Optically Injection-Locked Optoelectronic Oscillators with Low RF Threshold Gain

Hyuk-Kee Sung, Erwin K. Lau, Xiaoxue Zhao, Devang Parekh, Connie J. Chang-Hasnain and Ming C. Wu
Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720
hyukee92@eecs.berkeley.edu

Abstract: We experimentally investigate the optical and RF characteristics of optically injection-locked optoelectronic oscillators. With strong optical injection and optimized frequency detuning, we have achieved a very low RF threshold gain of 7dB for optoelectronic oscillation.

OCIS codes: (140.3520) Lasers, injection-locked; (230.4910) Oscillators

Optoelectronic oscillators (OEOs) can generate high-purity RF signals with very low phase noise [1]. The application covers a wide area of photonic and RF systems such as microwave frequency standards, radars, RF photonics and optical signal processing [2]. Excellent performance has been demonstrated at X-band (10 GHz). Conventional OEOs employ lithium niobate modulators. They have two potential drawbacks: RF amplifiers with high gain (up to ~ 60 dB) are needed to compensate the RF link loss of the feedback loop; and high frequency operation is challenging. Direct modulation of semiconductor lasers under *strong* optical injection locking offers an attractive alternative for OEOs because of their superior high frequency performance [3]. Enhanced resonance frequency as high as 72 GHz has been demonstrated experimentally [4]. In addition, the high modulation efficiency at resonance could alleviate the need for RF amplifiers. A tunable microwave source has been demonstrated using semiconductor laser dynamics [5]. In this paper, we investigate the RF and the optical properties of a 15-GHz OEO with an optical injection-locked semiconductor laser source. The amount of RF gain required to reach oscillation (threshold gain) is greatly reduced by the enhanced resonance. By employing strong optical injection and optimized frequency detuning, we have achieved a very low RF threshold gain of 7 dB.

Figure 1 shows the experimental setup of the optically injection-locked OEO. First, we characterize the modulation properties of the slave laser at resonance in the open-loop condition. We used an external cavity tunable laser (ECTL) followed by an erbium-doped fiber amplifier (EDFA) as the master laser, and a 1550-nm distributed feedback (DFB) laser as the slave laser. The injection-locking parameters were adjusted such that the enhanced resonance frequency is 15 GHz. Figure 2 shows the RF transfer curve of the slave laser link for various frequency detuning ($\Delta f = f_{master} - f_{free\text{-}running\ slave}$) from -50 GHz (●) to -15 GHz (■). The injection ratio is fixed at 7 dB. The slave is modulated at its enhanced resonance frequency via a RF source. At large negative detuning (Δf = -50 GHz), linear modulation with unity slope in the transfer curve is observed. As Δf increases (i.e., less negative), the RF link gain increases and the modulation becomes nonlinear. The RF link gain is a strong function of the optical power in the cavity mode. Fig. 3 shows the cavity mode power ratio (CMPR) versus the frequency detuning (injection ratio = 1dB and RF gain = 23 dB). Without OEO feedback, the CMPR increases steadily with Δf across the locking range. With OEO feedback, the CMPR exhibits a quantum jump at Δf = -18.7 GHz (■ in Fig. 3), indicating the OEO has reached oscillation threshold.

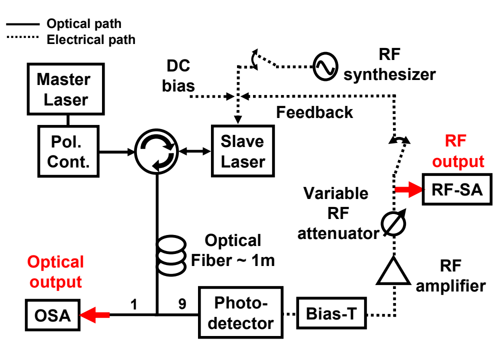

Fig. 1. Experimental setup for measuring RF modulation and feedback properties of injection locked system. (Pol. cont.: polarization controller; OSA: optical spectrum analyzer; RF-SA: RF-spectrum analyzer)

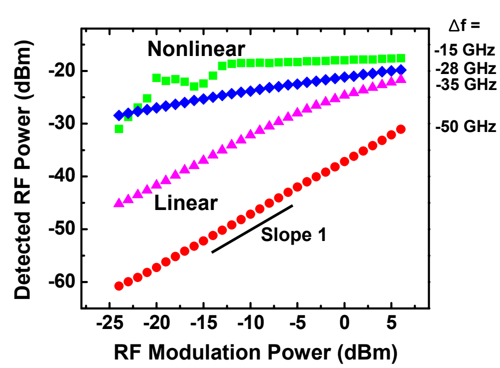

Fig. 2. RF power vs. RF modulation power for various frequency detuning values

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We have also measured the RF threshold gain of the OEO as a function of Δf, as shown in Fig. 4, for an optical injection ratio of 2 dB. The RF threshold gain is defined as the minimum RF gain needed to achieve oscillation. The threshold gain decrease as Δf is tuned towards positive detuning, where the enhanced resonance is stronger. The minimum threshold gain of 7 dB is obtained at Δf = -13 GHz.

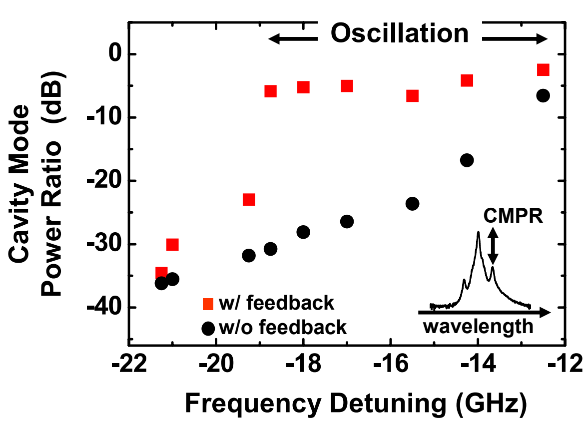

Fig. 3. Normalized cavity mode power vs. frequency detuning with and without OEO feedback. The OEO starts to oscillate at Δf = -18.7 GHz.

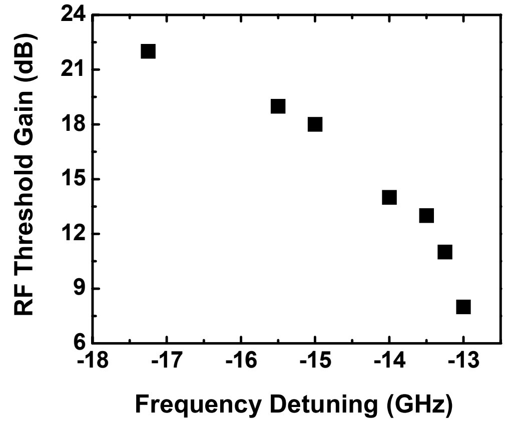

Fig. 4. RF threshold gain as a function of frequency detuning. The lowest threshold of 7 dB is attained at Δf = -13 GHz.

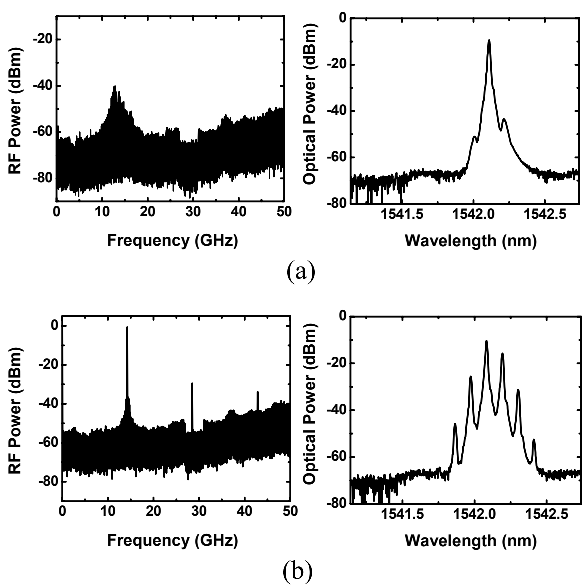

Fig. 5. Optical and RF spectra of the optical injection-locked OEO with feedback: (a) below threshold; and (b) above threshold.

Fig. 5(a) shows the optical and RF spectra of the OEO below threshold (injection ratio = 1 dB, RF gain = 23 dB, Δf = -21.25 GHz). A broad hump was observed in the RF spectrum and the cavity mode in the optical spectrum is greatly suppressed (CMPR = -34.6 dB). Fig. 5(b) shows the corresponding spectra of the OEO above threshold (RF gain = 23 dB, Δf = -18 GHz). A stable RF peak was observed at 14.25 GHz. The harmonic and other spurious peaks can be suppressed by adding a narrow bandpass filter in the OEO loop. The optical power in the cavity mode is significantly higher (CMPR = -5.2 dB). Other peaks in the optical spectrum were due to four-wave mixing in the slave lasers.

In conclusion, we have investigated the modulation and feedback properties of the strongly optical injection-locked laser. The RF threshold gain of the resulting optoelectronic oscillator is a function of frequency detuning. A minimum threshold of 7 dB was achieved in this experiment. Further optimization could potentially eliminate the RF amplifiers in the OEO, greatly reducing its power consumption.

Acknowledgment

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