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Optoelectronic Oscillator Using Injection-Locked VCSELs

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Optoelectronic oscillators (OEOs) producing signal frequencies in the radio frequency (RF) regime with very low phase noise are crucial for applications such as microwave frequency standards, radars, RF photonics and optical signal processing [1]. Recently, Yao and Maleki demonstrated a novel OEO configuration using a CW laser, a high-speed external modulator, a fiber loop and high-speed photodetector. The CW laser is coupled into the external modulator and fiber loop, which is detected by the high-speed photodetector. The detected RF signal is amplified and fed back to the modulator. Provided with high enough RF amplification, this configuration results in an RF oscillator with a long, but low-loss cavity length, formed by the fiber loop [2]. The long fiber loop resulted in a high-Q cavity, leading to very low phase noise. However, in this configuration, a very high gain (60 dB) RF amplifier chain is necessary to reach the oscillation threshold. The RF amplifiers and external modulator present an upper limit of the RF signal frequency; it is challenging to achieve > 10 GHz oscillation. Optical injection-locked (OIL) VCSELs have been demonstrated to exhibit high speed frequency response (~ 50 GHz) and large tunability of the resonance peak under direct modulation [3]. In addition, the red-shifted OIL VCSEL cavity amplifies the modulation sideband, which enhances the modulation efficiency at the resonance frequency [4]. In this paper, we propose a novel OIL OEO leveraging the high frequency and high gain resonance peak of an OIL VCSEL, and we also demonstrate a pure RF signal at 20 GHz with phase noise performance 20 dB better than a commercial RF synthesizer.

The experimental setup is shown in Fig. 1. A 1.55-μm VCSEL is injection-locked by a DFB laser through an optical circulator. Polarization controller is used to match the polarization of the DFB and the VCSEL. The VCSEL is coupled through a lensed fiber, which gives coupling efficiency about 70%. 1% of the output light goes in to an optical spectrum analyzer (OSA) to monitor the locking condition, while 99% of the output runs through a long fiber loop and is delivered to a photodetector. After going through an RF filter centered at 20 GHz and an RF amplifier, the detected RF signal is subsequently fed back to modulate the VCSEL via a bias Tee. Half of the RF signal is tapped off as the output for characterization.

Open-loop RF characteristic of the OIL OEO is studied first based on various injection locking parameters to determine the appropriate operating condition. The OIL VCSEL is directly modulated by an external RF synthesizer at a single tone frequency of 20 GHz. The output of the loop is analyzed with no OEO feedback applied to the laser. Under strong injection, when the master laser is tuned towards the long wavelength side, the slave laser cavity mode is more suppressed [4], as shown by the top figure of Fig. 2a. This results in a more stable locking condition, but lower RF gain or amplification at the resonance frequency. As the master wavelength is tuned towards short wavelength, the slave laser cavity mode is less suppressed, as shown by the bottom figure of Fig. 2a. The wavelength detuning monotonically translates into cavity mode suppression ratio (CMSR), defined as the power ratio between the OIL mode (master mode) and the slave laser cavity mode. The transfer function of the open loop link at 20 GHz is shown in Fig. 2 (b) for various CMSR conditions. The larger the CMSR is, the more stable the

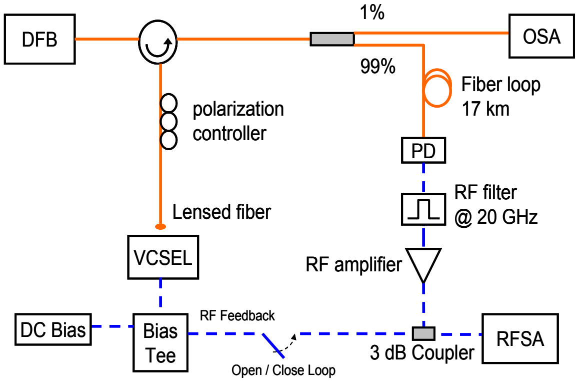
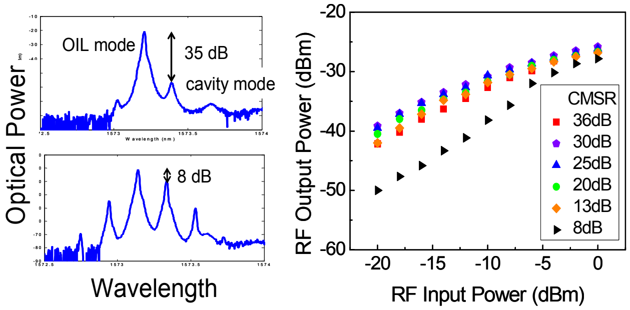


Fig. 1. Experimental setup (OSA: optical spectrum analyzer, PD: photodetector, RFSA: RF spectrum analyzer). Solid lines: optical path, dashed lines: electrical path.



(a) (b)

Fig.2. Open-loop characteristic. (a) Optical spectra at locking conditions with CMSR 35 dB and 8dB (b) Transfer function of the open-loop link at various CMSR values. The slave laser is modulated by a single tone corresponding to the spacing between the OIL mode and the cavity mode externally.

1-4244-0925-X/07/$25.00 ©2007 IEEE

locking and the lower the RF gain. A stable locking condition (high CMSR) is desirable to achieve high signal purity as the beating noise is reduced. However, high gain from the high cavity mode (low CMSR) will help reduce the gain required from the RF amplifier to reach oscillation threshold in the loop. So there exhibits a trade-off between low phase noise and low RF gain simultaneously. The detuning should be adjusted to obtain an optimal CMSR. Two optical spectra are shown in Fig. 2(a) indicating two extreme cases with CMSR of 35 dB and 8 dB. As can be seen, when the CMSR is 8 dB, strong four-wave mixing occurs and the VCSEL is no longer locked to the master laser. This manifests itself on the transfer function as a drop of the RF gain. From Fig. 2(b), CMSR about 30 dB is a good operating condition.

Once the locking condition is selected, the loop is closed to generate the RF signal. Figure 3 shows the open- and closed-loop optical spectra. The cavity mode is enhanced dramatically after the loop is closed indicating oscillation is achieved. The phase noise measurement is shown in Fig.4. Comparing with a 20-GHz signal generated by an HP 83650B synthesizer, the phase noise of the 20-GHz signal produced by an OIL OEO using VCSEL is 23 dB lower at 3-kHz offset and 21 dB lower at 5-kHz offset. To achieve good phase noise performance, long fiber loop, 17 km, is employed since the phase noise is inversely proportional to the square of the loop length [2]. However, this long fiber loop will result in a very small free spectra range, which in turn introduces numerous spurious tones and mode competition. The sharp increase of the phase noise close to 10-kHz offset in Fig. 4 is due to the adjacent mode from the fiber loop. To reduce the mode competition thus stabilizing the tone, an RF filter centered at 20 GHz with 20 MHz bandwidth is used. This helps to stabilize the signal, but also limits the frequency tunablity of the signal. An RF amplifier with 45-dB gain is also employed in the link. Since the interest is focused on the signal stability and purity, the RF amplifier is not optimized for the minimum gain operation. Figure 5 shows the RF spectra of the OIL OEO generated and HP 83650B generated signal at 20 GHz with 10 kHz span. This is consistent with the phase noise measurement showing a 20 dB lower noise floor within 5-kHz offset from the center frequency.

It should be mentioned that all experiments are done without a temperature oven or frequency stabilized master laser, which may be used to further improve the phase noise performance.

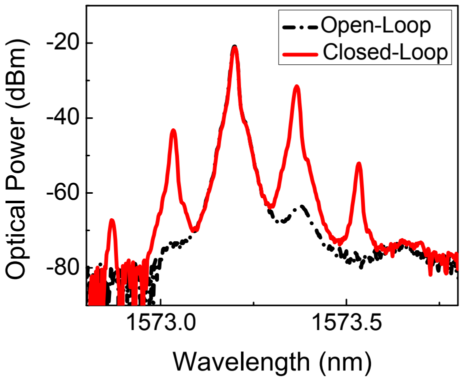


Fig. 3. Optical spectra when the loop is open (black dash) and closed (red solid)

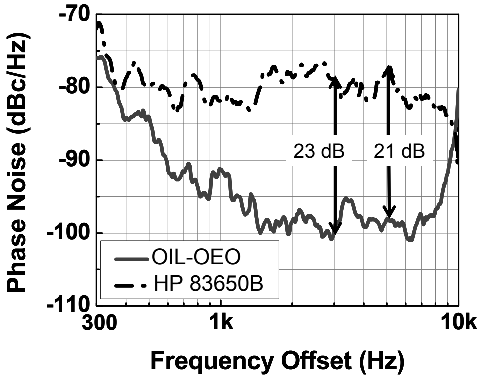


Fig. 4. Measured phase noise of an OIL-OEO generated signal and an HP 83650B generated signal, both centered at 20 GHz. The improvement OIL OEO is > 20 dB.

Acknowledgement

We would like to thank Professor Markus C. Amann and Werner Hofmann for providing us the VCSELs, and DARPA aPropos program for funding us under contract # W911NF-06-1-0269.

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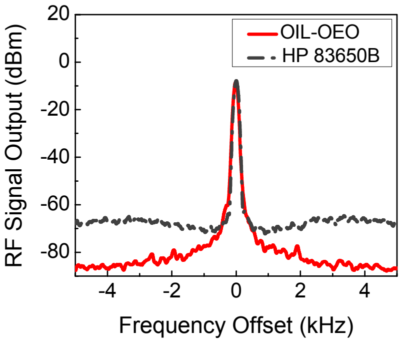

Fig. 5. RF spectrum of an OIL OEO generated signal and an HP 83650B generated signal, both centered at 20 GHz.