Dual-Loop Dual-Modulation Optoelectronic Oscillators With Highly Suppressed Spurious Tones

Jae-Young Kim, Jun-Hyung Jo, Woo-Young Choi, and Hyuk-Kee Sung

***Abstract*— We successfully demonstrate an optoelectronic oscillator (OEO) low radio-frequency- (RF)-threshold gain and a low level of spurious tones using semiconductor lasers under optical injection in dual fiber-loop configuration. Our 15-GHz OEO exhibits spurious tones suppressed over 70 dB by dual-loop modulation, maintaining a low RF-threshold gain of 27 dB and phase noise of 104 dBc/Hz at 10-kHz frequency offset.**

***Index Terms*— Dual-loop modulation, optical injection locking, optoelectronic oscillator (OEO).**

I. Introduction

OPTOELECTRONIC oscillators (OEOs) have been widely investigated for both optical and RF applications since they provide low phase noises in the high frequency range beyond X-band [1]-[3]. Their superior phase noise performance is achieved with long loop delay through inherently low-loss optical fiber that results in high quality (Q) factor [2], [3]. However, the long fiber loop produces spurious tones which limit OEO applications. Several approaches such as dual-loop OEO [4], [5], coupled OEO [6], and injection-locked OEO [7], [8] have been reported that tried to reduce OEO spurious tones. These approaches are based on the conventional OEO configuration in which optical signals are modulated with an external optical modulator, and high-gain electrical amplifiers are required for link loss compensation.

Recently, we demonstrated an OEO having low threshold gain for loop oscillation by utilizing the resonant effect in the semiconductor laser under strong optical injection [9]. This OEO has reduced threshold gain since optical single sideband (SSB) modulation under optical injection can greatly enhance the laser modulation efficiency [10-12]. A 20-GHz OEO with phase noise of −123 dBc/Hz at 5-kHz frequency offset and 7-dB RF threshold gain was achieved without sophisticated frequency or temperature stabilization [9]. Although our OEO does not need any high-speed modulator nor any high-gain electrical amplifier, spurious tones produced by the long fiber loop necessitate the use of an high-Q electrical bandpass filter (BPF).

In this letter, we demonstrate a new OEO configuration in which optical SSB modulation of an optically-injected semiconductor laser is used in a dual-loop configuration. The new OEO configuration can simultaneously achieve low threshold gain, low phase noise, and low spurious tones. For our demonstration, we realized a 15-GHz OEO with RF threshold gain of 30 dB, phase noise of −104 dBc/Hz at 10-kHz frequency offset, and spurious tone suppression over 70 dB.

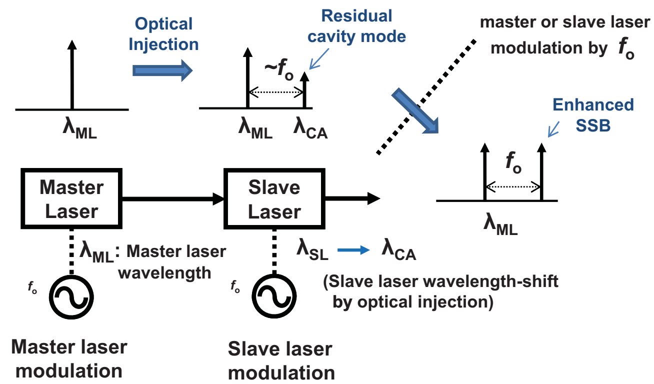

Fig. 1. Operation principle of optically injected single-sideband modulation. Master and slave LDs are modulated with the same RF signal to achieve dual-loop (see Fig. 2) configuration. LD: laser diode.

II. Operating Principles

Figure 1 shows the optical single sideband modulation scheme. Under a proper optical injection condition, injection of master lasing signals into the slave laser generates a residual cavity mode whose wavelength is slightly longer than the free-running slave mode. Consequently, the electrical modulation of master or slave laser generates optical SSB signals by resonant amplification in the slave laser [10], [12]. This can be used for realization of OEO with low RF threshold gain, in which both master laser and slave laser are modulated with the same signal. Dual modulation enhances modulation efficiency and makes dual fiber loop OEO configuration possible as shown in Figure 2. The optical SSB signal generated by optical injection is transmitted through the "short" optical fiber first. It is amplified and filtered in RF chain, and modulates both master

Manuscript received November 22, 2011; revised February 2, 2012; accepted February 2, 2012. Date of publication February 10, 2012; date of current version March 30, 2012. This work was supported in part by KESRI 2010T100100855, which is funded by the Ministry of Knowledge Economy, and in part by the National Research Foundation of Korea under the Basic Science Research Program 2011-0009493.

J.-Y. Kim was with the Department of Electrical and Electronic Engineering, Yonsei University, Seoul 120-749, Korea. He is now with the NTT Microsystem Integration Laboratories, NTT Corporation, Kanagawa 243-0198, Japan (e-mail: kim.jaeyoung@lab.ntt.co.jp).

J.-H. Jo and H.-K. Sung are with the School of Electronic and Electrical Engineering, Hongik University, Seoul 121-791, Korea (e-mail: kadokal@hotmail.com; hksung@hongik.ac.kr).

W.-Y. Choi is with the Department of Electrical and Electronic Engineering, Yonsei University, Seoul 120-749, Korea (e-mail: wchoi@yonsei.ac.kr).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2012.2187278

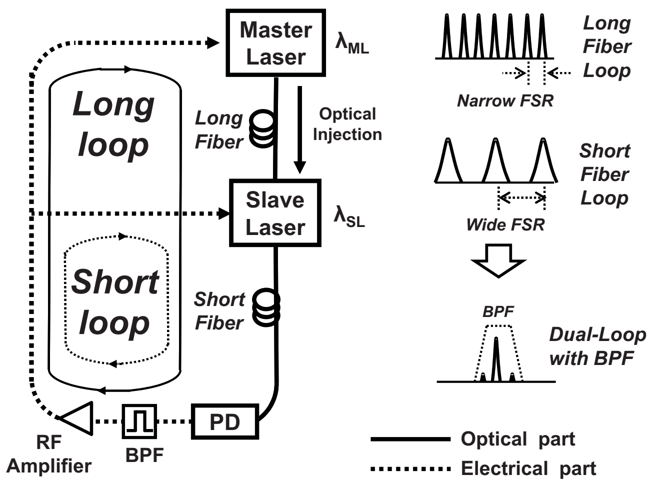

Fig. 2. Schematic of dual-loop, dual-modulation OEO under optical injection. LD: laser diode. PD: photodetector. BPF: bandpass filter.

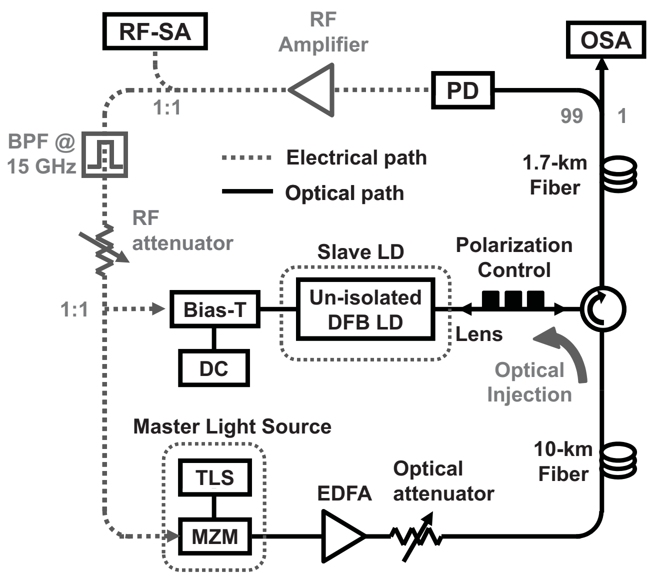

Fig. 3. Experimental setup. TLS: Tunable laser source. MZM: Mach–Zehnder modulator. EDFA: erbium-doped fiber amplifier. BPF: bandpass filter. OSA: optical spectrum analyzer. RF-SA: RF spectrum analyzer.

laser and slave laser to close the OEO loop. The "long" optical fiber, inserted between master and slave laser, completes dual-loop (short and long loops) and dual-modulation (for both master and slave laser) configuration. The long loop provides high Q and the short loop rejects spurious tones from the long fiber loop cavity. Consequently, the signal selected by an electrical BPF exhibit a pure oscillation in a single frequency with highly-suppressed spurious tones [4], [5].

III. Experimental Setup and Results

Figure 3 shows the experimental setup for the dual-loop, dual-modulation OEO. In our feasibility demonstration of this new configuration, a tunable laser and a Mach–Zehnder modulator (MZM) are used as a master light source so that the optical injection locking condition could be more easily controlled. This can be replaced with a directly-modulated semiconductor laser for realizing lower cost configuration. For

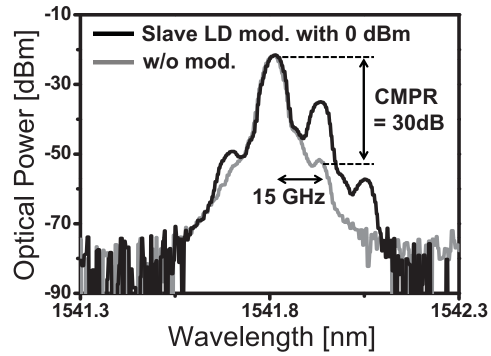

Fig. 4. Optical spectrum of optically injection-locked LD with and without RF modulation of $f = 15$ GHz, when optical injection condition is CMPR = 30 dB with 15-GHz mode spacing.

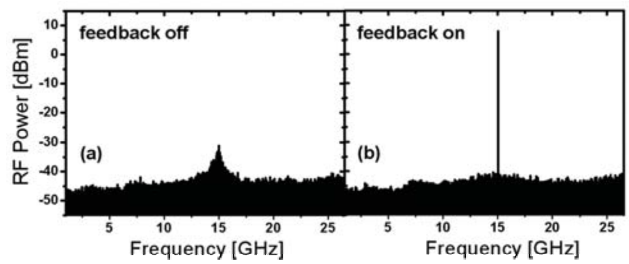

Fig. 5. RF spectrum of dual-loop OEO in (a) open loop and (b) closed loop. Optical Injection condition is set at CMPR = 30 dB with 15-GHz mode spacing.

the slave laser, a distributed feedback (DFB) LD with no built-in isolator is used. The output power of the slave LD is 5.3 dBm at 20-mA current bias.

An erbium-doped fiber amplifier (EDFA) and an optical attenuator are used for achieving strong optical injection as well a fine tuning of the injection power. The optical signal from the master light source is injected into the slave laser through a 10-km-long optical fiber. The optical circulator between two lasers prevented unwanted coupling from the slave LD into the master light source. The optical signal from the slave LD passes through a 1.7-km-long optical fiber. It is converted to an electrical signal in a photo-detector. The electrical signal is then amplified and filtered by the RF amplifier and a BPF. A variable RF attenuator controls RF gain of the loop. The spectrum of OEO signal is measured with an optical spectrum analyzer (OSA) and a RF spectrum analyzer (RF-SA) using a 99:1 optical coupler and a 3-dB RF power divider, respectively.

Figure 4 shows the measured optical spectrum when the optical injection condition is controlled so that the cavity mode power ratio (CMPR) of 30 dB is achieved. The CMPR is defined as the power ratio of injection-locked mode in master light source wavelength over the residual cavity mode of slave LD. By directly modulating the master or slave LD with a 15-GHz signal from an external RF synthesizer, the residual cavity mode is resonantly enhanced resulting in optical SSB generation. The enhanced optical sideband can significantly reduce the required RF gain for loop oscillation when the enhanced SSB is applied to OEO. Figure 5 shows the measured

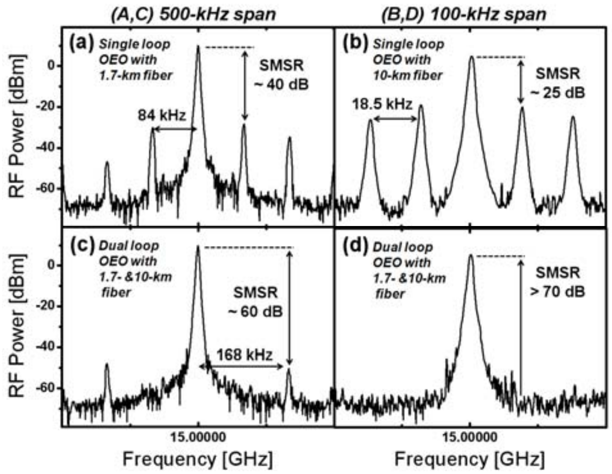

Fig. 6. Measured RF spectrum of (a) single-loop OEO with 1.7-km fiber loop (500-kHz span), (b) single-loop OEO with 10-km fiber loop (100-kHz span), (c) dual-loop OEO (500-kHz span), and (d) dual-loop OEO (100-kHz span). Optical Injection condition is set at CMPR = 30 dB for a 15-GHz optical SSB signal.

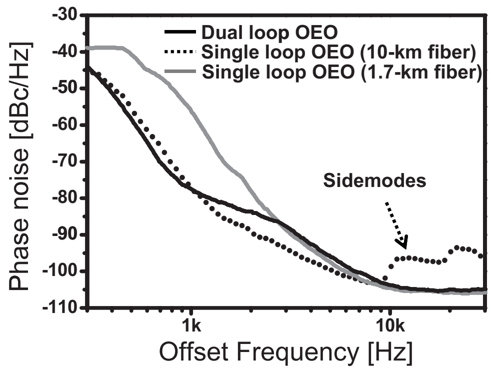

Fig. 7. Measured phase noise of dual-loop OEO and single-loop OEO with 1.7- and 10-km optical fiber loop, respectively. Optical Injection condition is set at CMPR = 30 dB with 15-GHz mode spacing.

RF spectrum of the dual-loop, dual-modulation OEO with and without loop feedback. The CMPR is set at 30 dB as shown in Fig. 4. The RF threshold gain, which is defined as a minimum RF gain required for the OEO loop to achieve stable oscillation, is about 27 dB with 30-dB CMPR. For the OEO demonstration, no external RF signals are applied. The noisy spectrum around 15 GHz for open loop measurement in Fig. 5(a) is due to signal beating between optical modes separated by about 15 GHz. When the loop is closed, a pure oscillation signal appears at 15 GHz due to loop oscillation as shown in Fig. 5(b).

Figure 6 shows the measured RF spectrums of the OEO signal for a single-loop OEO with 1.7-km (Fig. 6(a)), 10-km (Fig. 6(b)), and dual-OEO (Fig. 6(c), (d)). In the single-loop OEO, only a slave LD is modulated. As shown in Fig. 6(a) and (b), the sidemode suppression ratios (SMSRs) of the single-loop OEOs with 1.7-km and 10-km fibers are 40 dB with 84-kHz and 25 dB with 18.5-kHz free spectral range (FSR), respectively. The OEO signal with a longer loop delay exhibits a less noisy spectrum. By applying a dual-loop OEO, the SMSR is greatly enhanced maintaining the oscillation signal quality. As shown in Fig. 6(c) and (d), the spurious tones from 1.7-km and 10-km fibers are suppressed over 60 and 70 dB, respectively. Figure 7 shows the measured phase noise performance. In the low frequency offset, the phase noise of dual-loop OEO follows that of long-loop OEO (10-km optical fiber) resulting in lower phase noise. In high frequency offset, the phase noise of dual-loop OEO follows that of short-loop OEO (1.7-km optical fiber) with higher suppression of spurious tones. The dual-loop OEO has phase noise of 104-dBc/Hz at 10-kHz offset frequency. This is slightly worse than that of our previously reported injection-locked OEO [9] because in this work experimental conditions and devices are selected for comparison of single- and dual-loop OEO performances rather than optimization of phase noise performance.

IV. Conclusion

We have proposed and demonstrated a dual-loop OEO with optical SSB modulation using dual modulation for both master and slave lasers under optical injection. An OEO having low phase noise, low RF threshold gain, and highly-supressed spurious tones is achieved by utilizing the resonant amplification of optically injected lasers and the coupled resonator effect in dual loop modulation.

References

[1] X. S. Yao and L. Maleki, “Optoelectronic oscillator for photonic systems,” *IEEE J. Quantum Electron.*, vol. 32, no. 7, pp. 1141–1149, Jul. 1996.

[2] X. S. Yao and L. Maleki, “Optoelectronic microwave oscillator,” *J. Opt. Soc. Amer. B*, vol. 13, no. 8, pp. 1725–1735, Aug. 1996.

[3] S. Römisch, J. Kitching, E. Ferrè–Pikal, L. Hollberg, and F. L. Walls, “Performance evaluation of an optoelectronic oscillator,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 47, no. 5, pp. 1159–1165, Sep. 2000.

[4] X. S. Yao and L. Maleki, “Multiloop optoelectronic oscillator,” *IEEE J. Quantum Electron.*, vol. 36, no. 1, pp. 79–84, Jan. 2000.

[5] E. Shumakher and G. Eisenstein, “A novel multiloop optoelectronic oscillator,” *IEEE Photon. Technol. Lett.*, vol. 20, no. 22, pp. 1881–1883, Nov. 15, 2008.

[6] E. Salik, N. Yu, and L. Maleki, “An ultralowphase noise coupled optoelectronic oscillator,” *IEEE Photon. Technol. Lett.*, vol. 19, no. 6, pp. 444–446, Mar. 15, 2007.

[7] W. Zhou and G. Blasche, “Injection-locked dual opto-electronic oscillator with ultralow phase noise and ultralow spurious level,” *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 3, pp. 929–933, Mar. 2005.

[8] K. H. Lee, J. Y. Kim, and W.-Y. Choi, “A 30-GHz self-injection-locked oscillator having a long optical delay line for phase-noise reduction,” *IEEE Photon. Technol. Lett.*, vol. 19, no. 24, pp. 1982–1984, Dec. 15, 2007.

[9] H. K. Sung, X. Zhao, E. K. Lau, D. Parekh, C. J. Chang-Hasnain, and M. C. Wu, “Optoelectronic oscillators using direct-modulated semiconductor lasers under strong optical injection,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 15, no. 3, pp. 572–577, May/Jun. 2009.

[10] H. K. Sung, E. K. Lau, and M. C. Wu, “Optical single sideband modulation using strong optical injection-locked semiconductor lasers,” *IEEE Photon. Technol. Lett.*, vol. 19, no. 13, pp. 1005–1007, Jul. 1, 2007.

[11] H. S. Ryu, Y. K. Seo, and W. Y. Choi, “Generation of optical single sideband using a semiconductor laser under modulated light injection,” *Jpn. J. Appl. Phys.*, vol. 42, no. 9A/B, pp. 1064–1065, Sep. 2003.

[12] J. Y. Kim, W. Y. Choi, and H. K. Sung, “A study on modulation configuration of optoelectronic oscillators using direct modulation of semiconductor lasers,” *Jpn. J. Appl. Phys.*, vol. 50, pp. 032504-1–032504-4, Mar. 2011.