A 30-GHz Self-Injection-Locked Oscillator Having a Long Optical Delay Line for Phase-Noise Reduction

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

***Abstract*—We demonstrate a millimeter-wave self-injection-locked (SIL) oscillator having a long optical delay line as a feedback route. In the SIL oscillator, a part of output signal is self-injected into the oscillator after passing through a long optical delay line, resulting in locked oscillation and phase-noise reduction. By controlling the self-injection power, we achieve 30-GHz oscillation with a sidemode suppression ratio larger than 50 dB and about 18-dB phase-noise reduction at 10-kHz frequency offset.**

***Index Terms*—Optoelectronic oscillator (OEO), self-injection locking, single-mode oscillation.**

I. INTRODUCTION

OSCILLATORS are one of the key components required in many communication systems for commercial and military applications, and their stability and low phase-noise characteristics are important performance parameters.

A self-injection-locked (SIL) oscillator has been actively investigated for generation of stable and low phase-noise signals. It can be easily realized by self-injection of a part of output signals after passing through a high quality (Q)-factor external resonator or a long delay line. Many successful demonstrations have been reported [1]–[4]. For example, phase noises of about -50 dBc/Hz (20-dB phase-noise reduction) at 10-kHz offset for 8-GHz band [1] and -120.1 dBc/Hz (4-dB phase-noise reduction) at 1-MHz offset for 9.6-GHz band [3] have been achieved by a delay line in the feedback loop, while -95 dBc/Hz at 100-kHz offset for 60-GHz band has been obtained by a ceramic high-Q resonator in the loop [4].

Although it is possible to further reduce phase noises in the RF domain by using a longer delay line or a higher Q external resonator, they are very impractical especially for millimeter-wave applications, since the delay line length is limited by large loss and high-Q devices are not easily available [5].

However, long optical delay lines have been used for generation of a very high-Q external resonator in an optoelectronic oscillator (OEO) because of low transmission loss of optical fiber [6], [7]. An OEO can generate high-spectral-purity micro/millimeter waves with a long optical delay line, but the optical loop should have loop gain for self-oscillation requiring very high electrical and optical gain to compensate the large electrical-to-optical-to-electrical (E/O/E) conversion loss.

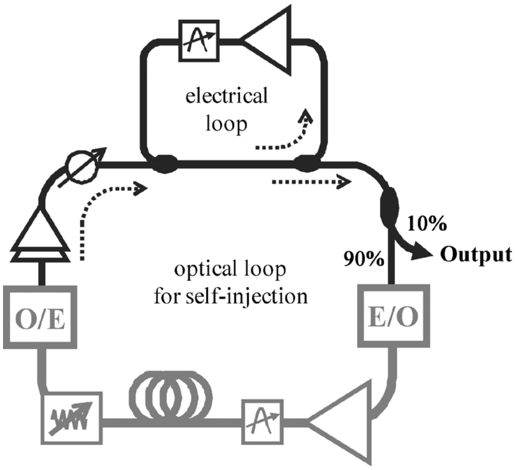

Fig. 1. Configurations of the proposed SIL oscillator having a long optical delay line.

In this letter, we demonstrate an SIL oscillator with a long optical delay line that can significantly reduce the output phase noise. Its configuration is shown in Fig. 1. Unlike OEOs, the optical loop works as a passive feedback loop. With this SIL oscillator, we successfully demonstrate single-mode oscillation at 30-GHz bands with a sidemode suppression ratio (SMSR) larger than 50 dB and output phase-noise reduction of about 18 dB at 10-kHz frequency offset. In addition, dependence of SMSR and the output phase noise on the self-injection power is investigated.

II. THEORY AND OPERATING PRINCIPLE

Our SIL oscillator is composed of a hybrid of an electrical and an optical loop. The electrical loop has sufficient gain to oscillate by itself, while the optical loop does not. Therefore, the optical loop works as a feedback route for self-injection of electrical signals.

A part of output signals from the electrical oscillator, as can be seen in Fig. 1, is injected into the oscillator after passing through a long optical delay line and it locks the electrical oscillator, achieving self-injection locking. Once the oscillator is locked by the delayed replica of its output signal, its frequency and phase fluctuations are reduced and the phase-noise reduction ratio (η) near the carrier frequency can be described as [1], [2]

$$\lim_{\omega\to 0}\eta(\omega) \rightarrow \frac{1}{(1+\sqrt{\kappa}\omega_{3\ \mathrm{dB}}\tau)^2} \tag{1}$$

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where ω is the offset frequency from the center frequency, τ is the optical-loop delay, $\omega_{3\text{ dB}}$ is the half-width at half-maximum of the resonator inserted in the electrical oscillator, and κ is the self-injection power normalized to the oscillator output power. In (1), it is assumed that there is no steady-state phase difference between self-injected and oscillator output signals. As shown in (1), a longer delay line or larger power injection produces more phase noise reduction. In our experiment, 2.4-km-long single-mode fiber (SMF) was used as a delay line.

III. Experimental Setup and Results

As shown in Fig. 1, the electrical loop was configured with an electrical amplifier having RF gain of about 18 dB, an RF filter having Q of 1000 at 30 GHz with about 3.16-dB insertion loss, and a four-port 3-dB RF coupler having insertion loss of about 1.8 dB. Ninety percent of output signals from the electrical loop were converted to the optical signal by an E/O converter made up of a tunable laser source and a Mach–Zehnder modulator (MZM) having 40-GHz modulation bandwidth, and passed through 2.4-km-long SMF.

Optical signals were converted to electrical signals by a high-speed photodiode having 60-GHz bandwidth and self-injected to lock the electrical oscillator. An Er-doped fiber amplifier and two electrical amplifiers having the total gain of about 46 dB were inserted to partially compensate large conversion (E/O/E) loss, and an optical filter was inserted for filtering out the lower sideband in MZM output signals to avoid any RF signal-fading problem induced by fiber dispersion [8]. The power and phase of self-injected signals were adjusted by an optical attenuator and an RF phase shifter, respectively.

Ten percent of output signals from the electrical loop were measured by an RF spectrum analyzer (HP8563E) connected with an external mixer (HP11970A) having conversion loss of about 26 dB after attenuation of about 2.67 dB. This attenuation was needed due to the display limit (−6.1 dBm) of the spectrum analyzer used in the measurement.

The output spectra measured at various κ are shown in Fig. 2. Fig. 2(a) is the output spectrum measured at $\kappa = 0$ (no self-injection), while (b) and (c) are the spectra measured at κ of 1.6×10^{-3} and 2.5×10^{-1}, respectively. These figures show that self-injection-locking reduces phase noise and larger κ provides larger improvement. However, unwanted sidemodes separated by about 84 kHz from the center frequency can be observed in Fig. 2(b) and (c), and they increase as κ increases. These are due to coupled-loop oscillation. Although the optical loop cannot oscillate alone due to large loop loss, the coupled-loop can oscillate if electrical-loop gain compensates optical-loop loss [9]. Therefore, as the injection power increases, causing optical-loop loss reduction, the coupled-mode becomes stronger. These unwanted signals can be suppressed by adding an additional optical delay line having different length [10].

In order to clearly verify phase-noise reduction performance, single-sideband (SSB) phase noises of output signals shown in Fig. 2 were measured and the results are shown in Fig. 3. The measured phase-noise values at 10-kHz frequency offset are −91.83 dBc/Hz ($\kappa = 0$), −110.17 dBc/Hz ($\kappa = 1.6 \times 10^{-3}$), and −118.5 dBc/Hz ($\kappa = 2.5 \times 10^{-1}$). The phase-noise peaking at ~20-kHz frequency offset is believed due to our measurement setup using an external mixer. Clearly, the self-injection locking drastically enhances phase quality of output signals.

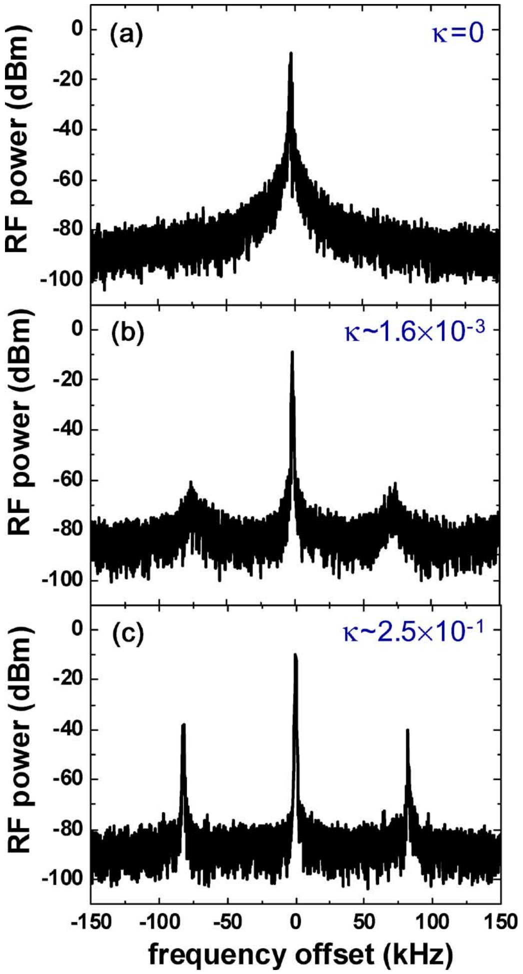

Fig. 2. Measured RF spectra of the output signals at (a) $\kappa = 0$, (b) $\kappa \sim 1.6 \times 10^{-3}$, and (c) $\kappa \sim 2.5 \times 10^{-1}$. The center frequencies are 29.9773362, 29.9770507, and 29.9768307 GHz, respectively. In all figures, the frequency span and resolution bandwidth settings were 300 kHz and 300 Hz, respectively.

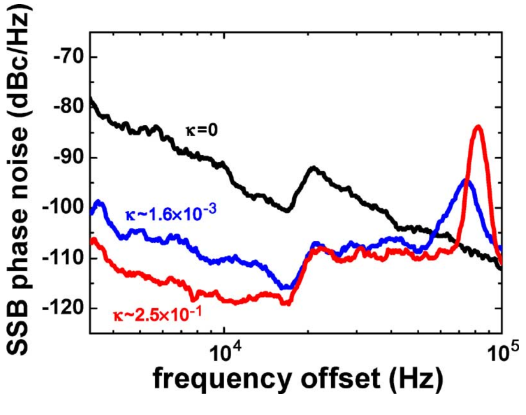

Fig. 3. Measured phase noises of the output signals at $\kappa = 0, \kappa \sim 1.6 \times 10^{-3}$, and $\kappa \sim 2.5 \times 10^{-1}$.

Fig. 4 shows dependency of SSB phase noises measured at 10-kHz frequency offset and SMSR on κ. As shown in the figure, both SMSR and SSB phase noises are reduced with

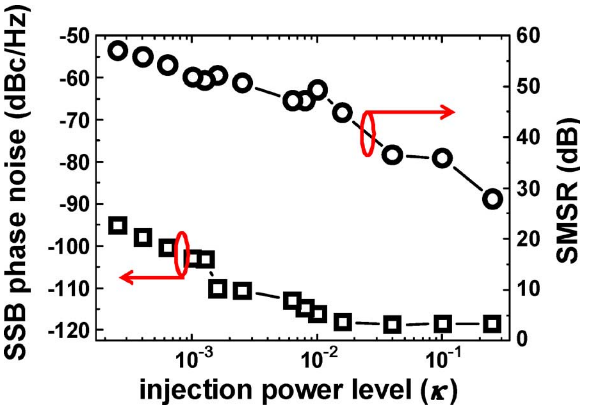

Fig. 4. SSB phase noise at 10-kHz frequency offset from the center frequency and SMSR according to the injection power level.

increasing κ. For κ larger than 10^{-2}, phase noises are saturated due to the sensitivity limit of our spectrum analyzer used in the measurement.

IV. CONCLUSION

We have demonstrated SIL oscillators with 2.4-km-long SMF as a long feedback line for output phase-noise reduction at 30-GHz bands and found that the higher self-injection power provides larger phase-noise reduction but with lower SMSR. At the injection-power level of about 1.6×10^{-3}, 30-GHz oscillation with SMSR larger than 50 dB and output phase-noise reduction of about 18 dB at 10-kHz frequency offset have been successfully demonstrated.

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