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# PHASE-LOCKED DUAL-POLARIZATION FIBER LASERS AS COMPACT OPTICAL-MICROWAVE SOURCES

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**KEYWORDS:** microwave photonics, fiber laser, laser stabilization

## ABSTRACT:

Fully fibered microwave-optical sources at 1.5  $\mu\text{m}$  are 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, that uses the pump-power induced-birefringence as 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. An Erbium-Ytterbium co-doped fiber laser is also investigated. Such dual-frequency stabilized lasers could provide compact integrated components for RF and microwave photonics applications.

## 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 an acetylene 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 2 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 3 is then devoted to the optical phase-locked loop based on

pump-power control. In Section 4 we extend the same principle to a laser emitting a 10 GHz beat note. Preliminary results on  $\text{Er}^{3+}:\text{Yb}^{3+}$ -codoped lasers are presented in Section 5. Finally, conclusions are given in Section 6.

## 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 continuous-wave 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 (SMF) on both sides. All the lasers are pumped at 980 nm on the output coupler side through a standard 980/1550 wavelength-division multiplexer. The laser output is transmitted through an isolator, a polarization controller, 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.

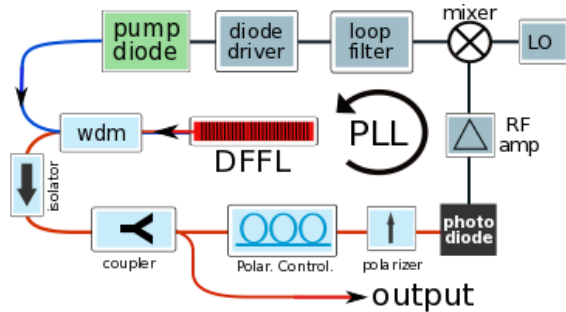


Figure 1. Optical phase-locked loop (OPLL) experimental set-up. DFFL: dual-frequency fiber laser; WDM, pump-signal coupler; LO, local oscillator

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 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 birefringence of the photo-induced 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 (from APEX). As can be seen in Fig. 2, 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 in the structure. 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-polarization maintaining, fiber, in agreement with the typical residual anisotropy induced by the photo-inscription process [14]. Depending on the sample under test, birefringence values between  $6.8 \cdot 10^{-6}$  (0.9 GHz) and  $1.1 \cdot 10^{-5}$  (1.5 GHz) have been found.

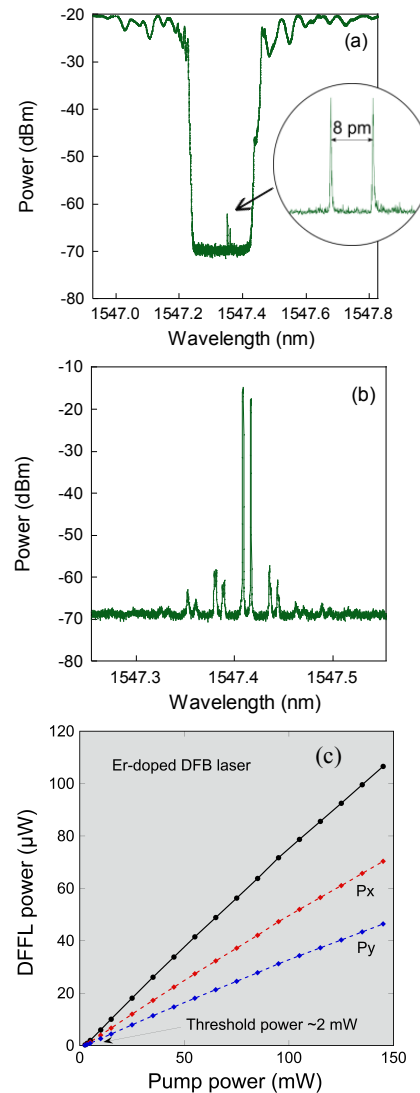


Figure 2. Dual-polarization laser operation. a) Un-pumped DFB transmission spectrum, RBW 0.8 pm. Insert: zoom on the dual-mode structure (linear scale). (b) Laser spectrum showing the two frequencies with a 1 GHz (8 pm) difference (c) Total (black) and polarization-resolved (red and blue) laser power curves.

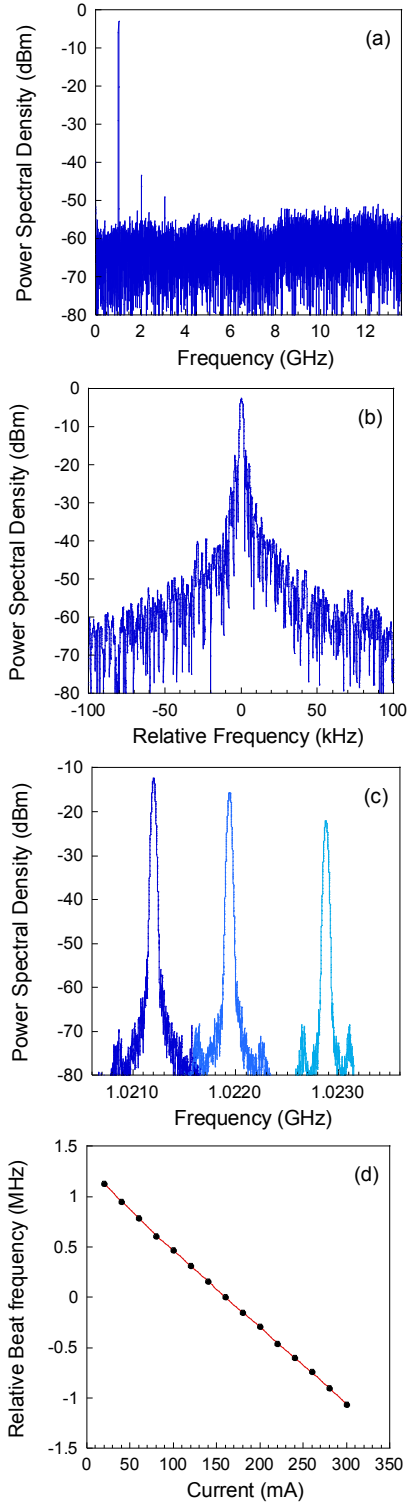


Figure 3. DFFL beat note at 1 GHz. (a) Span 13.6 GHz, RBW 3 MHz, secondary peaks are beat harmonics. (b) Span 200 kHz, RBW 2 kHz, sweep time 100 ms. (c) Pump-power induced tuning: from right to left 45 mW (100 mA), 94 mW (200 mA), 144 mW (300 mA). (d) Beat frequency variation vs pump current (Slope:  $-8$  kHz/mA).

The fiber laser is pumped by a laser diode emitting 120 mW at 980 nm. The pump power at laser threshold is 3 mW and the laser emits at 1547 nm a maximum output power of 100  $\mu$ W. 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. We verify that the two orthogonally polarized optical modes have the same pump threshold and are emitted with quite balanced powers, as shown in Fig. 2(c). Behind the polarizer, the high-bandwidth photodiode then detects the dual-polarization beat note. Fig. 3 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 a single 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)].

### 3. OPTICAL PHASE-LOCKED LOOP

We first investigate the temperature tuning. 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  $-8$  kHz/mA, as shown in Fig. 3(c)-(d). Moreover, we find that this slope is independent of the laser temperature. 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 should be sufficient to counteract the environmental drifts. In the context of a phase-locked loop (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 rather limited in bandwidth. Nevertheless, as will be seen in the following, it permits 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 adjustable proportional gain and integrator stages. 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 acts as an integrator stage since it converts the correction signal into frequency shift. Fig. 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.

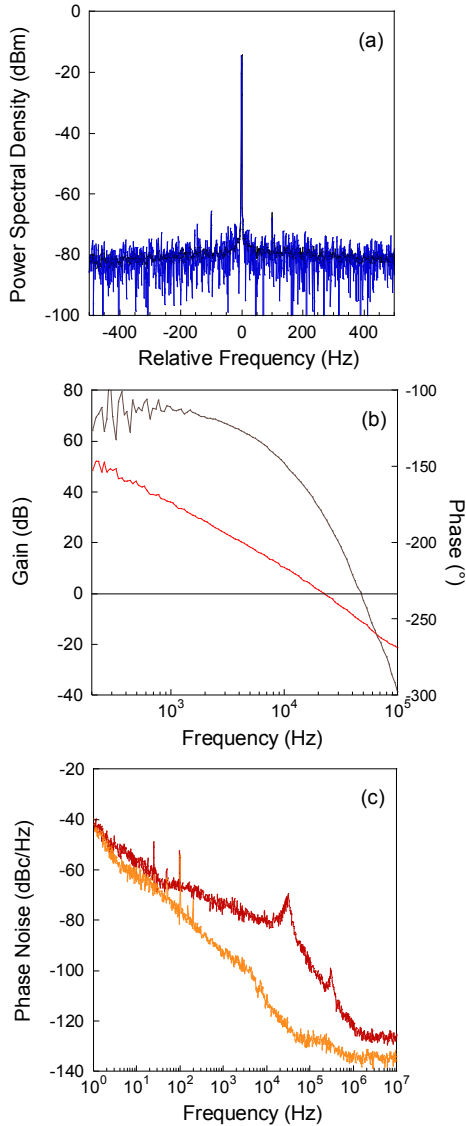


Figure 4. Locked beat note at 1 GHz. (a) Electrical spectrum. (blue, single trace; black average 10) Span 1 kHz, RBW 1 Hz, VBW 10 Hz. (b) Open-loop transfer function (red, gain; grey, phase). (c) Phase noise spectra (red, locked beat note; orange, LO).

The open-loop transfer function can be observed from in-loop measurement using a dedicated low-signal network analyzer (Stanford Research SR780). 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 are 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. For comparison the orange curve in Fig. 4(c) plots the direct OL measurement. Using the measured transfer function from 200 Hz to 100 kHz, one can calculate the free-running beat note phase noise that is also reproduced in Fig. 4(c). This evidences the strong stabilization and noise reduction effect of the OPPL.

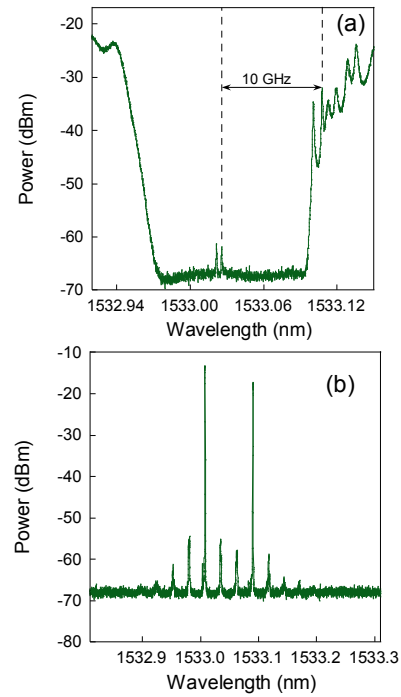


Figure 5. Optical spectrum of sample 10 G. (a) Transmission spectrum (un-pumped). (b) Emitted laser spectrum.

#### 4. LOCKING AT 10 GHz

In this section we briefly discuss the extension to our pump-based OPPL 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  $L_{\text{eff}} = 3.3$  mm. A  $\pi$  phase-shift is

made at 27 mm from the beginning of the grating, leading to mirror intensity transmissions of  $-59$  dB and  $-28$  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 (see the optical transfer function in Fig. 5(a), and the emitted optical spectrum in Fig. 5(b)). The beat note is reproduced in Fig. 6, within a 26 GHz window in Fig. 6(a), and a close-up in Fig. 6(b) showing a kHz-scale free-running linewidth similar to the 1G sample. 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.

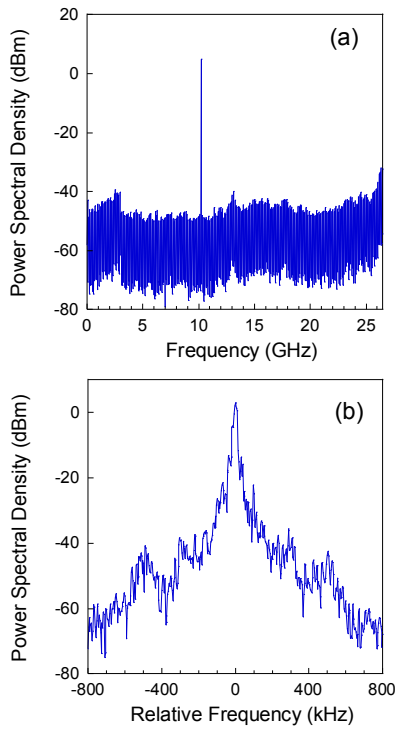


Figure 6. Beat note spectrum at 10 GHz. (a) span 26 GHz, RBW 3 MHz. (b) Span 1.6 MHz, RBW 20 kHz.

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 MHz/mA in this case, which is much higher than for sample 1G. We then used a low noise, low gain (1 mA/V) diode driver (Vescent). We also had to upgrade both mixer and LO for operation at 10 GHz. Loop filter adjustments then lead to a proportional gain of 35 dB.

As in case 1G, the laser beat at 10 GHz can be efficiently captured and locked, as shown in Fig. 7(a). The open-loop transfer function can be observed from in-loop measurement. The resulting Bode diagram is shown in Fig. 7(b), where one can measure an open-loop 50 dB gain at low frequency and a unit-gain frequency of 37 kHz. In these conditions, the phase noise spectrum is displayed in Fig. 7(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  $-75$  dBc/Hz below 20 kHz offset from carrier. Finally the tracking range is 4 MHz, which again permits to maintain the beat locked for days in the laboratory environment.

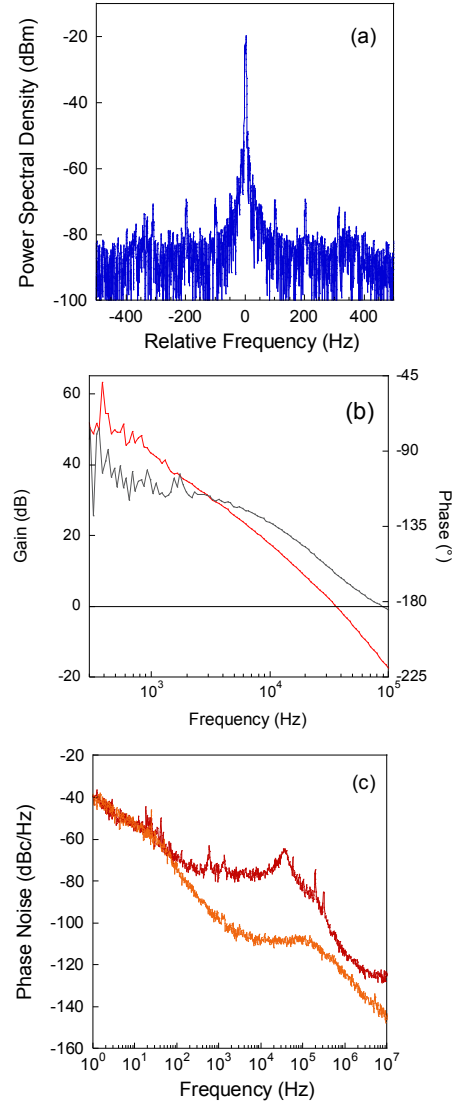


Figure 7. 10 GHz beat stabilization. (a) Electrical spectrum; Span 1 kHz; RBW 1 Hz; VBW 1 Hz. (b) Open-loop transfer function (red, gain; grey, phase). (c) Phase noise spectra (red, stabilized beat note; orange, measurement noise floor).

## 5. Er:Yb DUAL-FREQUENCY FIBER LASERS

As a final part of this conference paper, we present some preliminary results obtained with a DFB fiber laser based on  $\text{Er}^{3+}:\text{Yb}^{3+}$ -codoping.  $\text{Yb}^{3+}$  doping prevents from Er-Er ion clustering, leading to a higher Er doping concentrations without self-pulsing effects, and hence to higher output power [15-17]. The output power of these laser samples is in the 10 mW range (to be compared to 100  $\mu\text{W}$  for the erbium-doped lasers described above). Fig. 8 shows that the output power is well balanced between the two orthogonally polarized modes.

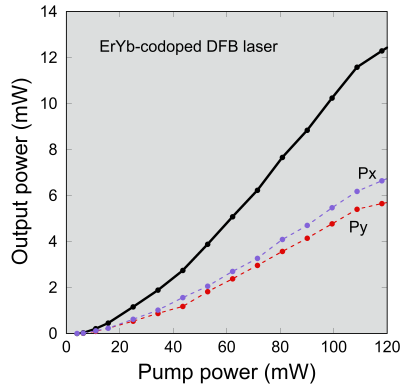


Figure 8. Total (black) and polarization-resolved (red and blue) laser power curves.

We find experimentally that the laser emission spectrum consists in orthogonally polarized lines separated by 2.4 pm (0.3 GHz). Lower birefringence than sample 1G may be due to different sample compositions. For example, Fig. 9 shows the beat note spectrum at 300 MHz and its tuning curve via the pump power. At the time of publication, the corresponding optical phase-locked loop is under completion.

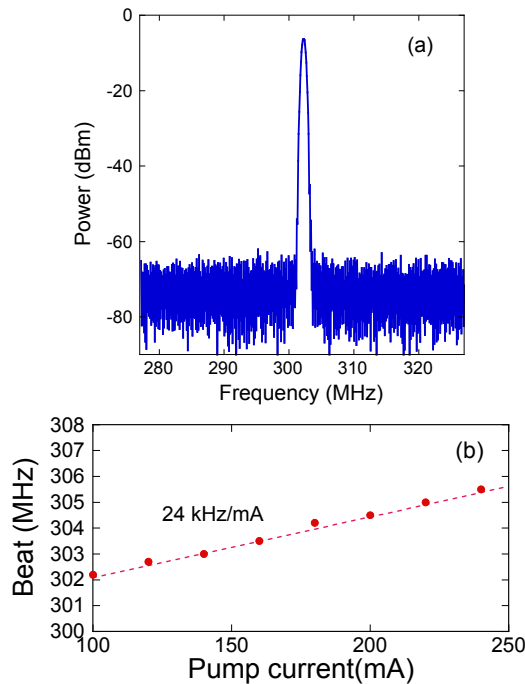


Figure 9. Er:Yb-DFFL beat note at 300 MHz. (a) Span 50 MHz, RBW 3 MHz, (b) Pump-power induced tuning.

## 6. CONCLUSION

Our experiment is a first demonstration of beat note phase-noise reduction in dual-frequency DFB erbium-doped lasers. We have implemented a simple optical phase-locked loop on dual-frequency DFB lasers 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  $-75$  dBc/Hz at 100 Hz offset frequency. The method may apply to

other compact dual-polarization fiber lasers such as DBR structures [18-19] or polarization-maintaining fiber-based lasers [20]. Since the locking mechanism is based on the pump-power to signal frequency conversion, it could be interesting to compare 976 nm and 1470 nm pumping bands. Such dual-frequency stabilized lasers could provide all-fibered and integrated components for microwave photonics applications.

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