Improvement of Phase Noise in a Widely Tunable Optoelectronic Oscillator Based on Balanced Detection

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***Abstract*—A widely tunable optoelectronic oscillator based on balanced detection is proposed and experimentally demonstrated. A frequency tunable range from 4 GHz to 16 GHz is achieved. The phase noise of the generated signal is reduced to about -105 dBc/Hz.**

Keywords*—*optoelectronic oscillator; phase noise; balanced detection

I. Introduction

Generation of widely tunable microwave signals using optoelectronic oscillator (OEO) has numerous applications, such as wireless communication, radar, and optical signal processing. Traditional OEO employs an electrical bandpass filter (BPF) to select the oscillation frequency [1]. Thus the tunable frequency range is limited because of the narrow bandwidth of the BPF although the phase noise is quite low. To overcome this limitation, an OEO using a widely tunable microwave photonic filter (MPF) as the mode selector has been recently proposed [2, 3]. The tunable MPF incorporates a broadband optical source (BOS) and a Mach-Zehnder interferometer (MZI) to provide a large tunability. However, the MPF usually has quite a broad bandwidth and generates high noise which limits the performance of OEO. Several methods like dual loop [6] or employing an infinite impulse response (IIR) filter have been used to reduce the mode-hopping effects [7]. Nevertheless, the phase noise of OEO still remains a high level (about -100 dBc/Hz) and leads to a bad purity of the generated signal [2, 7].

In this paper, we propose a widely tunable OEO based on balanced detection. We employ a balanced photodetector (BPD) to convert the optical signal to electrical signal and reduce the optical intensity noise at the same time. The experimental results show that the phase noise of the OEO can be effectively reduced. Further analyses on frequency dependency of phase noise and the influence of polarization are also presented.

II. Operation Principle

The schematic of the proposed OEO is shown in Figure 1. A BOS consisted of an amplified spontaneous emission (ASE) source and a tunable optical filter (TOF) is split into two parts via a 3-dB optical coupler (OC1). One part of the structure is delayed by a variable optical delay line (VODL). The other part is modulated by a Mach–Zehnder modulator (MZM). The polarization states of the two parts are optimized by two polarization controllers (PCs) in order to maximize the optical power. The two parts are then combined through another 3-dB optical coupler (OC2), forming an inline MZI. The two outputs of the OC2 are directed into a dispersion compensation fiber (DCF) through two circulators and then converted to an electrical signal by a BPD. The interferometric structure and dispersive element works as a single bandpass MPF [4, 5], which is used here to select the wanted microwave frequency of the proposed OEO. In addition, we use a bidirectional erbium-doped optical fiber amplifier (EDFA) and electrical amplifier (EA) to meet the oscillating condition of the OEO (i.e., gain > loss).

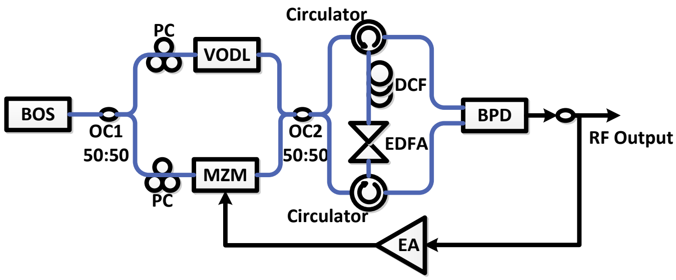

Fig. 1. Experimental setup of the proposed OEO. BOS: broadband optical source; OC: optical coupler; PC: polarization controller; VODL: variable optical delay line; MZM: Mach–Zehnder modulator; DCF: dispersion compensation fiber; EDFA: Erbium-doped Optical Fiber Amplifier; BPD: balanced photodetector; EA: electrical amplifier.

The electrical signal at the output of the BPD is given by the subtraction of the two optical inputs laid after two respective circulators. At the output of the BPD, the generated signals are the beating of carriers and sidebands in the MZI structure, while the noises are DC and high order components mainly caused by the beating of carriers. As the signals at the input of the BPD are counter-phase while the noises are in-phase [5], one can enhance the RF signals at the output of the BPD and eliminate the optical intensity noise. Meanwhile, the baseband of the MPF can also be eliminated by the BPD and only the passband remains. If only one input of the BPD is used [4], the MPF response can be described as

$$H_1(\omega) \propto m\cos\left(\varphi + \frac{\beta_2\omega^2}{2}\right) \times H_b(\omega)$$
$$+\exp\left[j\left(\Omega_0\Delta\tau - \frac{\beta_2\omega^2}{2}\right)\right] \times H_b\left(\omega - \frac{\Delta\tau}{\beta_2}\right)$$
$$+\exp\left[j\left(-\Omega_0\Delta\tau + \frac{\beta_2\omega^2}{2}\right)\right] \times H_b\left(\omega + \frac{\Delta\tau}{\beta_2}\right) \quad (1)$$

where $H_b(\omega)$ is the baseband response defined by

$$H_b(\omega) = \frac{1}{2\pi}\int_0^{+\infty} N(\Omega)\exp[-j\omega\beta_2(\Omega - \Omega_0)]\,d\Omega \quad (2)$$

where $N(\Omega)$ is the optical power spectral density (PSD) of the BOS, m is a constant factor, φ is the phase difference between carrier and sidebands depending on the modulation type, β_2 is the group velocity dispersion (GVD) of DCF, and $\Delta\tau$ is the time delay between the two branches of the MZI. The first term in Eq. (1) indicates the baseband of MPF, and the last two terms in Eq. (2) indicate the passbands.

If the BPD are used, the MPF can be described as

$$H_2(\omega) \propto \exp\left[j\left(\Omega_0\Delta\tau - \frac{\beta_2\omega^2}{2}\right)\right] \times H_b\left(\omega - \frac{\Delta\tau}{\beta_2}\right)$$
$$+\exp\left[j\left(-\Omega_0\Delta\tau + \frac{\beta_2\omega^2}{2}\right)\right] \times H_b\left(\omega + \frac{\Delta\tau}{\beta_2}\right) \quad (3)$$

Comparing Eq. (3) with Eq. (1), one can see that the baseband is consequently removed and only the passband is maintained. Figure 2(a) represents the simulation of the MPF response using only one input of BPD. It is shown that the baseband response is left if the bias voltage of MZM is not well controlled. When using two inputs of the BPD, the baseband response vanishes whatever the bias voltage is. This simulated result is obviously illustrated in Figure 2(b). Furthermore, it is pointed out that the profile of the MPF response is determined by the profile of BOS and the total dispersion of DCF.

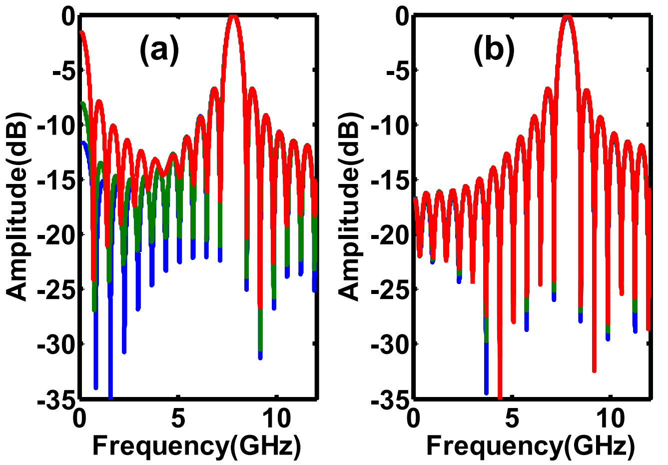

Fig. 2. Simulated MPF response with different bias voltages of MZM using (a) one input of BPD and (b) two inputs of BPD.

From Eq. (3), the center frequency of the single bandpass MPF can be described as

$$f_c = \frac{\Delta\tau}{2\pi\beta_2} \quad (4)$$

Note that the center frequency of the MPF determines the oscillation frequency of the OEO. Therefore, the oscillation frequency can be easily detuned by tuning the delay of VODL.

III. Experimental Results and Discussion

In the experiment, the BOS sliced by a TOF has a bandwidth of 15 nm. The DCF is 2.66 km long and has a total dispersion of 374 ps^2. The EA has a relative flat gain of 60 dB from 4 GHz to 16 GHz. To enable the OEO to oscillate in the frequency range, we use a vector network analyzer (Agilent N5247A) to measure the MPF and make sure that the amplitude response of the MPF is larger than unity. To study the usage of BPD for reducing noise and be superior to the dual loop OEO [6, 7], we use two circulators and one DCF to strictly keep the same length of the two optical paths after OC2.

Firstly, we investigate the influence of polarization state on the single sideband (SSB) phase noise of the proposed OEO. The SSB phase noise at 4.58 GHz for different polarization states is compared in Figure 3. Different polarization states result in different responses of MPF and influence the optical power in the optical link. Accordingly, polarization optimization is necessary for improvement of the phase noise of OEO. By simply tuning the VODL in the inline MZI, the frequency of the signal can be detuned from 4 GHz to 16 GHz. The generated signals of the proposed OEO are illustrated in Figure 4, where different colors correspond to different frequencies. The signals have a relatively high noise floor determined by the optical link noise and EA noise. Due to the different amplitude response of the EA laid after the BPD, the powers of the generated signals at different frequencies vary from each other. Note that the range of the tunable frequency range is limited by the bandwidth of the EA (4 GHz to 16 GHz).

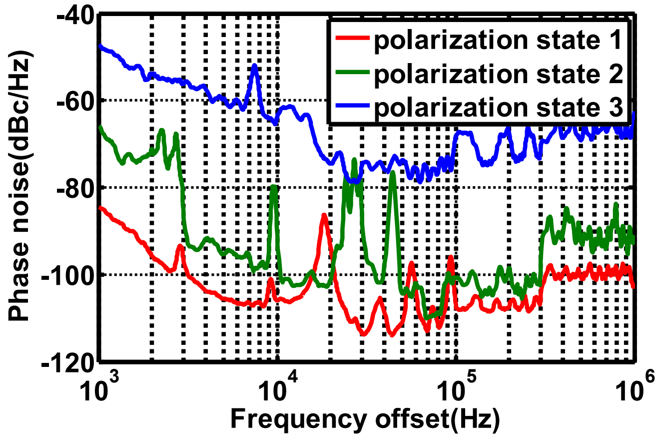

Fig. 3. SSB phase noise of the generated signal with different polarization states at 4.58 GHz.

The SSB phase noise of the proposed OEO by using one input or two inputs of the BPD is also investigated. In Figure 5, we keep the same optical power at the input of the BPD in order to reasonably compare the phase noises. The phase noises are experimentally measured at both 4.58 GHz and 9.33 GHz. It can be seen that the phase noise is below -105 dBc/Hz at an offset frequency of 10 kHz using two inputs of the BPD while the phase noise is only about -90 dBc/Hz using only one input of the BPD. The peaks at high offset frequencies result from the sidemodes of the OEO. Thanks to the elimination of optical intensity noise by the BPD, the phase noise can be decreased by about 15 dBc/Hz. Compared to the phase noise of -95 dBc/Hz measured in previous work [2], we also obtain a more than 10 dBc/Hz improvement.

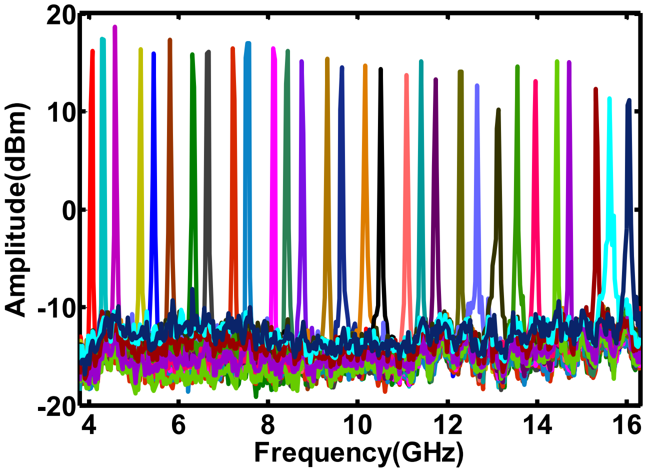

Fig. 4. Electrical spectra of the generated microwave signals at different frequencies.

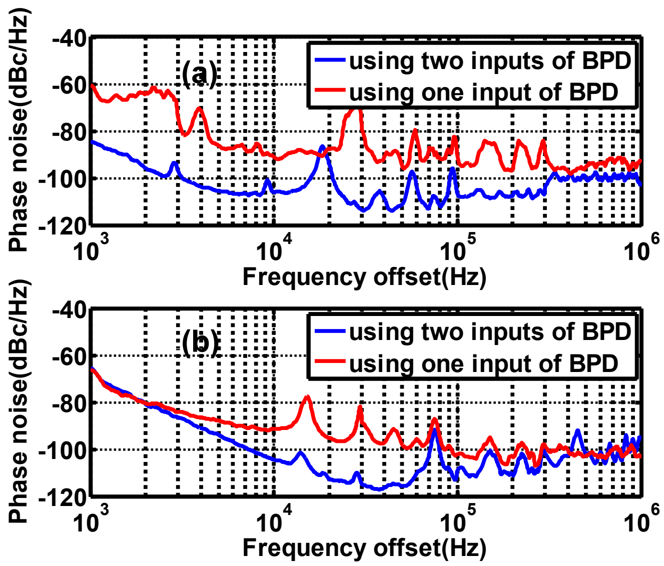

Fig. 5. SSB phase noise of the generated signal at (a) 4.58 GHz and (b) 9.33 GHz.

In addition, the SSB phase noise at different frequencies of the proposed OEO is also measured. Just by tuning the VODL in the tunable range and maintaining the input power of the BPD, we obtain the phase noise at various frequencies. As illustrated in Figure 6, there is no clear evidence that the phase noise is frequency dependent. The distinction shown in this figure is owing to the differences of the EA amplitude responses at different frequencies (see Figure 4). It can be deduced that if the EA amplitude responses are flat enough in the frequency range, the phase noises are identical at different frequencies as well. It is worth noting that the generated signal is not so stable because of the mode-hopping effects. Further work will be focused on this problem in the condition of keeping a low phase noise.

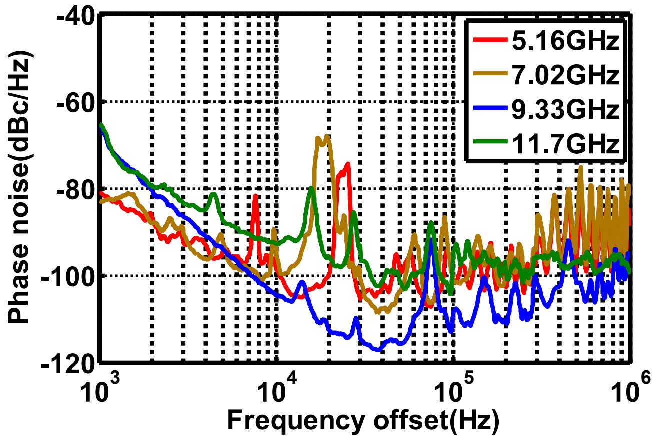

Fig. 6. SSB phase noise of the generated signal at different frequencies.

IV. Conclusion

A widely tunable OEO based on balanced detection was proposed and demonstrated. This method was proven to be effective to reduce the phase noise of the OEO. By using a BPD, the optical intensity noise can be greatly eliminated and thus the phase noise of the OEO is improved. The oscillating signal has a tunable range from 4 GHz to 16 GHz by tuning the VODL. A comparatively better phase noise of about -105 dBc/Hz at an offset of 10 kHz was achieved.

Acknowledgment

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