Injection-Locked Hybrid Optoelectronic Oscillators for Single-Mode Oscillation

Kwang-Hyun Lee, Jae-Young Kim, and Woo-Young Choi

***Abstract*—We demonstrate single-mode extraction from multiple modes in a 30-GHz optoelectronic oscillator (OEO) by injecting OEO modes into an electrical oscillator. The electrical oscillator is injection-locked by one OEO mode resulting in single-mode oscillation. The single-mode oscillation frequency can be tuned by changing the electrical oscillation frequency.**

***Index Terms*—Injection-locked oscillator, optoelectronic oscillator (OEO), phase noise, single-mode oscillation.**

I. Introduction

OPTOELECTRONIC oscillators (OEOs) have been actively investigated as a low phase-noise signal source. The long optical delay line in an OEO provides an external resonator having very high Q [1]–[3]. In particular, a dual-loop OEO composed of a short and a long optical loop is of great interest since it can simultaneously achieve low phase noises with the long loop and the high sidemode suppression ratio (SMSR) with the short loop [4]. However, coupling of long and short loops limits the SMSR that can be achieved with a dual-loop OEO [5].

In order to further increase SMSR, an injection-locked dual OEO has been proposed by Zhou and Blasche, in which a long-loop OEO injection-locks a short-loop single-mode OEO [5]. In this scheme, the short-loop OEO acts as a filter which selects only a single mode from the injected long-loop OEO modes and, consequently, very high SMSR can be achieved. However, the short-loop OEO usually has a narrow locking range, making stable injection-locking difficult to achieve. Moreover, the system cost increases as the number of high-speed optical and electrical components is doubled.

In this letter, we demonstrate an injection-locked hybrid OEO in which the short-loop OEO in the injection-locked dual OEO is replaced with an electrical oscillator. Only one OEO mode can injection-lock the electrical oscillator, achieving single-mode oscillation. With this scheme, the wider locking range can be achieved at a given injection power since electrical oscillators usually have lower Q than OEO. In addition, the frequency of the desired single mode can be easily tuned by changing the electrical oscillation frequency. As a demonstration of our scheme, we perform single-mode extraction from multiple OEO modes having about 84-kHz mode spacing in 30-GHz band.

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II. Operating Principle

Fig. 1 shows the experimental setup for demonstration of the injection-locked hybrid OEO along with output spectra of optoelectronic and electrical oscillators. The hybrid OEO consists of a conventional OEO (master oscillator) and an electrical oscillator (slave oscillator) which is composed of an electrical amplifier, a bandpass filter (BPF), a phase shifter, and a four-port 3-dB directional coupler. Each oscillator has sufficient gain for oscillation by itself. Due to the long optical loop, the OEO has many oscillation modes with the fixed mode spacing, called free-spectral range (FSR), while the electrical oscillator has only one mode whose oscillation frequency is determined by the center frequency of the inserted BPF and the loop phase.

As shown in the figure, multiple OEO modes are injected into the electrical oscillator and the mode closest in frequency to the electrical oscillator mode injection-locks the electrical oscillator mode, while other modes are drastically suppressed due to destructive interference in the electrical loop [6]. Consequently, single-mode selection can be realized. If more than two OEO modes are within the locking range of the electrical oscillator, both can survive resulting in unstable oscillation. Therefore, the locking range of the electrical oscillator should be narrower than half of the OEO FSR so that the injection-locking condition is satisfied for only one mode.

III. Experiment Results and Discussion

For our demonstration, 30-GHz OEO was first realized with about 2.4-km-long single-mode fiber (SMF). Gain for electrical and optical amplifiers was set to compensate the round-trip loss and a BPF having Q of 1500 at 30 GHz with about 6.8-dB insertion loss was inserted in the loop. The eletrical–optical converter was composed of a laser diode and a Mach–Zehnder modulator and optical–electrical conversion was performed by a high-speed photodiode.

The electrical oscillator was configured with an electrical amplifier having RF gain of about 18 dB, an RF filter having Q of 1000 at 30 GHz with 3.16-dB insertion loss, a phase shifter for tuning the oscillation frequency, and a four-port 3-dB directional coupler for signal injection and extraction. The directional coupler also blocks coupling of output signals from the slave electrical oscillator to the master OEO.

The locking range (Δf) of the electrical oscillator was measured to determine the range of injection power for stable operation. For this measurement, 30-GHz signals generated by an RF signal generator were injected into the electrical oscillator and the oscillation frequency was observed by an RF spectrum analyzer, as shown in the inset of Fig. 2. Δf was determined by measuring the maximum frequency difference be-

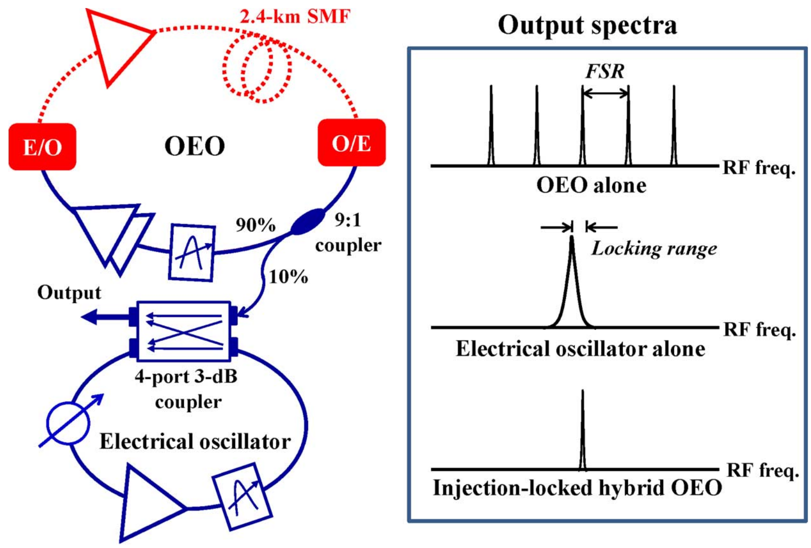

Fig. 1. Configuration for injection-locked hybrid oscillator and output spectra for different oscillators.

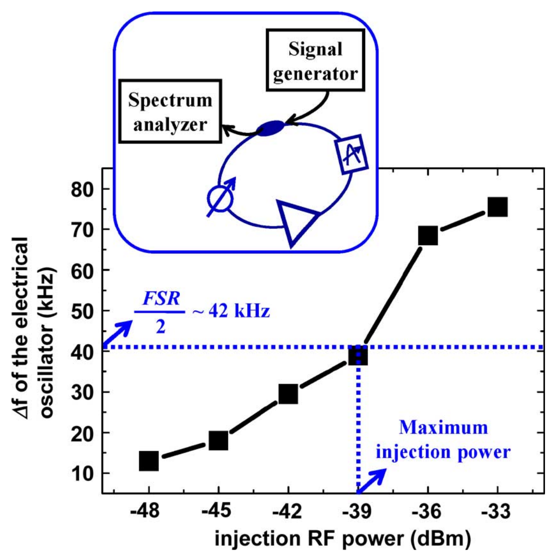

Fig. 2. Measured locking ranges of the electrical oscillator as a function of the injection RF power (signal generator output power). Inset shows the measurement setup.

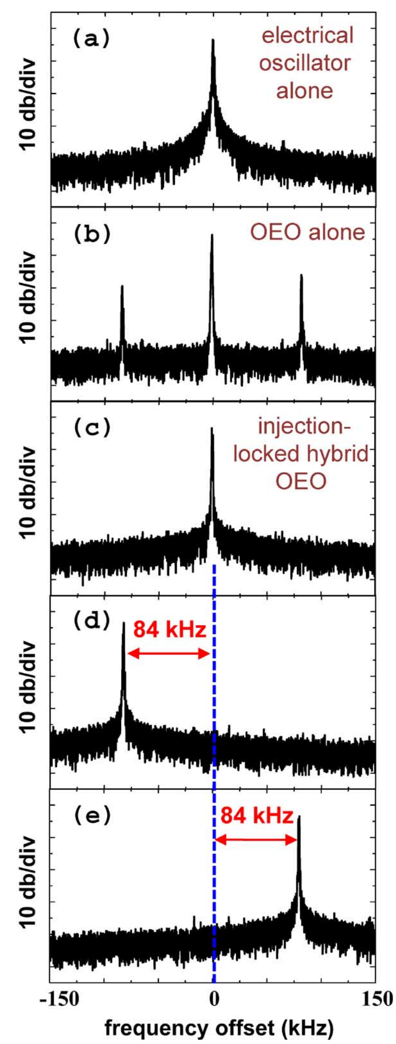

Fig. 3. Measured output spectra of different oscillators: (a) electrical oscillator alone, (b) OEO having 2.4-km-long SMF alone, and (c)–(e) injection-locked hybrid OEO. (c), (d), and (e) were obtained under the same experimental conditions except the different amount of phase shifts in the electrical loop.

tween the free-running (without any signal injection) mode and the stable injection-locked mode at a given injection RF power measured at the output port of the signal generator. Fig. 2 shows the results. The maximum injection power with which Δf is lower than half of the FSR (84 kHz) can be determined as about -39 dBm. This value is much lower than the power required in injection-locked dual OEO which requires injection power of a few decibel milliwatts [5].

Fig. 3 shows the measured output spectra of different oscillators when the injection power was about -42 dBm. Fig. 3(a) and (b) shows the output spectrum of the electrical oscillator and OEO, respectively, and Fig. 3(c) shows the injection-locked hybrid OEO output spectrum. The measurement was done with an RF spectrum analyzer (HP8563E) connected to an external mixer (HP11970A) after attenuated about 9 dB due to the display limit of the spectrum analyzer. The center frequencies are 30.0070968, 30.0083235, and 30.0104099 GHz, respectively. The slight center frequency difference is due to the difference in loop phases. As shown in the figure, single-mode extraction is achieved with the signal quality of the locked mode approaching that of the injection-locked hybrid OEO mode.

The electrical oscillation frequency can be changed by tuning the phase shifter in the loop, and this can be used for selecting the desired OEO mode for single-mode oscillation. Fig. 3(d) and (e) shows the selected OEO mode located just left and right side from the selected mode shown in Fig. 3(c), respectively. They were obtained under the same experimental condition for Fig. 3(c) except the different amount of phase shift in the electrical loop.

In order to investigate the signal quality in detail, the single-sideband phase noises of output signals from the electrical, optoelectronic and injection-locked hybrid oscillators were measured and the results are shown in Fig. 4. At low frequency offset, the OEO has the smallest phase noise due to the long optical loop, but its phase noise deteriorates at high frequency offset. The deterioration is believed to be due to the sidemodes. On the other hand, the injection-locked hybrid oscillator has smaller phase noises at high frequency offset but larger phase noises at low frequency offset than the OEO. This can be explained by the following equation. The phase noise of the locked signal is given by

$$\left\langle |\varphi_{\text{locked}}(f)|^2 \right\rangle = \frac{\cos^2(\phi_0)}{\cos^2(\phi_0) + \left(\frac{f}{\Delta f}\right)^2} \left\langle |\varphi_{\text{in}}(f)|^2 \right\rangle + \frac{\left(\frac{f}{\Delta f}\right)^2}{\cos^2(\phi_0) + \left(\frac{f}{\Delta f}\right)^2} \left\langle |\varphi_{\text{free}}(f)|^2 \right\rangle$$

where $\langle|\varphi_{\text{in}}(f)|^2\rangle$ represents an ensemble average of phase noises for the injected OEO mode, $\langle|\varphi_{\text{free}}(f)|^2\rangle$ for the output signal from the electrical oscillator without signal injection, Δf is the locking range of the electrical oscillator, ϕ_0 is the constant phase difference between injected and locked signals, and f is the offset frequency [7]. This equation shows that the phase noise is limited by the OEO (master oscillator) in small frequency offset, and the electrical oscillator (slave oscillator) in large frequency offset. This agrees well with the measurement results shown in Fig. 4.

Our hybrid OEO has higher phase noises than those in the previously reported dual OEO scheme [5]. The reason for this in small frequency offset is because our master OEO has a shorter delay line (2.5 km in our work versus >6 km in [5]). In high frequency offset, it is because the electrical oscillator used as a slave oscillator has lower Q than an OEO. The lower-Q slave oscillator in our scheme, however, provides a wider locking range, resulting in more stable injection-locking.

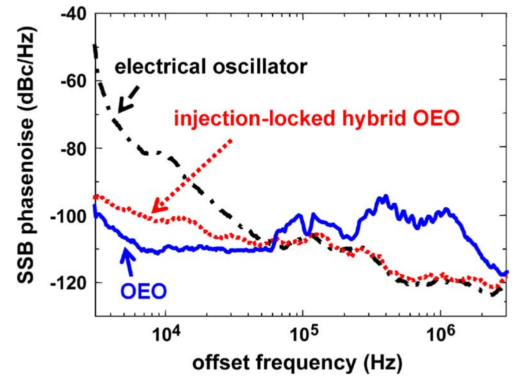

Fig. 4. Measured phase noises for the electrical, optoelectronic, and injection-locked hybrid OEO.

IV. Conclusion

We have demonstrated single-mode extraction from multiple modes in an OEO at 30-GHz bands by injecting OEO modes into an electrical oscillator. Although the phase noise is degraded about 8 dB at 10-kHz frequency offset, extraction of a desired OEO mode among many separated by 84 kHz can be successfully achieved.

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