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A Study on Modulation Configuration of Optoelectronic Oscillators Using Direct Modulation of Semiconductor Lasers

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Optoelectronic oscillators (OEOs) are demonstrated using optical single sideband (SSB) which is generated by resonance effect in directly-modulated semiconductor lasers under optical injection. The resonant amplification of modulated optical sideband enhances the optical link efficiency in a target oscillation frequency so that RF threshold gain of OEO can be significantly reduced. The OEOs based on two different modulation configurations — master laser and slave laser modulation — show comparable efficiency and phase noise performance.

1. Introduction

Optoelectronic oscillators (OEOs) have been widely investigated due to their capability for generation of high-frequency signals with low phase noises in both optical and RF systems.[1–4] The superior phase noise performance of OEOs is provided by a long delay loop through a low loss optical fiber resulting in high quality factor (Q).[2,3] In addition, the dual-loop approaches such as dual-loop OEO,[5–7] coupled OEO,[8,9] and injection-locked OEO[10–12] have been investigated in order to simultaneously achieve signals with low phase noises and high sidemode suppression ratios (SMSRs). Frequency-tunable OEOs have been demonstrated by utilizing dispersive optical fibers,[13] an optical phase modulator.[14] Most of the OEO configurations cited have been implemented based on a standard OEO configuration. Figure 1(a) shows a standard OEO configuration which utilizes the typical double sideband optical modulation by a laser source and an external modulator. The modulated optical signal is converted into the electrical signal and passes through a bandpass filter centered at f_O and an RF amplifier to modulate the optical signal again. The modulating signal starts from broadband optical and electrical noises. When the loop gain is large enough to overcome the optical and RF link loss, the loop can oscillate by itself. However, this configuration generally suffers from a high RF link loss (>50 dB) and has to be compensated with a high-gain electrical amplifier for loop oscillation (~60 dB). Also, high frequency operation of OEO is limited by the modulation bandwidth of the optical modulator.

Optically injection-locked lasers have to be found effective to generate high-frequency microwave signals because of laser dynamics change under optical injection.[15–19] The optical single sideband (SSB) generation method based on the direct modulation of a semiconductor laser under optical injection can be a good alternative for OEO.[20–23] In this scheme, the resonance effect of injection-locked laser diode (LD) under RF modulation can generate optical SSB signals. This can offer enhanced modulation efficiency for certain frequency ranges as shown in Figs. 1(b) and 1(c). The enhanced modulation efficiency can significantly reduce the required loop gain for the OEO operation. The reported threshold gain reduction is about 40 dB.[23] Two different types of optical SSB generation methods have been reported

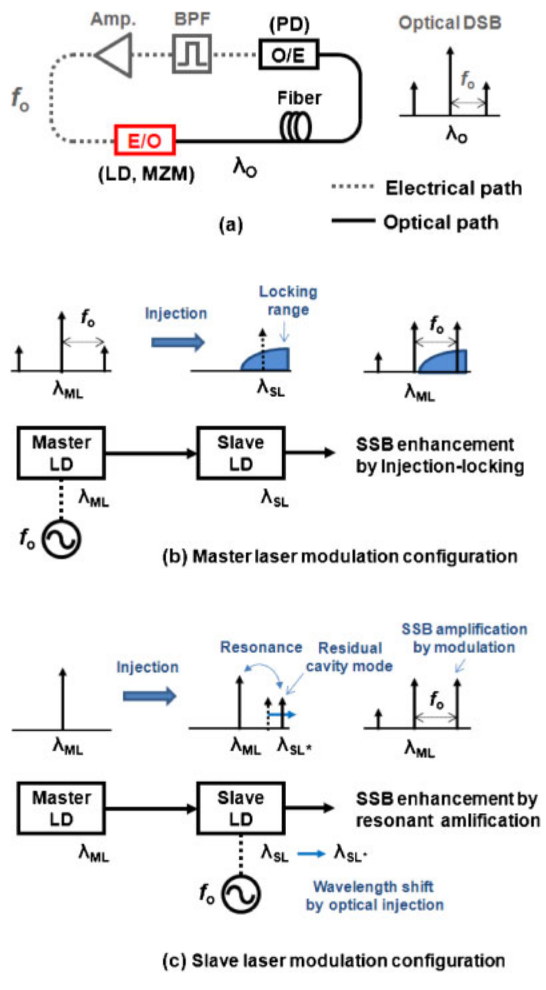

Fig. 1. (Color online) Schematic diagrams of (a) standard OEO and optically injection locked single sideband generation methods with (b) master modulation and (c) slave modulation. LD: laser diode; MZM: Mach–Zehnder modulator; PD: photo-detector; Amp.: RF amplifier; BPF: bandpass filter; DSB: double-side band.

utilizing injection locking dynamics of semiconductor lasers. Figure 1(b) shows the master modulation method. The wavelength-selective locking phenomenon in the slave LD elevates one of the modulated sidebands from the master LD.[17,20] The other approach is the slave modulation method shown in Fig. 1(c). In this scheme, under a proper injection-locking condition, injection of master LD signals into slave

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LD generates a residual cavity mode whose wavelength is slightly longer than the free-running slave mode. Consequently, the electrical modulation of slave LD generates optical SSB in longer wavelength side by the resonant amplification.[18,22] The 20-GHz-band optically injection-locked OEO has been demonstrated using this slave modulation method.[23]

In this paper, we demonstrate the optically injection-locked OEO (OIL-OEO) in 15-GHz band using the master and slave modulation method for optical SSB generation and compare OEO performances in both configurations. The master modulation method can be implemented either with direct modulation of LD or external modulation, so that offers more flexibility when the OEO is applied to optical and RF systems with various configurations. The OIL-OEO characteristics such as phase noise performance and threshold gain are measured depending on the injection locking conditions for both configurations. The master modulation method was compared with slave modulation method in modulation efficiency, electrical frequency response and resulting OIL-OEO performances.

2. Modulation Characteristics: Master Laser Modulated versus Slave Laser Modulated Configurations in Injection-Locked Lasers

Figure 2 shows the experimental setup for measuring RF modulation response of optically injection locked LD for master and slave modulation. For convenient control of optical injection locking condition, the master LD is replaced with a tunable laser source (TLS) and a Mach–Zehnder modulator (MZM). A distributed feedback (DFB) LD without an isolator was used as a slave laser. The DFB laser biased with 20-mA current exhibits output power of −5.3 dBm. The MZM and directly-modulated DFB LD used in this experiment have comparable modulation efficiency in 15-GHz band. The comparable efficiency provides a fair comparison of the master and slave modulation scheme in OEO. When the master and slave lasers are individually modulated with 15-GHz RF signals with 7-dBm power, the output optical power is −5.3 dBm and the detected RF powers using photo-detector (PD) are about −50 dBm in both cases. An erbium-doped fiber amplifier (EDFA) and an optical attenuator are used to achieve a strong optical injection as well a fine tuning of injection power. The optical power from master laser is injected to the slave laser through an optical circulator. The circulator prevents the unwanted signal coupling from the slave to the master laser. To measure the link efficiency, an RF signal is applied to the master laser modulation case (MZM) or slave laser directly (slave modulation case). The optical signal from the slave laser is separated by 99 : 1 power divider. The divided signals are measured in an optical spectrum analyzer (OSA) and a RF spectrum analyzer (RF-SA) after photo-detection.

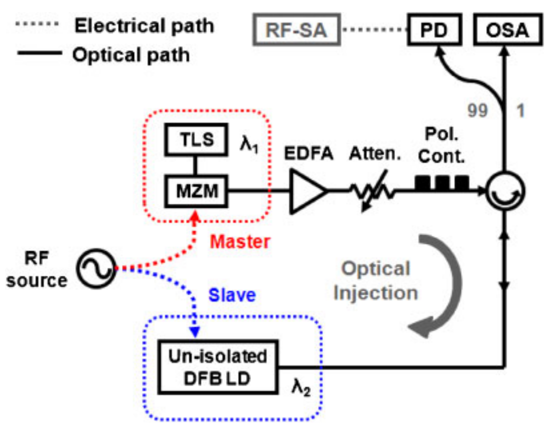

Fig. 2. (Color online) Experimental setup for measuring RF modulation response of optically injection locked LD. TLS: Tunable laser source, MZM: Mach–Zehnder modulator, EDFA: erbium-doped fiber amplifier, Atten: variable optical attenuator, Pol. Cont.: polarization controller, OSA: optical spectrum analyzer, RF-SA: RF spectrum analyzer.

The optical injection locking parameters are frequency detuning Δf and injection ratio R.[23] Δf is defined as the frequency difference between injected master laser and the free-running slave laser. R is defined as the power ratio between the injected optical power and the output power of the free-running slave laser:

$$\Delta f = f_{\text{master}} - f_{\text{free,slave}}, \quad (1)$$

$$R = \frac{P_{\text{master}}}{P_{\text{free,slave}}}. \quad (2)$$

In the optical injection locking condition, the cavity mode power ratio (CMPR) is defined as the power ratio of injection locked mode in master laser wavelength over the residual cavity mode of slave laser. The CMPR of injection locked LD can be controlled by tuning the optical injection parameters.[23] Figure 3 shows the optical spectrum of injection locked slave LD with and without RF modulation when the CMPR is 10 dB [Fig. 3(a)] and 30 dB [Fig. 3(b)], respectively. By tuning the optical injection locking parameters, the frequency difference between the injection-locked and cavity mode can be set to maintain 14.58 GHz for different CMPR values. This is required to investigate the dependence of OEO performance on CMPR values (in §3). When the master or slave laser is modulated by an RF signal with a frequency near the frequency difference, the optical mode in longer wavelength is significantly enhanced due to laser resonance enhancement effect. Corresponding optical spectrum results in optical SSB modulation [Figs. 3(a) and 3(b)]. As shown in the Figs. 3(a) and 3(b), the master laser and slave laser modulation method shows similar characteristics in optical modulation spectrum.

To characterize the RF frequency response of the master LD and slave LD modulation cases, a modulation RF signal is frequency-swept near 15 GHz and the photo-detected RF power is measured in the RF-SA. As shown in Fig. 4, the RF frequency response is significantly enhanced in narrowband nearby 14.58 GHz (= frequency difference between the injection-locked and cavity modes). In a lower CMPR condition (CMPR = 3 dB), the frequency response exhibits a higher and narrower peak than a higher CMPR case (CMPR = 20 dB). The high power in residual cavity mode (= low CMPR) offers stronger resonant effect during modulation process, instead, narrows locking range due to a lower correlation between the injection locked mode (= master laser wavelength) and cavity mode. The frequency responses of the master and slave laser modulation methods exhibit similar characteristics in peaking frequency, amplitude response and the resonant enhancement under a same CMPR condition. The CMPR value is an important

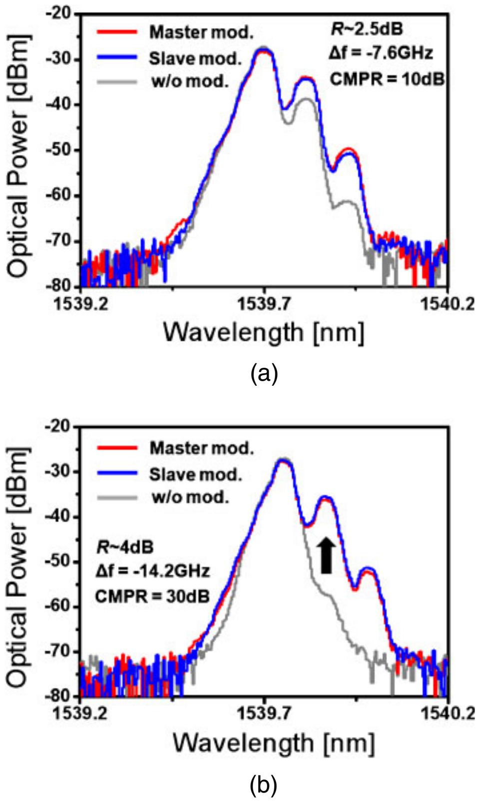

Fig. 3. (Color online) Optical spectrum of optically injection locked LD with RF modulation of $f = 14.58$ GHz, power $= +7$ dBm and without modulation. Injection locking conditions are (a) $R \sim 2.5$ dB, $\Delta f = -7.6$ GHz and CMPR = 10 dB (b) $R \sim 4$ dB, $\Delta f = -14.2$ GHz and CMPR = 30 dB. Resonant frequency of the injection locked LD is tuned to about 14.58 GHz to attain resonantly-amplified modulation sideband for master and slave modulation, respectively.

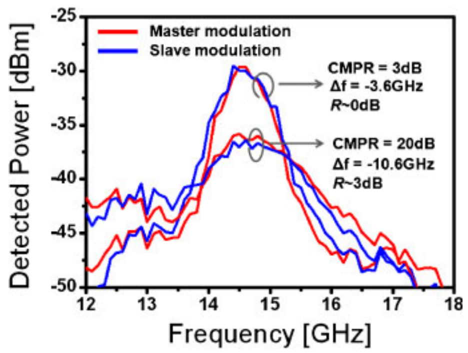

Fig. 4. (Color online) Frequency response of optically injection locked LD with RF modulation power of 7 dBm. CMPR is 3 and 20 dB, respectively, and resonance frequency is 14.58 GHz, identically.

parameter determining the phase noise and RF threshold gain of OIL-OEO. Therefore, the modulation efficiency enhancement of master and slave modulated LD under optical injection can be utilized in OIL-OEO to improve a gain limitation of oscillators.

3. Characteristics of OEOs Using Directly-Modulated Semiconductor Lasers under Optical Injection

Based on the enhanced modulation response and for master

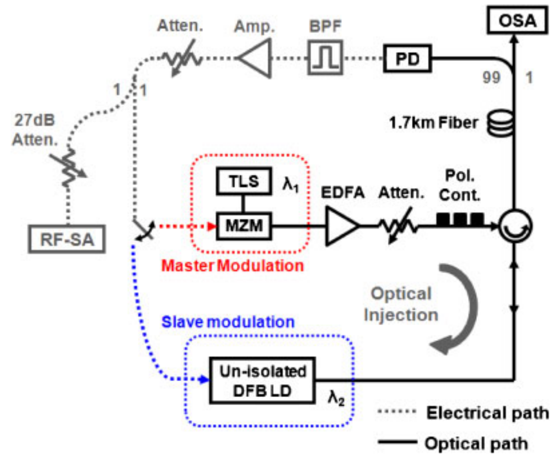

Fig. 5. (Color online) Experimental setup for measuring an OIL-OEO performance with master LD and slave LD modulation, respectively. TLS: Tunable laser source, MZM: Mach–Zehnder modulator, EDFA: erbium-doped fiber amplifier, Atten: variable optical or RF attenuator, Pol. Cont.: polarization controller, BPF: bandpass filter, Amp.: RF amplifier, OSA: optical spectrum analyzer, RF-SA: RF spectrum analyzer.

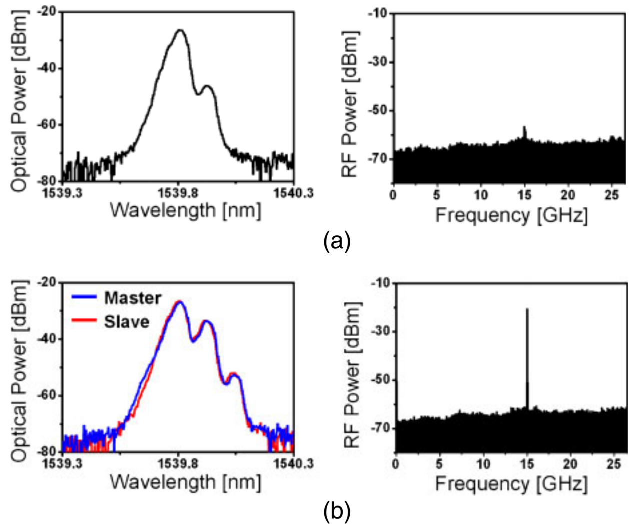

Fig. 6. (Color online) Optical and RF spectrum of OIL-OEO in (a) open loop and (b) closed loop (master LD and slave LD modulation). Injection locking condition is set at $R \sim 3$ dB, $\Delta f = -10.6$ GHz and CMPR = 20 dB.

and slave modulation configurations, OIL-OEO is implemented in 15-GHz band. Figure 5 shows the experimental setup for measuring the OEO performance. OEO feedback loop consists of 1.7-km-long optical fiber, photo-detector and RF chain. A variable RF attenuator is used to control RF gain. The spectrum of OEO output signal is measured with RF-SA using a 3-dB power divider and 27-dB attenuation.

Figure 6 shows the optical and RF spectrum with and without feedback. The CMPR is set at 20 dB in open-loop condition (injection locking parameters $R \sim 3$ dB and $\Delta f = -10.6$ GHz). Corresponding net RF gain of the closed-loop is 31 dB compared with open-loop case. The noisy spectrum of open loop around 15 GHz is from the beating between the two modes shown in optical spectrum in Fig. 6(a). When the feedback loop is closed, a clean oscillation signal appears in

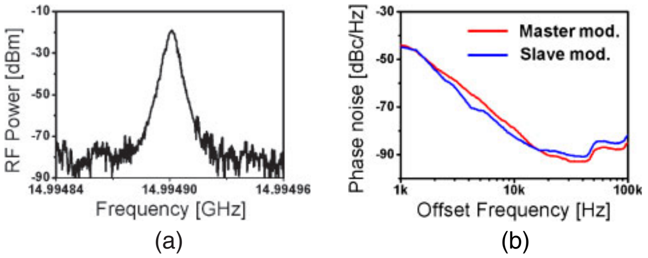

Fig. 7. (Color online) (a) RF spectrum and (b) phase noise of OIL-OEO with 1.7-km optical fiber loop. Injection locking condition is $R \sim 3$ dB, $\Delta f = -10.6$ GHz and CMPR = 20 dB.

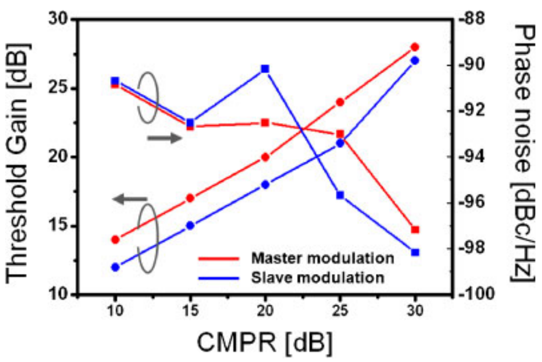

Fig. 8. (Color online) RF threshold gain of OIL-OEO (left axis) and measured phase noise at 30-kHz offset frequency (right axis) as a function of CMPR.

15 GHz. The power of the modulation sideband is greatly enhanced as shown in Fig. 6(b). Figure 7 shows the output RF spectrum under 120-kHz span and a measured phase noise of OEO signal. The measured phase noise increases at around 110-kHz offset due to free spectral range by the 1.7-km-long fiber.

Figure 8 shows RF threshold gain and phase noise of the OIL-OEO as a function of CMPR. The RF threshold gain is defined as a minimum required RF gain of the RF chain to achieve stable oscillation. As shown in Fig. 4, the frequency response of the optically injection locked laser is strongly dominated by the CMPR values. The modulation efficiency of the optically injection locked laser at the resonance peak increases as the CMPR decreases. Therefore, the OIL-OEO under a lower CMPR condition requires a lower RF gain for loop oscillation. The phase noise shown in Fig. 8 is measured at 30-kHz offset frequency. The overall gain of the RF chain is fixed as 31 dBm for phase noise measurement in various CMPR values. As the CMPR decrease, the correlation between the injection locked mode and the resonantly modulated sideband is weakened. The phase noise performance is degraded as the CMPR decreases. The trade-off between the phase noise and threshold gain has been also reported in.[23] As shown in Fig. 8, OIL-OEOs with the master laser modulation and slave laser modulation show similar characteristics and performances. In the figure, the RF threshold gain between two cases shows a slight difference ($\simeq$2-dB difference). This is due to a measurement condition change such as vibration, temperature and optical alignment. Therefore, these two modulation schemes can be applied to RF and optical systems requiring flexible OEO configurations.

4. Conclusions

We demonstrated and characterized OEOs based on a directly-modulated laser under optical injection with master laser and slave laser modulation configurations. By the resonantly-amplified sideband in the optically injection-locked laser, the slave laser modulation scheme exhibits enhanced modulation efficiency and provides a significant reduction in a required RF gain. The master laser modulation scheme offers similar optical and RF characteristics with the slave modulation scheme. Both configurations show similar resonance frequency, modulation efficiency and OEO performances under a same injection locking condition. Consequently, more flexible OIL-OEO configurations are feasible such as dual RF modulation in master and slave lasers to achieve more reduction in RF threshold gain or weighted RF modulation considering the further performance optimization.

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