Long-Term Stabilization of an Actively Mode-Locked Optoelectronic Oscillator Using Phase-Locked Loop

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***Abstract*—We demonstrate an improved frequency stability of microwave frequency comb (MFC) signals generated by actively mode-locked optoelectronic oscillator (AML-OEO) by locking the MFC signals to a stable reference signal using phase-locked loop. The frequency stability of MFC signals improves by two orders of magnitude on a second-level timescale compared to the free-running AML-OEO.**

***Keywords*—microwave frequency comb (MFC), optoelectronic oscillator (OEO), active mode lock, frequency stability, phase-locked loop (PLL)**

I. Introduction

Optoelectronic oscillator (OEO) is a microwave photonic system with a closed amplified positive feedback loop that can produce high-quality microwave signals [1]. Besides high quality single frequency microwave signal generated by conventional OEO is vital important to many applications, MFC signals or microwave pulses with fixed carrier also play important role in radar [2], fiber optic sensing [3], arbitrary waveform generation[4] and so on. The conventional way to generate MFCs is electrical methods which suffer from the well-known electronic bandwidth bottleneck [5]. Recent years, the AML-OEO has drawn considerable attention and is recognized as an attractive method to generate MFCs with an ultra-low phase noise over a broad frequency range [1, 5, 6]. However, most researches about the AML-OEO focused on exploring different active mode-locking structures, achieving wideband tunability and reducing the physical package [5, 6]. The AML-OEO's long-term phase fluctuation and frequency drift, which is of great importance for high-precision applications such as optical sampling [7], have not been fully investigated.

In this paper, we proposed and demonstrated a long-term stabilization scheme using phase-locked loop (PLL) technique in actively mode-locked optoelectronic oscillator. By locking the MFC signals generated by AML-OEO to a highly stable microwave reference through a PLL, we can obtain the MFC signals with improved long-term stability.

II. Method and Results

Figure 1 illustrates the scheme for improving the long-term stabilization of MFC signals generated by AML-OEO using a PLL technique. The laser diode emits a continuous wave (CW) laser at a wavelength of 1550 nm and a power of 19 dBm. This CW laser passes through a dual-drive Mach-Zehnder modulator (MZM) biased at the quadrature point, with a bandwidth of 10 GHz, and then an 8.9 km single-mode fiber. The modulated laser is converted into an electrical signal through a photodetector. A bandpass filter with a center frequency of 1 GHz and a bandwidth of 30 MHz is used to select the desired frequency oscillating in the OEO loop. After closing the OEO loop and amplifying the electrical signal using a low-noise amplifier with a 35 dB gain, the OEO starts oscillating with a main oscillation mode frequency of 1.02829 GHz and a free spectral range (FSR) of 22.4358 kHz, as shown in Figure 2.

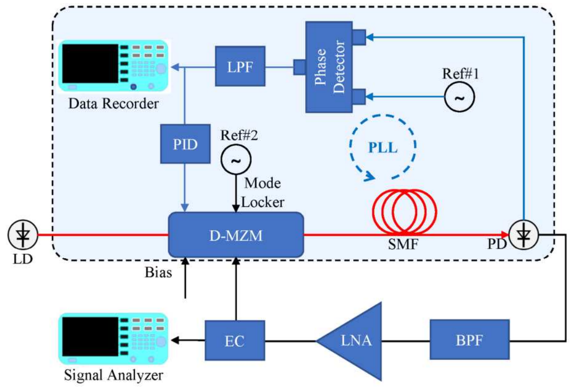

Fig. 1. Experimental setup of the long-term stabilized AML-OEO. LD: laser diode; D-MZM: dual-drive Mach-Zehnder modulator; SMF: single-mode fiber; PD: photodetector; BPF: bandpass filter; LNA: low-noise amplifier; EC: electrical coupler; Ref: microwave reference; LPF: lowpass filter; PID: proportion integration differentiation.

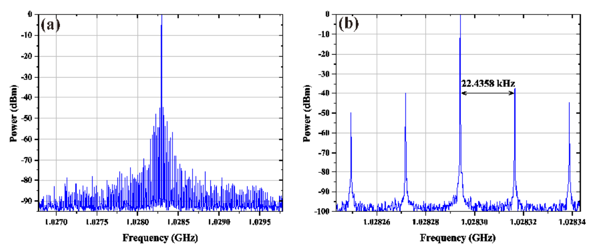

Fig. 2. Spectral measurement of free oscillation OEO.

To generate MFC signals, we load a reference signal Ref#2 with a frequency exactly equal to the FSR of OEO to achieve fundamental active mode locking of the OEO. The spectrum of the MFC signals generated by the fundamental mode-locked OEO is shown in Figure 3.

Because the frequency detuning of the oscillator is linearly proportional to the EOM bias voltage [8], improving MFC signal frequency stability by locking it to a stable reference signal using a PLL technique is promising. The PLL consists

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of a phase detector, a loop filter, and a voltage-controlled oscillator. In this case, we use a mixer as the phase detector, a low-pass filter as the loop filter, and the AML-OEO as the voltage-controlled oscillator, with the voltage control port being the bias port of the MZM.

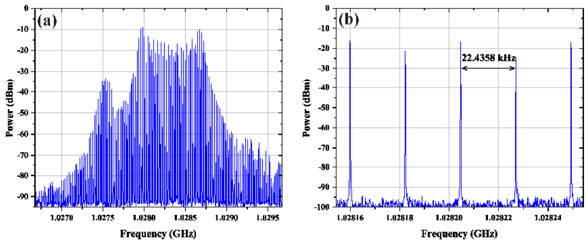

Fig. 3. Spectral measurement of MFC signals generated by fundamental mode-locked OEO.

We set reference signals Ref#1 to 1.02829 GHz and obtain the error signal by mixing the MFC signals with reference signals Ref#1. When the PLL loop is open, we use a digital multimeter (Agilent DMM 34401A) to record the error signal and calculate the Allan deviation, which represents frequency stability. The frequency stability of the MFC signals in free-running mode-locked OEO is shown in Figure 4(a). After closing the PLL loop and locking the MFC signals to Ref#1, we remeasure and calculate the frequency stability of the MFC signals as shown in Figure 4(b). By comparing the frequency stability of MFC signals in free-running and phase-locked mode-locked OEO, we observe that the frequency stability improves by more than two orders of magnitude on a second-level timescale and even more on a hundred-second timescale after using the PLL technique.

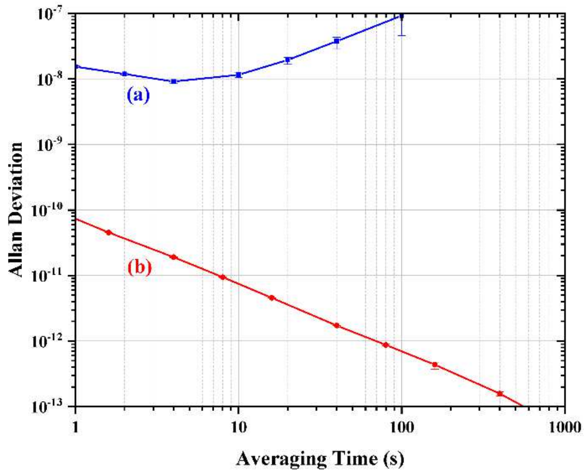

Fig. 4. Frequency stability measurement of MFC signals generated by fundamental mode-locked OEO (a) before PLL locking and (b) after PLL locking.

III. Conclusion

In conclusion, we constructed the AML-OEO and achieved fundamental active mode-locking with a center frequency of 1.02829 GHz. Using the PLL technique, we significantly improved the frequency stability of the MFC signals generated by the AML-OEO. Combining the inherent low phase noise of these MFC signals with their enhanced long-term frequency stability makes them suitable for many critical applications.

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