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Photonic microwave oscillator based on monolithic DFB lasers with frequency-shifted feedback

L. Wang, M. Romanelli, F. Van Dijk and M. Vallet

A photonic oscillator, locked to a master RF synthesiser, was built by using a monolithic dual-wavelength DFB semiconductor laser submitted to a frequency-shifted optical feedback. A [3; 10] GHz tuning range is reported, with a phase noise level lower than -70 dB rad^2/Hz at a 10 Hz offset from the carrier.

Introduction: The potentialities of optical heterodyning for photonic oscillators are now firmly established [1], the optically carried microwave being provided by the beat note between two laser modes. Active phase locking to a microwave local oscillator (LO), by means of analogue [2] or digital [3] phase-locked loops, has been shown to transfer the spectral purity of the LO to the beat note. However, such architectures inherently need a way to tune the frequency difference electronically. Conversely, optical injection locking schemes are free from electronics and it has been recently proved that dual-frequency erbium (Er^{3+})-doped lasers can be locked to an external LO by using an optical feedback frequency-shifted with a Bragg cell [4]. However, optical injection in rare earth lasers presents a small locking range. Since semiconductors are well known to be sensitive to injection with a large locking range [5], we choose here to use DFB lasers. Moreover, the use of a Bragg cell for a single-side-band modulation limits the frequency to below the gigahertz range [4]. We thus propose in this Letter to submit the DFB to an intensity modulated optical feedback by using an electro-optic modulator (EOM), in order to benefit from the bandwidth (BW) of EOMs.

Experimental setup: The optical source at $1.55 \mu\text{m}$ is similar to the one described in [6]. It consists of two 2.5 mm-long DFB semiconductor lasers grown on the same wafer (see the inset of Fig. 1). The lasers are electrically pumped by two current sources, so that both frequencies ν_1 and ν_2 can be tuned independently using the bias currents I_1 and I_2 . The two output beams are coupled by a -3 dB coupler providing a 7° angled output to reduce back reflections, followed by a lens fibre and a 20/80 coupler. The 26 m-long feedback loop contains a Mach-Zehnder intensity modulator (EOM, BW = 10 GHz) driven by a synthesiser which provides a frequency reference f_{LO} . Next, an erbium-doped fibre amplifier (EDFA, 30 dB gain) and a programmable attenuator (from 0 to -60 dB) allow controlling the feedback power. An optical circulator closes the loop. The power sent back to the DFBs is monitored from one output of the coupler. The other output provides the useful output beam, whose beat note is analysed by an InGaAs photodiode (40 GHz BW) followed by an electrical spectrum analyser.

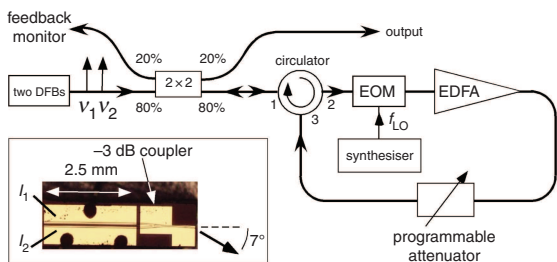


Fig. 1 Schematic of setup (see text for details)

Results: The typical power coupled into the fibre is 1 mW. In the free running regime, the frequency difference $\Delta\nu = \nu_1 - \nu_2$ is finely tunable from 0.3 up to 15 GHz by sweeping the bias current of one DFB section from 230 to 440 mA, whereas the other is biased at a constant current of 200 mA. It is important to note that $\Delta\nu$ is much more stable than ν_1 and ν_2 , since the two lasers share the same temperature fluctuations on the chip. The -3 dB linewidth of the beat note is 630 kHz for typical bias currents that are, respectively, 320 and 194 mA, as shown in Fig. 2a.

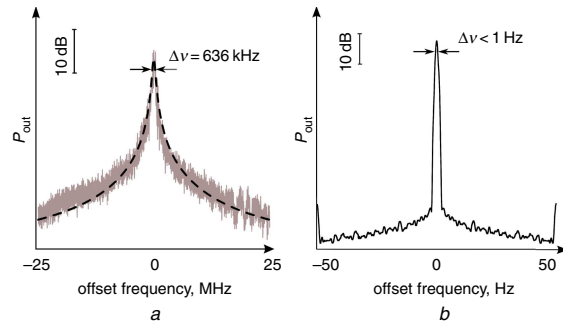


Fig. 2 Beat note RF spectra

Solid line: measured data; dashed line: Lorentzian fit
 a Free running, RBW: 30 kHz, span: 50 MHz
 b With feedback, RBW: 1 Hz, span: 100 Hz

When the optical feedback loop is closed, if the reinjected light is sufficient, the beat note locks to f_{LO} . In this case, the -3 dB linewidth of the beat note is measured to be equal to 1 Hz, with the instrument limited (see Fig. 2b). Furthermore, the laser remains stable and locked for several hours. The beat note can be locked from 3 to 10 GHz. The lower boundary is set by the relaxation oscillation frequency that are known to destabilise injection locking [5], and the upper one is fixed by the BW of the electronic amplifier for the EOM. In the experiments described below, we chose the frequency of the beat note at 7.3 GHz.

Fig. 3 reports the locking range against the feedback level η . The latter is defined as the ratio of the amplitude of the feedback optical field with respect to the laser output optical field. We observe that when the feedback level goes from 0.02 to 1.2, the locking range increases linearly, as in the master-slave injection locking. Moreover, a locking range as large as 1 GHz can be demonstrated. For low feedback levels, the locking range is typically of several tens of megahertz. The modulation depth of the EOM was independently measured to be equal to 80%. At variance with experiments using pure frequency-shifters [4], a certain amount of self-injection is unavoidable in our setup. Namely, not only the frequencies $\nu_1 \pm f_{LO}$, $\nu_2 \pm f_{LO}$, but also ν_1 and ν_2 are reinjected. Yet, our experiment shows that, at least in the explored range of parameters, self-injection does not seem to play an important role.

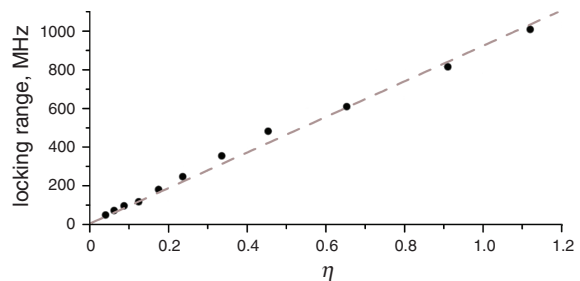


Fig. 3 Measured locking range with different feedback levels

Dots: measured data; dashed line: linear fit

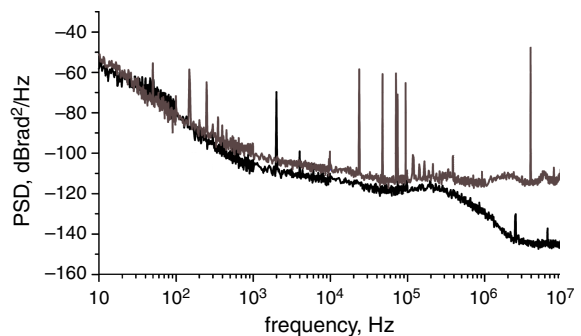


Fig. 4 Measured phase noise spectra

Grey: photonic RF oscillator; black: noise floor

To characterise the spectral purity of the photonic oscillator, we have measured the phase noise spectrum in the locking regime. As shown in

Fig. 4, it coincides with the noise floor of the detection at low frequency, showing that our oscillator has a better stability than the available measurement apparatus. The phase noise is thus lower than -70 dBc/Hz at 10 Hz from the carrier. To check the insensitivity of the locking to the length of the loop, we inserted a delay line (700 m, $\tau = 3.5$ μ s) in the feedback loop. We could hardly measure a difference between these two cases.

Conclusion: We have demonstrated a photonic oscillator based on monolithic DFB semiconductor lasers, driven by a master microwave synthesiser. The oscillator is stable, finely tunable and displays a large locking range and a low phase noise level. Our scheme could be extended to the millimetre-wave frequencies [7] by using, for example, an inloop fast EOM or harmonics from a nonlinear modulator [8].

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One or more of the Figures in this Letter are available in colour online.

L. Wang, M. Romanelli and M. Vallet (*Institut de Physique de Rennes, UMR Université de Rennes 1 – CNRS 6251, Campus de Beaulieu, 35042 Rennes Cedex, France*)

E-mail: marc.vallet@univ-rennes1.fr

F. Van Dijk (*III-V Laboratory, a Joint Lab of Thales Research and Technology, Alcatel-Lucent Bell Labs France and CEA Leti, 91767 Palaiseau Cedex, France*)

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