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Hybrid opto-electronic oscillator for single-sideband microwave photonics.

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ABSTRACT: We demonstrate a single-sideband opto-RF oscillator, based on a monolithic InGaAsP chip containing two DFB lasers. The heterodyne signal is stabilized by a hybrid method, combining optical and electronic feedback. It leads to a locking of the beating frequency onto a filtered version of itself. Our table-top setup provides a phase noise level down to -75 dBc/Hz at 1kHz offset from a 10 GHz carrier. Potential phase noise improvement and integration scheme in a single component are discussed.

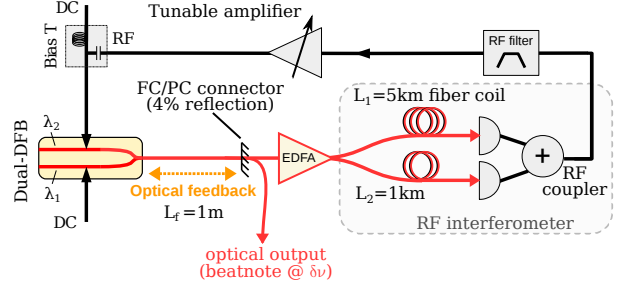


FIG. 1. Experimental setup.

INTRODUCTION

Optically carried single-sideband microwave sources are a key requirement in many microwave photonics system, as they are not sensitive to dispersion fading in long fiber links [1]. They can be generated by miscellaneous methods, such as, e.g., optical filtering [2], “period-one” dynamical effects in lasers [3] or optical heterodyning [4]. This last technique by which two optical frequencies beat on a photodetector, allows arbitrary RF frequencies and a 100% modulation depth. But it also requires the frequency difference to be somehow stabilized, as each laser will experience different environmental fluctuations. Recently, we have proposed a method based on optical feedback applied to a monolithic DFB laser [5]. It relies on the ability of a semiconductor laser to synchronize its phase with an injected field [6]. It was shown that this property can be used in a configuration similar to opto-electronic oscillators (OEO) [7], where the beatnote is locked on itself after propagation along an optical delay line. Yet, the long-term stability of this setup was not satisfactory, as it could randomly switch between different resonances of the closed optical delay line, on a typical timescale of a few minutes. Here we propose a more compact setup that allows to overcome the mode-hopping issue, and paves the way to integration into a single photonic chip.

EXPERIMENTAL SETUP

The two laser beams are provided by a custom-made InGaAsP chip containing two DFB lasers operating at

wavelengths λ_1 and λ_2 around $1.5 \mu\text{m}$. Such monolithic dual-DFBs, detailed in Ref. [8], have proven to be efficient for heterodyning, as the lasers are identical by design and experience almost the same frequency drifts caused by environmental fluctuations. The frequency difference can be controlled by the two pump currents from quasi-DC up to tens of GHz. We choose here to operate at a frequency difference $\delta\nu = 10$ GHz. Additionally, the pump current of one laser can be modulated with a RF signal, superimposed on its DC input by a bias tee (as shown on Fig.1). The modulation bandwidth of the laser has been measured to be about 14 GHz at -3 dB cutoff frequency.

The lasers are combined by an on-chip -3 dB coupler, and the output is then injected into a $L_f = 1$ m-long microlensed single-mode fiber, in which around $500 \mu\text{W}$ of power can be coupled. This fiber is connected to a flat FC/PC connector, leading to a 4% optical feedback into the lasers. The rest of the signal goes through two optical paths of different lengths ($L_1 = 5$ km and $L_2 = 1$ km), and each of them ends on a Nortel PP-10G photodiode. The RF signals are recombined by a directional RF coupler. Thus, the summation of the two delayed signals acts as a RF interferometer, with very selective phase resonances. This technique has been proven to be very efficient for reducing spurious phase noise resonances in standard OEOs [9]. It has also been used as an opto-microwave frequency discriminator in actively stabilized of dual-frequency lasers [10].

The resulting signal is then filtered by a 80 MHz BW bandpass filter (Lorch, model CF7), centered at 10 GHz. After an amplification stage, it is fed back into the RF input of one of the lasers, generating small modulation

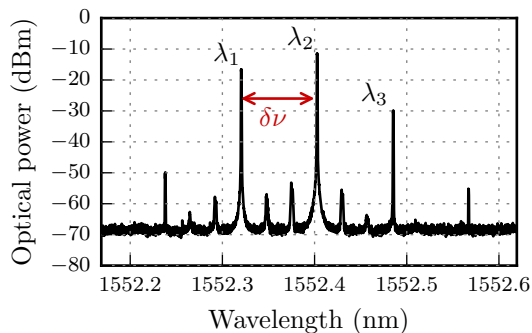


FIG. 2. Output optical spectrum, monitored by an optical spectrum analyser (OSA). The output signal is the beatnote at frequency difference $\delta\nu = 10$ GHz.

sidebands, i.e., lower than -20 dB around λ_2 . Owing to the optical feedback, these modulation sidebands lead to mutual optical injection between the two lasers, which causes their optical phases to lock, thus stabilizing their frequency difference. A typical output optical spectrum is reported in Fig. 2. The three main peaks correspond to the emission at λ_1 and λ_2 , and to one modulation sideband of DFB2 respectively (the other sideband being coincident with the optical frequency λ_1 of DFB). We point out that the residual peaks at level < -55 dBm are spurs caused by the detection setup (OSA Apex 2083A).

If the output signal is submitted to dispersion fading, for instance in a long fiber link, the presence of a third optical wavelength λ_3 will not deteriorate significantly the quality beatnote modulation, as the amplitude level of this wavelength is 15 dB below that of λ_2 . Indeed, the beating between λ_2 and λ_3 may interfere destructively with the beating between λ_1 and λ_2 , but a straightforward calculation shows that the modulation depth reduction is expected to be less than -1.6 dB.

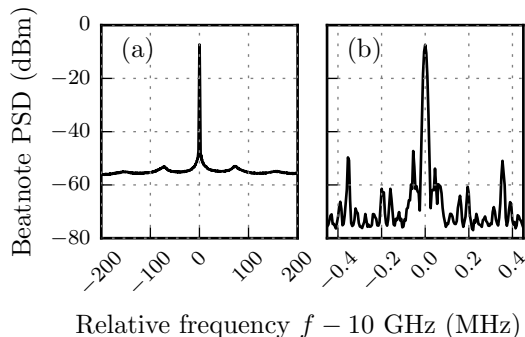


FIG. 3. Experimental RF spectrum with two different spans. (a) RBW = 1 MHz, (b) RBW = 10 kHz

STABILITY

We measure the RF spectrum at the output of a Discovery 401HG photodiode. Without any stabilization, the beatnote linewidth is 600 kHz [8]. When the optoelectronic loop is closed, the linewidth is dramatically reduced to less than 100 Hz. A look at the electrical spectrum on Fig. 3 shows a 40 dB rejection between the carrier and the surrounding spurs. Under our laboratory conditions, the beatnote remains stabilized for hours.

On the largest span (Fig. 3a), it can be noted that external cavity modes, linked to the delay introduced by the optical feedback, and expected to be seen at $1/\tau_f = c/2nL_f = 75$ MHz are completely filtered out by the commercially-available RF filter. This removes the possibility for mode hopping on another external cavity mode, and contributes to a greater frequency stability compared to a stabilization scheme with a longer optical feedback [5]. The smaller span of Fig. 3b shows the filtering effect of the dual-loop setup, as resonant frequencies from the two RF delays, respectively at 40 kHz and 200 kHz contribute to residual spurs at a level lower than 40dB from carrier.

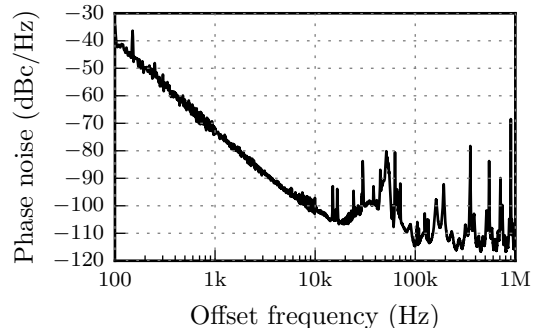


FIG. 4. Measured phase noise of the RF beatnote

PHASE NOISE PERFORMANCES

Electrical phase noise of the RF signal was measured using a Rohde & Schwarz FSVP, and is presented on Fig. 4. It reaches less than -70 dBc/Hz at 1 kHz offset from the carrier. Above 20 kHz, sharp spurious resonances associated with the RF delays can be seen, but the two-coils RF interferometer scheme allows to keep the phase noise below -75 dBc/Hz. This is a strong improvement compared to the single-coil scheme, which features peaks up to -50 dBc/Hz. Cautious engineering, based on a precise characterization of the noise sources, could be done to tune the length of the fibers and reduce this value by a few dBc/Hz [11]. At low frequencies, better phase noise performances would be reached by implementing

techniques found in standard OEO, such as additional feedback loops and temperature control on the fibers.

CONCLUSION

We have presented an efficient way to self-stabilize the frequency difference between two DFB lasers, combining optically injected semiconductor lasers and techniques commonly found in OEO designs, such as the dual RF-loop scheme.

At variance with [5], we did not use any intensity modulator nor optical amplifier, thus reducing drastically the length of the optical feedback loop and preventing mode-hopping of the oscillator. We have shown that the use of current modulation does not have an important impact on the amplitude of the generated RF signal, inducing only negligible dispersion fading.

The ability to shorten the optical feedback path opens interesting perspectives towards an integrated self-stabilized heterodyne oscillator. Further miniaturization would require optical components with more integrated features. Preliminary work has already been done in this direction [12]. Finally, an all-integrated setup would benefit from much more compact optical delay lines, such as optical microresonators.

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