Optoelectronic Oscillators Using Direct-Modulated Semiconductor Lasers Under Strong Optical Injection

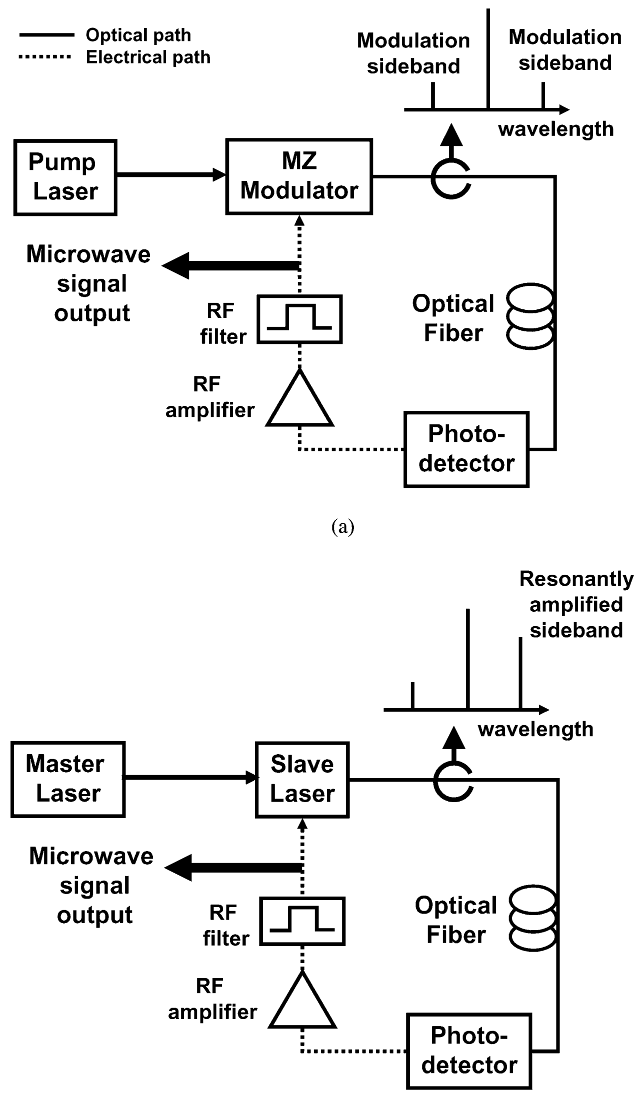
Hyuk-Kee Sung, *Member, IEEE*, Xiaoxue Zhao, *Student Member, IEEE*, Erwin K. Lau, *Member, IEEE*, Devang Parekh, *Student Member, IEEE*, Connie J. Chang-Hasnain, *Fellow, IEEE*, and Ming C. Wu, *Fellow, IEEE*

***Abstract*—In this paper, optoelectronic oscillators (OEOs) are demonstrated by using *direct*-modulated edge-emitting lasers under strong optical injection. The optically injection-locked OEO (OIL-OEO) enables a stable optoelectronic oscillation by converting an optical signal to an electrical signal through a long optical fiber loop. Low RF threshold gain of 7 dB for loop oscillation is attained by utilizing the cavity resonance amplification of an injection-locked semiconductor laser. We investigated both the open- and closed-loop characteristics of the OIL-OEO link by varying the injection locking parameters. Using this novel technique with optimized locking parameters, a 20-GHz RF signal with a phase noise of −123 dBc/Hz is successfully achieved without sophisticated frequency or temperature stabilization.**

***Index Terms*—Direct modulation, optical injection locking (OIL), optoelectronic oscillator (OEO), semiconductor laser.**

I. Introduction

OPTOELECTRONIC oscillators (OEOs) have attracted great attention in recent years due to their outstanding phase noise performance and potential for high-frequency signal generation in various optical and RF systems [1], [2]. The applications cover a wide range of photonic and RF systems such as microwave-frequency standards, radars, RF photonics, and optical signal processing [3]. The phase noise performance of the OEO can be greatly improved by introducing a long delay in the oscillator loop, which is usually provided by a low-loss optical fiber loop with a high quality factor (Q-factor) [2]. Yao and coworkers and Maleki and coworkers successfully demonstrated several types of OEOs, generating RF signal in the X-band with low phase noise [4]–[7]. A standard OEO configuration is shown in Fig. 1(a). Recently, Zhou and Blasche demonstrated a dual-loop OEO by using two standard OEO loops with different fiber lengths to eliminate spurious OEO signals [8]. However, the standard OEO using a continuous-wave (CW) laser and an external modulator has two potential drawbacks: RF amplifiers with high gain (up to ∼60 dB) are necessary to compensate



(a)

(b)

Fig. 1. Schematic of (a) standard OEO and (b) OEO using OIL semiconductor lasers. Optical spectrum of OIL OEO exhibits a significant enhancement of the longer wavelength modulation sideband due to the cavity resonance amplification in the injection-locked lasers.

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H.-K. Sung was with the Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720 USA. He is now with the School of Electronic and Electrical Engineering, Hongik University, Seoul 121-791, Korea (e-mail: hksung@hongik.ac.kr).

X. Zhao, E. K. Lau, D. Parekh, C. J. Chang-Hasnain, and M. C. Wu are with the Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720 USA (e-mail: wu@eecs.berkeley.edu).

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the RF link loss of the feedback loop and high-frequency operation is challenging due to the requirement of external modulators with large modulation bandwidth and high efficiency. Direct modulation of semiconductor lasers under strong optical injection offers an attractive alternative for OEO because of their superior high-frequency performance [9]–[11]. A tunable

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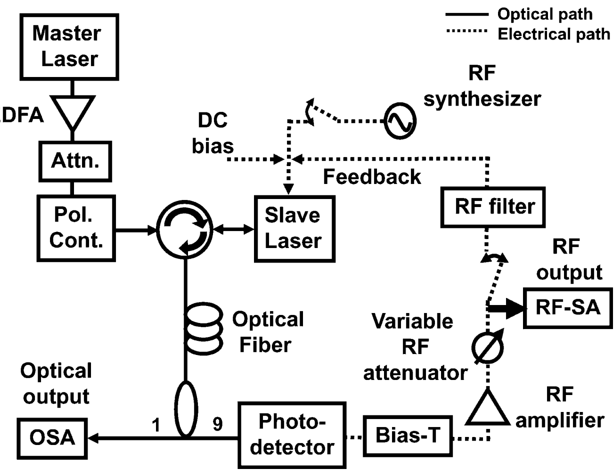

Fig. 2. Experimental setup for measuring RF modulation and feedback properties of an OIL-OEO. EDFA: erbium-doped fiber amplifier; Attn.: optical attenuator; Pol. cont.: polarization controller; OSA: optical spectrum analyzer; RF-SA: RF-spectrum analyzer.

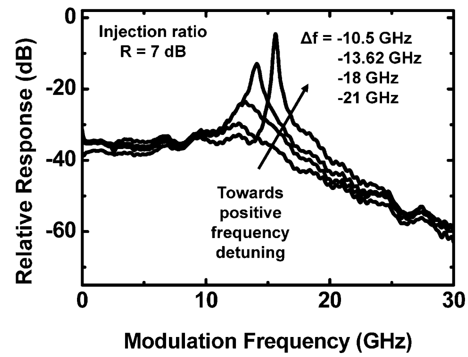

Fig. 3. Measured frequency responses of the open-loop system shown in Fig. 2. Narrow-band enhancement is achieved when the frequency detuning is close to the positive edge of the locking range.

microwave source has been demonstrated using semiconductor laser dynamics [12]. Enhanced resonance frequencies as high as 72 GHz have been demonstrated experimentally [10]. In addition, the high modulation efficiency at resonance could alleviate the amount of RF threshold gain necessary for loop oscillation [13].

In this paper, we propose a novel OEO using direct-modulated semiconductor lasers under strong optical injection. The oscillator is composed of a master and a slave laser instead of a CW laser and an external modulator, as shown in Fig. 1(b). We characterize the open- and closed-loop performance of the optically injection-locked OEO (OIL-OEO). The link exhibits various modulation characteristics depending on the injection locking parameters, such as injection ratio, frequency detuning, and cavity mode power ratio (CMPR). By tuning these parameters of the injection-locked semiconductor lasers, we demonstrate a low RF threshold gain of 7 dB to obtain an oscillation in OIL-OEO. Low phase noise and stable RF signals at 20 GHz are also achieved in a loop with 17-km fiber employed.

II. Open-Loop Characteristics

Fig. 2 shows the experimental setup for measuring RF modulation and feedback properties of an OIL-OEO loop. An external cavity laser is used as a master laser, and the output is amplified by an erbium-doped fiber amplifier (EDFA) to achieve strong optical injection. An optical attenuator controls the injection ratio. An optical circulator with >40 dB isolation prevents coupling from the slave to the master laser. A distributed feedback (DFB) laser, biased at ∼25 mA ($=2.7I_{\rm th}$) and output power of ∼2 dBm, is used as the slave laser. The output from the slave laser is collected by an optical fiber. 10% of the light is tapped off for monitoring by an optical spectrum analyzer with a resolution bandwidth of 0.01 nm, while 90% of the light is detected by a high-speed photodetector with a bandwidth of 34 GHz. The detected RF signal is then amplified or attenuated to control the feedback strength. For the open-loop characterization, no feedback signal is applied to the slave laser. Instead, an RF signal from an external RF synthesizer is applied to the slave laser to investigate the direct-modulated link performance. First, we characterize the modulation properties of the slave laser by tuning the injection locking parameters. The parameters of interest are frequency detuning Δf and injection ratio R. Frequency detuning Δf is defined as the frequency difference between the master and the free-running slave lasers ($\Delta f = f_{\rm master} - f_{\rm free,slave}$). Injection ratio R is defined as the power ratio between the injected power and the lasing power of the free-running slave laser inside the laser cavity.

Fig. 3 shows the frequency response of the optically injection-locked slave laser measured by a vector network analyzer in the open-loop condition. The frequency detuning is varied from -21 to -10.5 GHz while the injection ratio is set at $R \sim 7$ dB. The injection locking range at this injection ratio is measured from -38 to -17.5 GHz. The injection locking range is skewed toward negative detuning range due to the nonzero linewidth enhancement factor (Henry's factor) [14], [15]. The locking range is defined as the frequency detuning at which the CMPR between the injection-locked peak and the residual cavity mode is 35 dB because there is no wavelength hop at the positive detuning edge [11]. As reported in [16], a positively detuned injection-locked laser exhibits high narrow-band RF modulation efficiency due to the resonant amplification of the modulation sideband by the red-shifted slave laser cavity mode. As shown in Fig. 3, the frequency response at 15 GHz is improved by >30 dB at a detuning of -10.5 GHz. This enhancement of the modulation efficiency can be utilized in the OIL-OEO system to reduce the RF threshold gain when generating the RF signal at the resonance peak.

Fig. 4 shows the corresponding optical spectra for the two different frequency detuning values ($\Delta f = -18$ and -10.5 GHz). CMPR is defined as the power at the injection-locked wavelength (i.e., master laser's wavelength) divided by the power of the cavity mode. When detuning is changed from $\Delta f = -18$ to -10.5 GHz, cavity mode power at ∼1543 nm increases and the CMPR decreases from 36 to 7 dB. The CMPR increases when frequency detuning is set to large negative frequency detuning according to the evolution of the cavity mode [11]. The modulation response with the larger enhanced resonance (Fig. 4,

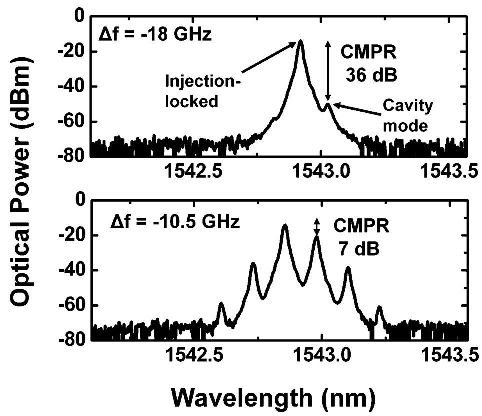

Fig. 4. Optical spectra of open-loop system without RF modulation for $\Delta f = -18$ GHz (top) and $\Delta f = -10.5$ GHz (bottom). CMPR is 36 and 7 dB, respectively.

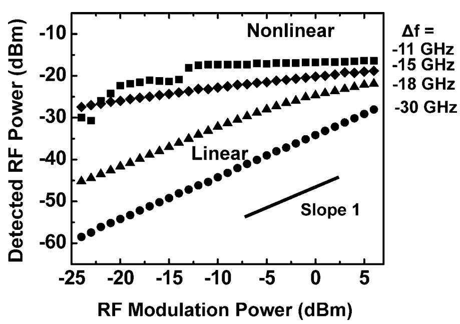

Fig. 5. RF output power versus RF modulation power for various frequency detuning values. Corresponding CMPRs are 6.3 dB ($\Delta f = -11$ GHz), 19 dB ($\Delta f = -15$ GHz), 36 dB ($\Delta f = -18$ GHz), and >50 dB ($\Delta f = -30$ GHz).

lower panel) results in a narrow-band RF gain when the slave laser is modulated by an RF signal corresponding to the spacing between the injection-locked mode and the cavity mode.

Fig. 5 shows the RF transfer curve of the open-loop link for various frequency detuning values from -30 (●) to -11 GHz (■). The injection ratio is fixed at $\sim$7 dB, and the CMPRs are 6.3 dB ($\Delta f = -11$ GHz), 19 dB ($\Delta f = -15$ GHz), 36 dB ($\Delta f = -18$ GHz), and >50 dB ($\Delta f = -30$ GHz). The slave laser is modulated by a single tone at its enhanced resonance frequency ($\sim$15 GHz) via an external RF synthesizer. At large negative detuning ($\Delta f = -30$ GHz), linear modulation with unity slope in the transfer curve is observed. As Δf increases (i.e., toward positive frequency detuning), the RF link gain increases and the modulation becomes nonlinear due to the high optical beating power in optical modes and the double-locking effect between the modulation sideband and the cavity mode [17].

III. Optically Injection-Locked OEOs

We have measured the closed-loop characteristics with a 125-m-long fiber loop. The absolute values of the locking parameters in this section are slightly different from those described in the previous section because the measurements were performed at different times. However, the typical trends such as the evolution of cavity mode and linear/nonlinear modulation

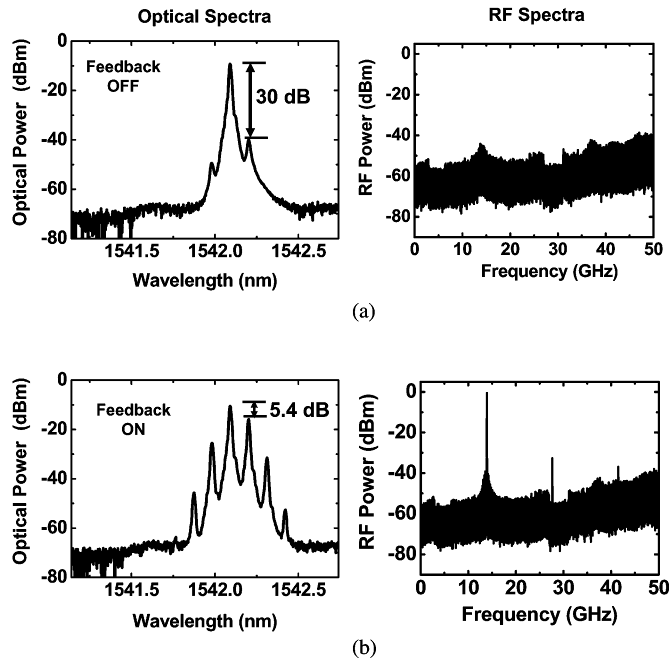

Fig. 6. Optical and RF spectra of OIL-OEO loop (a) without and (b) with feedback. $R \sim 5$ dB, $\Delta f = -18$ GHz. The feedback significantly enhances the modulation sidebands from loop oscillation.

characteristics are consistent with those obtained in the previous section. RF synthesizer in Fig. 2 is disconnected throughout the measurement performed in this section.

Fig. 6 shows the measured optical and RF spectra with and without optoelectronic feedback. Injection locking parameters are tuned at $\Delta f = -18$ GHz and $R \sim 5$ dB. Net RF gain of the loop is set at 25 dB by adjusting an RF attenuator. Optical spectrum without feedback exhibits a CMPR of 30 dB. However, when the optoelectronic feedback is turned on, the modulation sidebands enhance significantly due to loop oscillation, resulting in a CMPR of 5.4 dB. The RF spectrum without feedback exhibits noise peaked around 14 GHz. The noisy spectrum originates from the optical beating between the injection-locked mode and the cavity mode, which are spaced around 14 GHz in the optical domain. When the feedback is turned on, a clean and high-power signal is observed at 14 GHz as well as its harmonics. The significant increase in RF power and signal purity indicates that the loop is oscillating.

The RF link gain is a strong function of frequency detuning, as shown in Fig. 5. Therefore, the OIL-OEO with a fixed RF gain can enter into or exit out of oscillation simply by tuning the frequency detuning values. Fig. 7 shows the CMPR versus the frequency detuning with fixed injection ratio $\sim$5 dB and RF gain = 23 dB. Without optoelectronic feedback, the CMPR decreases steadily with Δf across the locking range (**O** in Fig. 7). However, with feedback, the CMPR exhibits a discrete drop at $\Delta f = -18.7$ GHz (■ in Fig. 7), indicating that oscillation threshold is reached. We have also measured the RF threshold gain of an OIL-OEO as a function of Δf, as shown in Fig. 8. The RF threshold gain is defined as the minimum RF gain needed in the loop to achieve oscillation. The threshold gain reduces

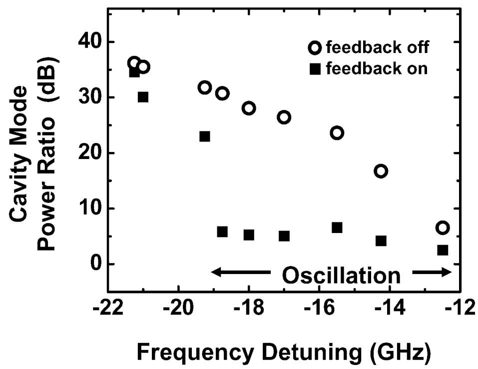

Fig. 7. CMPR versus frequency detuning with (open circle) and without (solid square) optoelectronic feedback. The loop starts to oscillate at $\Delta f = -18.7$ GHz.

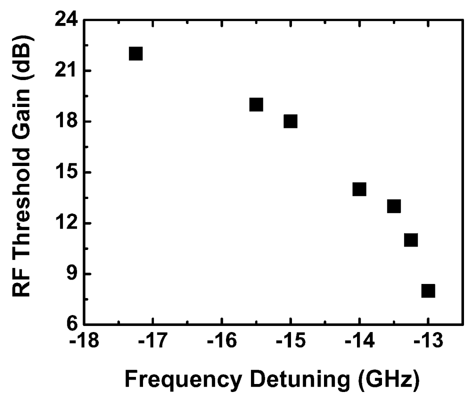

Fig. 8. RF threshold gain as a function of frequency detuning. The lowest threshold gain of 7 dB is achieved at $\Delta f = -13$ GHz.

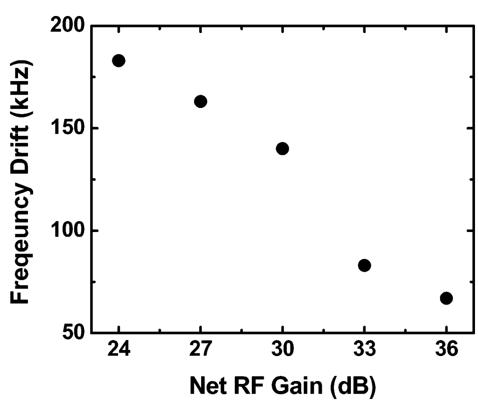

Fig. 9. Measured frequency drift of OIL-OEO signal as a function of RF gain of the link. RF gain is adjusted by an RF attenuator. The frequency drift is measured over a 30-s window.

as Δf is tuned toward positive detunings, where the modulation efficiency at the resonance peak is stronger, as shown in Fig. 3. The minimum threshold gain of 7 dB is obtained at $\Delta f = -13$ GHz. At lower RF gain, the peak RF frequency drifts slowly over time. To investigate the dependence of the frequency stability on the net RF gain, the drift of the peak RF frequency is measured over a 30-s window, as shown in Fig. 9. The frequency drift measured is 183 kHz at 24-dB gain. The drift reduces with increasing RF gain. It is reduced to 67 kHz at 36-dB gain.

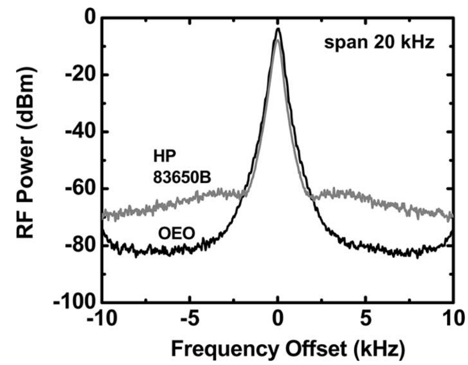

Fig. 10. Measured RF spectrum of an OIL-OEO-generated RF signal with a 17-km fiber loop employed. The OIL-OEO RF signal is generated at 20 GHz, and is compared with a 20-GHz RF signal directly from an HP 83650B synthesizer.

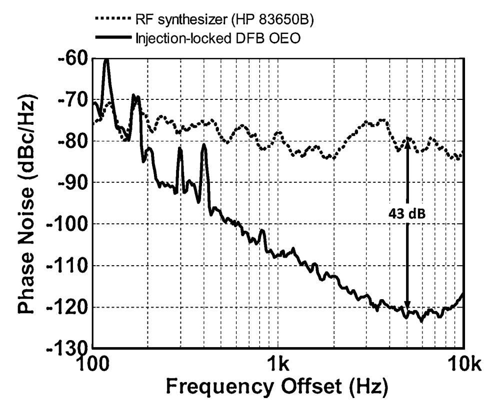

Fig. 11. Measured phase noise of an OIL-OEO-generated RF signal centered at 20 GHz using a DFB as the slave laser. 43-dB improvement occurs at frequency offset of 5 kHz, compared to the HP 83650B RF synthesizer.

To increase the frequency stability and reduce the phase noise, a 17-km-long fiber spool is used for the optical delay. Fig. 10 shows the measured spectra of the OEO with 45-dB RF gain. The RF frequency is 20 GHz for this experiment. The CMPR of the injection-locked laser is set to be $\sim$35 dB. A stable RF signal with low phase noise is observed, as shown in Fig. 10. As a comparison, we also measured the performance of a standard OEO with a CW laser and an external Mach–Zehnder modulator. The standard OEO requires an RF gain of 62 dB to achieve the same performance as the OIL-OEO system.

We then placed the OEO into a temperature-insulating box. Fig. 11 shows the measured phase noise of the OIL-OEO-generated RF signal. We compare it with the phase noise of a commercial RF synthesizer (HP 83650B). The RF signal is generated at a center frequency of 20 GHz. The signal from OIL-OEO exhibits a phase noise of -123 dBc/Hz at 5-kHz offset from the center frequency, which is 43 dB lower than the typical RF synthesizer HP 83650B. The ramp-up of the phase noise at around 10-kHz offset is due to the spurious tones from the 17-km fiber loop (free spectral range is about 11 kHz), which can be eliminated by using a dual-loop OEO [5], [8]. Finally, we measured the phase noise as a function of CMPR with a fixed RF gain of 45 dB. The measurement is performed without placing the OEO into a temperature-insulating box. The phase noise

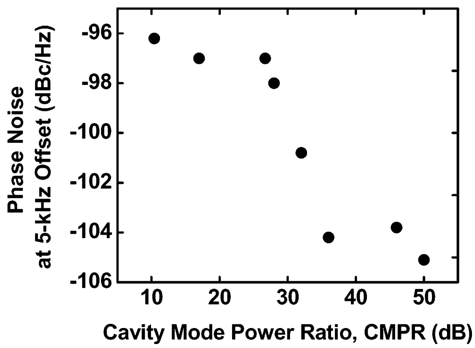

Fig. 12. Measured phase noise as a function of CMPR. Phase noise is measured at a frequency offset of 5 kHz at a center frequency of 20 GHz.

is degraded by 19 dB compared with the phase noise measured with a temperature-insulating box. As shown in Fig. 12, the phase noise increases when the CMPR is low. This is mainly due to the stronger optical beating noise from the injection-locked mode and the cavity mode when the CMPR is low. Therefore, there is a tradeoff between the reduction of an RF threshold gain and the phase noise performance. We believe that the tradeoff can be overcome by employing a more stable master laser and incorporating an optical phase-locked loop (OPLL) into the current OIL-OEO configuration. We have also performed similar experiments using vertical-cavity surface-emitting lasers (VCSELs) as a slave laser to demonstrate universal feasibility of this technique. The resulting OEO exhibited similar performances, and the results will be reported later.

IV. Conclusion

We have investigated the optical and RF performance of OIL-OEOs with DFB slave lasers. RF threshold gain and the signal phase noise are a function of the frequency detuning, and thus, the CMPR. However, they favor different detuning conditions, thus bringing a tradeoff when optimizing these two properties of interest. A minimum RF threshold gain of 7 dB was achieved by utilizing the resonance enhancement of the slave laser under optical injection locking. A 17-km-long fiber was employed and a stable, low-noise oscillation signal around 20 GHz was achieved. The phase noise is measured to be -123 dBc/Hz at 5-kHz offset frequency. The OIL-OEO is particularly attractive for tunable RF sources at high frequencies ($>$60 GHz) since the resonance frequency can be tuned by adjusting the injection parameters.

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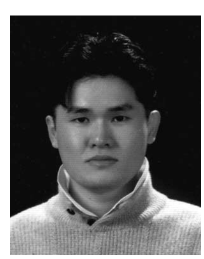

Hyuk-Kee Sung (S'02–M'07) received the B.S. and M.S. degrees in electrical and electronic engineering from Yonsei University, Seoul, Korea, in 1999 and 2001, respectively, and the Ph.D. degree in electrical engineering and computer sciences from the University of California, Berkeley, in 2006.

He was a Postdoctoral Researcher with the University of California. He is currently with the School of Electronic and Electrical Engineering, Hongik University, Seoul. His current research interests include the area of high-speed optoelectronics including optical injection locking of semiconductor lasers, RF photonics, optoelectronic oscillators, and optical communications.

Xiaoxue Zhao (S'04) received the B.S. degree in electronics from Peking University, Beijing, China, in 2003. She is currently working toward the Ph.D. degree in electrical engineering and computer sciences at the University of California, Berkeley.

Her current research interests include microwave photonics, high-speed modulation of vertical-cavity surface-emitting lasers, optical injection locking, and optical communication systems.

Erwin K. Lau (S'01–M'07) received the B.S. and M.Eng. degrees in electrical engineering from Massachusetts Institute of Technology, Cambridge, in 2000 and 2001, respectively, and the Ph.D. degree in electrical engineering and computer sciences from the University of California, Berkeley, in 2006.

In 2004, he spent a summer at the IBM Thomas J. Watson Research Center, Yorktown, NY, where he worked on noise of parallel digital optical interconnects. He is currently a Postdoctoral Researcher in electrical engineering and computer sciences at the University of California. His current research interests include optical injection locking of semiconductor lasers and high-speed RF photonics.

Devang Parekh (S'01) received the B.S. degree in electrical engineering and computer sciences in 2003 from the University of California, Berkeley, where he has been working toward the Ph.D. degree in electrical engineering and computer sciences since 2006.

From 2004 to 2006, he was an Electrical Engineer at Space and Naval Warfare Systems Center, San Diego, CA, where he was working on RF photonics. His current research interests include plasmonics, injection locking of vertical-cavity surface-emitting lasers (VCSELs), and optoelectronic oscillators.

Connie J. Chang-Hasnain (M'88–SM'92–F'98) received the B.S. degree from the University of California, Davis, in 1982, and the M.S. and Ph.D. degrees from the University of California, Berkeley, in 1984 and 1987, respectively, all in electrical engineering.

From 1987 to 1992, she was a Member of Technical Staff at Bellcore. From April 1992 to December 1995, she was an Associate Professor of electrical engineering at Stanford University, Stanford, CA. Since January 1996, she has been a Professor in the Department of Electrical Engineering, University of California, Berkeley, where she is the Director of Center for Optoelectronic Nanostructured Semiconductor Technologies (CONSRT) since 2004. She is the author or coauthor of more than 283 research papers in technical journals and conferences, and six book chapters. She is the holder of 26 patents granted. Her current research interests include nanostructured materials, nano- and microoptoelectronic devices, and their applications.

Prof. Chang-Hasnain is a Fellow of the Optical Society of America (OSA) and the Institution of Electrical Engineers (IEE), and an Associate Editor for the IEEE JOURNAL OF LIGHTWAVE TECHNOLOGIES. She was elected an Honorary Member of A.F. Ioffe Institute in 2005. She was named a Presidential Faculty Fellow, a National Young Investigator, a Packard Fellow, a Sloan Research Fellow, and an Outstanding Young Electrical Engineer of the Year by Eta Kappa Nu. She was the recipient of the 1994 IEEE Lasers and Electro-Optics Society (LEOS) Distinguished Lecturer Award, the 2000 Curtis W. McGraw Research Award from the American Society of Engineering Education, the 2003 IEEE William Streifer Scientific Achievement Award, and the 2005 Gilbreth Lecturer Award from the National Academy of Engineering.

Ming C. Wu (S'82–M'83–SM'00–F'02) received the B.S. degree in electrical engineering from the National Taiwan University, Taipei, Taiwan, and the M.S. and Ph.D. degrees in electrical engineering and computer sciences from the University of California, Berkeley, in 1985 and 1988, respectively.

From 1988 to 1992, he was a Member of Technical Staff at AT&T Bell Laboratories, Murray Hill, NJ. From 1992 to 2004, he was a Professor in the Electrical Engineering Department, University of California, Los Angeles, where he was the Vice Chair for Industrial Affiliate Program and the Director of Nanoelectronics Research Facility. In 2004, he moved to the University of California, Berkeley, where he is currently a Professor of electrical engineering and computer sciences. He is also the Co-Director of Berkeley Sensor and Actuator Center (BSAC). His current research interests include optical microelectromechanical systems (MEMS), high-speed semiconductor optoelectronics, nanophotonics, and biophotonics. He is the author or coauthor of more than 135 journal papers, 280 conference papers, and six book chapters. He is the holder of 14 US patents.

Prof. Wu is a member of the Optical Society of America. He was a Packard Foundation Fellow from 1992 to 1997. He is the founding Co-Chair of the IEEE/Lasers and Electro-Optics Society (LEOS) Summer Topical Meeting on Optical MEMS (1996), the predecessor of the IEEE/LEOS International Conference on Optical MEMS. He was a member of the program committees of many technical conferences, including MEMS, the Optical Fiber Communication Conference and Exposition (OFC), the Conference on Lasers and Electro-Optics (CLEO), LEOS, Microwave Photonics (MWP), the International Electron Devices Meeting (IEDM), the International Solid-State Circuits Conference (ISSCC). He was the Guest Editor of two special issues of IEEE journals on optical MEMS.