polarized optical modes have the same pump threshold and are emitted with quite balanced powers. The PC setting is chosen such that behind the polarizer, the high-bandwidth photodiode detects the dual-polarization beat note. Figure 3(a-b) presents the electrical spectrum of the beat over different spans and resolution bandwidths of the electrical spectrum analyzer (ESA). We verify that pure dual-frequency operation gives the radio-frequency tone at 1 GHz [see Fig. 3(a)]. A zoom in this peak shows the free-running 3 kHz line-width of the beat note [see Fig. 3(b)]. We observe a very stable beat power, with a typical 15% amplitude fluctuation (rms) over a few hours.

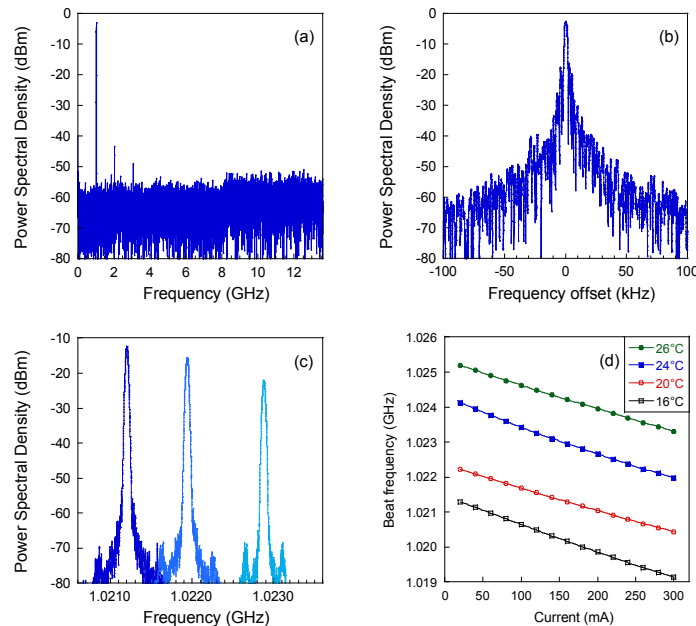


Fig. 3. DFFL beat note at 1 GHz. (a) Span 13.6 GHz, RBW 3 MHz, spurious harmonics due to detection electronics, pump power 114 mW (250 mA). (b) Span 200 kHz, RBW 2 kHz, sweep time 100 ms. (c) Pump-power induced tuning: from right to left 45 mW (100 mA), 94 mW (200 mA), 144 mW (300 mA). (d) Beat note vs pump current at different laser temperatures.

### 3. Optical phase-locked loop

We first investigate the temperature tuning. The DFB fiber laser temperature is controlled by means of a thermo-electric Peltier device. Using the high-resolution OSA, we measure a thermal response of about 4 pm/K for each optical frequency in the 14–30°C temperature range. The beat frequency also depends on temperature. We monitor the beat thermal drift using the ESA, and find that the thermal response depends on the operating point (temperature and pump power). The important point is that, at a fixed pump power, the beat frequency stays within  $\pm 4$  MHz in a  $\pm 5$  K temperature range around room temperature. In laboratory environment, without any temperature control, the drift is thus limited to about 2 MHz over a few hours. Second, we measure tuning characteristics provided by the pump power level. In contrast with the outside temperature control, it appears that the pump power gives a robust and reproducible means to control the beat frequency. Indeed, we find a DC response of the beat frequency to pump current change of  $-7$  kHz/mA, as shown in Fig. 3(c)-(d), quite independently of the laser temperature (linear fits yield slopes between  $-6.7$  and  $-7.3$  kHz/mA). Considering our pump diode, the power-to-frequency tuning curve then has a typical slope of  $-20$  kHz/mW. It follows that pump power variations could be sufficient to counteract the environmental drifts. In the context of a PLL, the laser is a “voltage”-

controlled oscillator (VCO) at the beat frequency, where “voltage” accounts for the pump power. The VCO gain is mainly related to the thermal heating induced by pump absorption. As a result, the VCO effect is expected to be limited in bandwidth. Nevertheless, as will be seen in the following, it allows us to build an efficient PLL.

The optical phase-locked loop is implemented as follows. The 11 GHz-bandwidth photodiode is followed by a DC block, a 3 dB attenuator, and by a 30 dB-gain amplifier. This RF signal is mixed with the local oscillator (LO) provided by a synthesizer at 1 GHz whose output power is 10 dBm. At the mixer output, the error signal feeds a loop filter with proportional gain and integrator stages whose parameters are freely adjustable. The resulting signal is added to the DC current driving the pump diode (see Fig. 1). In our set-up the diode driver has a gain of 0.65 A/V. When the loop is closed, the beat note can be locked. Our loop filter consists in a proportional gain of 23 dB. It is worthwhile to mention that the laser itself acts as an integrator stage since it converts the correction signal into a frequency shift. Figure 4(a) shows the stabilized spectrum. The measured line-width is 1 Hz (Full-Width at Half-Maximum), limited by the resolution bandwidth of our ESA. We measure a 1.5 MHz tracking range. Under our laboratory conditions, the beat then stays locked for days.

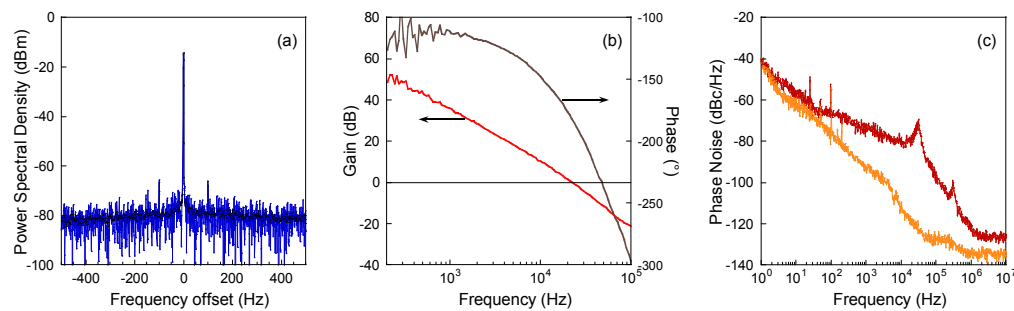


Fig. 4. Locked beat note at 1 GHz. (a) Electrical spectrum (blue, single sweep; black average 10); Span 1 kHz, RBW 1 Hz, VBW 10 Hz, sweep 4.2 s. (b) Open-loop transfer function (red, gain; grey, phase). (c) Phase noise spectra (red, locked beat note; orange, LO). Pump power 92 mW (200 mA).

The open-loop transfer function can be observed from closed-loop measurement using a low-signal network analyzer. This instrument is inserted between the mixer output and the loop filter input. The resulting Bode diagram is shown in Fig. 4(b), giving insight to the low-frequency behavior of the pump-controlled oscillator. The smooth gain decrease is due to the thermal response of the FBG laser, where the non-radiative relaxation of erbium ions in the fiber core is dominant. Indeed, we verified independently that the other loop elements have a flat gain up to at least 200 kHz. Thus the loop bandwidth (unit gain frequency) can be adjusted with the loop proportional gain. Under our experimental conditions, we can push the loop bandwidth (unit-gain frequency) up to 22 kHz. The corresponding phase noise is displayed in Fig. 4(c). We measure a typical  $-65$  dBc/Hz at 100 Hz offset and almost  $-80$  dBc/Hz at 10 kHz offset from carrier. The small bump at around 300 kHz comes from the laser relaxation oscillations. For comparison the orange curve in Fig. 4(c) plots the direct LO measurement. The beat and LO phase noises are almost equal at low frequencies, showing the stabilization and noise reduction effect of the OPLL.

#### 4. Locking at 10 GHz

In this section we briefly discuss the extension to our pump-based OPLL to a dual-frequency fiber laser presenting a higher-frequency beat note. We consider another DFB sample, labeled 10G, that is based on the same glass as sample 1G, but has notable processing differences. The active medium is made with a 50 mm-long erbium-doped fiber, whose cladding diameter is 125  $\mu\text{m}$ , and whose absorption is 11.1 dB/m at 1530 nm. The FBG is photo-induced at 248 nm, its central wavelength is  $\lambda_B = 1533$  nm, its length is  $L_B = 41$  mm, and its strength is  $\kappa =$

$275 \text{ m}^{-1}$ . The resulting calculated effective length is  $L_{\text{eff}} = 3.3 \text{ mm}$ . A  $\pi$  phase-shift is made at 27 mm from the beginning of the grating, leading to mirror intensity transmissions of  $-59 \text{ dB}$  and  $-28 \text{ dB}$ . While the birefringence is of the same order of magnitude as sample 1G, we have observed dual-frequency operation with one frequency at the center of the stop band, as usual, and another at the edge of the stop band, 10.2 GHz apart. The emitted optical spectrum is shown in Fig. 5(a), and the resulting beat note on a 26 GHz window in Fig. 5(b). While the reason for this 10 GHz-beat oscillation is still unclear, we use this sample as a test device for a microwave OPLL based on the pump-power effect.

Laser 10G presents roughly the same pump threshold and output power as laser 1G. An important difference is that the VCO gain is measured to be  $0.5 \text{ MHz/mA}$  in this case, which is much higher than for sample 1G. We then used a low noise, low gain ( $1 \text{ mA/V}$ ) diode driver. We also had to upgrade the mixer and the LO for operation at 10 GHz. Loop filter adjustments then lead to a proportional gain of 35 dB leading to a loop bandwidth of 33 kHz. As in case 1G, the laser beat at 10 GHz can be efficiently captured and locked. The phase noise spectrum is displayed in Fig. 5(c). The close-to-carrier phase noise is limited by the LO, while the intermediate frequency band shows lower phase noise than before, due to the low-noise diode driver. A phase noise plateau is measured at  $-75 \text{ dBc/Hz}$  from 100 Hz to 20 kHz offset from carrier. Finally the tracking range is 4 MHz, which again permits to maintain the beat locked for days, with an instrument-limited 1 Hz measured linewidth.

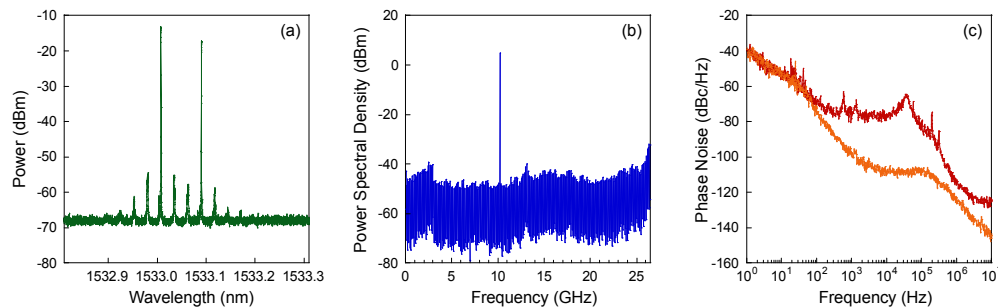


Fig. 5. 10 GHz beat note stabilization. (a) Optical spectrum. (b) Beat note at 10 GHz. (c) Phase noise spectra (red, 10 GHz stabilized beat note; orange, LO). Pump power 41 mW (160 mA).

## 5. Conclusion

Our experiment is a first demonstration of beat note stabilization and low-frequency phase-noise reduction in a dual-frequency DFB erbium-doped fiber laser. We have implemented a simple optical phase-locked loop on a dual-frequency DFB laser that uses the pump power as the laser actuator. Beat notes at 1 GHz and 10 GHz were successfully stabilized on the long-term, with a phase noise as low as  $-75 \text{ dBc/Hz}$  at 100 Hz offset frequency. The method may apply to other compact dual-polarization fiber lasers such as DBR [15-16], PM fiber-based lasers [17], or co-doped Er-Yb DFB lasers [18]. Since the locking mechanism is based on the pump-power to frequency conversion, it could be interesting to study pumping at 1470 nm. Simulation of the fiber thermal behavior with respect to pump power and outside temperature is under investigation.

## Funding

DGA (ANR-16-ASTR-0016); Région Bretagne, FEDER, Rennes Metropole (CPER SOPHIE-Photonique).