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Abstract. Realization of a wideband tunable optoelectronic oscillator based on a chirped Mach–Zehnder modulator (MZM) and a chirped fiber Bragg grating is proposed and demonstrated. By simply adjusting the direct-current bias of the chirped MZM, the frequency of the oscillating signal is tuned. A theoretical model is established, then verified by an experiment. A high-purity microwave signal with a tunable frequency from 5.8 to 11.8 GHz is generated. The single-sideband phase noise of the generated signal is −112.6 dBc/Hz at a frequency offset of 10 kHz. [DOI: 10.1117/1.OE.52.5.055005]

Subject terms: microwave generation; chirped fiber Bragg grating; chirped modulator; optoelectronic oscillator.

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1 Introduction

Photonic technologies are promising for the generation of high-frequency and frequency-tunable radio frequency (RF) signals, which have widespread applications in diverse fields such as metrology, communications, radars and electronic warfare.[1–3] One of the promising approaches for the photonic microwave signal generation is based on an optoelectronic oscillator (OEO). In the past few years, many schemes for implementing tunable OEOs have been proposed.[4–10] A continuously frequency-tunable OEO was proposed in Refs. 4, 5, but the frequency tuning range was only a few MHz. The Oewaves company demonstrates a tunable oscillator using the expensive and special whispering gallery mode resonator (WGM),[6] but the WGM is susceptible to the coupling prism. We have recently proposed an approach to tune the OEO in the optical domain by use of a Fabry-Perot laser diode (LD) based active filter.[7] A similar principle is used to construct a frequency tunable OEO based on a narrowband phase-shifted fiber Bragg grating (FBG).[8,9] These schemes, however, have a poor stability since the oscillator frequency is determined by the wavelength, and thus the wavelength drift of the LD will directly change the frequency of the OEO. More recently, a tunable OEO based on a polarization modulator and a chirped FBG (CFBG) was reported.[10] The frequency tuning is implemented by adjusting of a polarization controller (PC). The key limitation associated with this approach is that the precise setting of the polarization state is difficult.

In this paper, a simple and stable OEO with wide tunability consisting of a chirped MZM and a CFBG is proposed and demonstrated. The key device in the system is the chirped MZM, which is implemented by a dual-electrode MZM (DMZM). The DMZM functions, in conjunction with a CFBG, as a photonic microwave bandpass filter for frequency selection. By adjusting the bias voltage of the DMZM, the chirp parameter is tuned.[11] As a result, the center frequency of the photonic microwave filter is changed, which tunes the frequency of the oscillating signal. A proof-of-concept experiment is carried out. A high-purity microwave signal with a tunable frequency within 5.8 to 11.8 GHz is generated. The phase noise performance of the OEO is also studied. A phase noise as low as −112.6 dBc/Hz at 10-kHz offset is achieved.

2 Operating Principle

The schematic diagram of the proposed tunable OEO is shown in Fig. 1. The key component in the OEO is the tunable photonic microwave filter formed by a DMZM, a CFBG and a tunable voltage source. The light wave from an LD is modulated by an oscillating signal at the DMZM. For the DMZM, the chirp parameter is related to the amplitude and the sign of the RF drive signals to each electrode, given by[11,12]

$$\alpha = \frac{V_1 + V_2}{V_1 - V_2} \tan\left(\frac{\pi}{2} \frac{V_{\mathrm{dc}} - V_{\mathrm{o}} - V_\pi}{V_\pi}\right), \tag{1}$$

where V_o is the offset voltage corresponding to the phase retardation when no electric field is applied, V_{dc} is the bias voltage,

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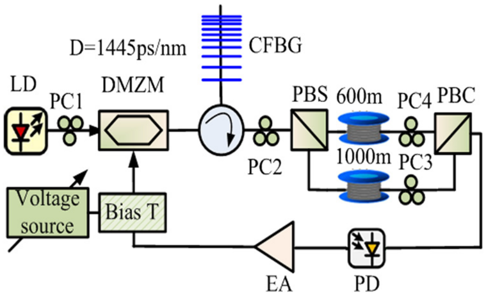

Fig. 1 Schematic diagram of the proposed tunable optoelectronic oscillator (OEO). LD: laser diode; PC: polarization controller; DMZM: dual-electrode Mach–Zehnder modulator; PBS: polarization beam splitter; PBC: polarization beam combiner; EA: electrical amplifier; PD: photonic detector; and CFBG: chirped fiber Bragg grating.

$V\pi$ is the half-wave voltage of the DMZM, V_1 and V_2 are the amplitude of RF signal applied to the DMZM.

In order to form a chirped MZM, we leave one arm unconnected, i.e., $V_2 = 0$, so the chirp of the DMZM is simplified to

$$\alpha = \tan\left(\frac{\pi}{2}\frac{V_{\rm dc} - V_{\rm o} - V_\pi}{V_\pi}\right). \tag{2}$$

Then, the magnitude response of the photonic microwave filter based on the DMZM and the CFBG can be written as[13]

$$|H(f_{\rm m})| \propto |\sqrt{1+\alpha^2}\,\cos(\pi D\lambda^2 f_{\rm m}^2/c + \arctan(\alpha))|, \tag{3}$$

where λ represents the wavelength of the optical carrier. Taking Eq. (2) into Eq. (3), we have

$$|H(f_{\rm m})| \propto \left|\sqrt{1+\alpha^2}\,\cos\left(\pi D\lambda^2 f_m^2/c + \frac{\pi}{2}\frac{V_{\rm dc} - V_o - V_\pi}{V_\pi}\right)\right|. \tag{4}$$

The photonic microwave filter reaches its peaks when

$$\pi D\lambda^2 f_m^2/c + \frac{\pi}{2}\frac{V_{\rm dc} - V_o - V_\pi}{V_\pi} = k\pi, k = 0, 1, 2\ldots, \tag{5}$$

So the center frequencies of the photonic microwave filter are

$$f_m = \sqrt{\left(-\frac{\pi}{2}\frac{V_{\rm dc} - V_o - V_\pi}{V_\pi} + k\pi\right)c/(\pi D\lambda^2)},\quad k = 0, 1, 2\ldots. \tag{6}$$

From Eq. (6), we can see that the center frequencies are sensitive to two parameters, i.e., the chromatic dispersion of the CFBG and the bias voltage of the DMZM. Since the adjustment of the CFBG is difficult and unstable, we can shift the center frequency of the photonic microwave filter to the desired frequency by adjusting the bias voltage. It should be noted that although the optical wavelength is present in Eq. (6), the center frequency of the proposed photonic microwave filter is not as sensitive to the wavelength drift of the LD as those in the previous methods.[7–9] For example, if the center frequency of the photonic microwave filter is 10 GHz and the wavelength drift of the LD is 0.01 nm, the center frequency would drift 1.25 GHz for other methods,[7–9] and only 64.5 kHz for the proposed method.

When the tunable photonic microwave filter is incorporated into the OEO, however, the 3-dB bandwidth is too wide to suppress the intensely spaced competing modes. In order to increase the Q value of the OEO cavity, an optical domain combined dual-loop OEO without adding any active electrical device[14] has been adopted, which is implemented by a polarization beam splitter (PBS), a polarization beam combiner (PBC), two PCs and two sections of single-mode fiber (SMF). When the loop is closed, and sufficient gain is provided by an electrical amplifier (EA), a tunable OEO with high side-mode suppression will be realized.

3 Experiment and Results

An experiment based on the configuration shown in Fig. 1 was carried out. A light wave generated by a tunable laser source (Aglient E1167A) was sent to a DMZM via a PC (PC1). The DMZM (Fujitsu FTM7921ER) has a 3-dB bandwidth of 12 GHz and a half-wave voltage of 4 V. The dispersive element used in the experiment is a CFBG, which has a full width at half maximum of 0.6 nm, a center wavelength of 1558 nm and a dispersion of 1445 ps/nm. The power of the incident light wave to the DMZM is about 13 dBm. The lengths of the SMF in the dual loops are ~600 and ~1000 m. The photonic detector (PD) has a bandwidth of 40 GHz and a responsivity of 0.65 A/W. The gain of the EA was about 40 dB with a bandwidth of 5.8 to 20 GHz. An electrical spectrum analyzer (Agilent E4447AU) was used to observe the electrical spectrum of the generated microwave signal and to measure its phase noise.

Figure 2 shows the open-loop response of the OEO under different bias voltages measured by a vector network analyzer (Agilent E5230B). As can be seen from Fig. 2, the peak of the open-loop response is shifted from 6.5 to 8.3 GHz by simply adjusting the bias voltage from 4.9 to 2.4 V. Although the adjustment of the bias voltage will affect the modulation efficiency of the DMZM since it would not work at the quadrature bias point, the EA in the loop would compensate the decrease of the modulation efficiency if it can provide sufficient gain. Because the frequency of the oscillator is mainly determined by the center frequency of the photonic microwave filter, a tunable OEO can be realized.

When the loop is closed, the OEO starts to oscillate at the frequency around the transmission peak of the photonic microwave filter. Though the band width of the filter is very large, thanks to the Vernier effect formed by the dual-loops which performs the fine mode selection for the OEO, a single

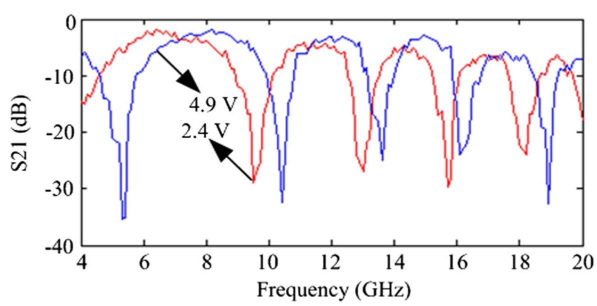

Fig. 2 The open-loop responses of the optoelectronic oscillator (OEO) at different bias voltage.

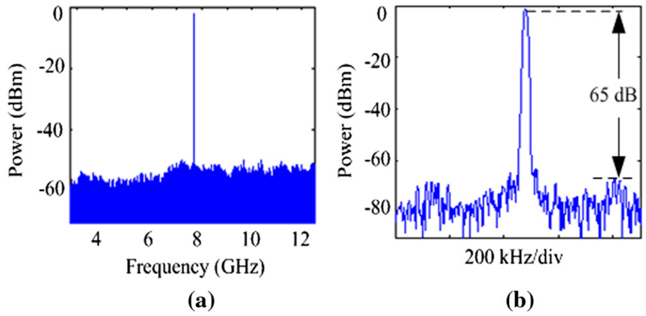

Fig. 3 Measured electrical spectra of the generated microwave signal. (a) The electrical spectrum of the 7.7-GHz microwave signal and (b) the zoom-in view of the 7.7 GHz signal at a span of 1 MHz.

mode frequency will oscillate in the loop. Detail analysis is shown.[8] Figure 3(a) shows a typical electrical spectrum of the oscillating signal, which has a frequency of 7.7 GHz. The zoom-in view of the microwave signal is shown in Fig. 3(b). The side mode suppression ratio is greater than 65 dB, indicating that the spectral purity of the OEO is high. Figure 4 shows the optical spectrum at the output of the PBC. As expected, stable and clear sidebands are observed due to the high-quality single-frequency oscillation. It is known that the PD and EA in the system are both wideband equipment. When the OEO system works, the oscillate frequency and harmonics frequency will also be generated at the output of PD, they are both amplified by the EA, and the power of oscillate frequency is higher than the harmonics frequency, so the harmonics frequency won't affect the performance of OEO.

To evaluate the phase noise performance, the single-sideband phase noise of the generated 7.7 GHz signal is measured with the result shown in Fig. 5. The phase noise of the

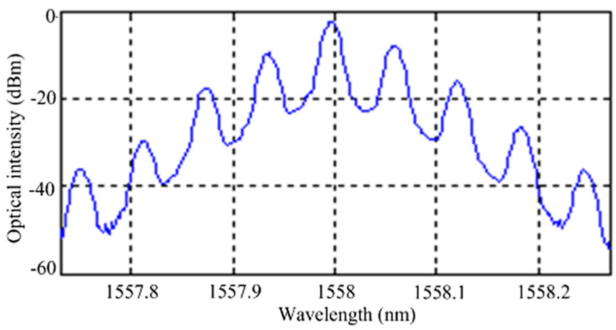

Fig. 4 Measured optical spectrum at the output of the PBC.

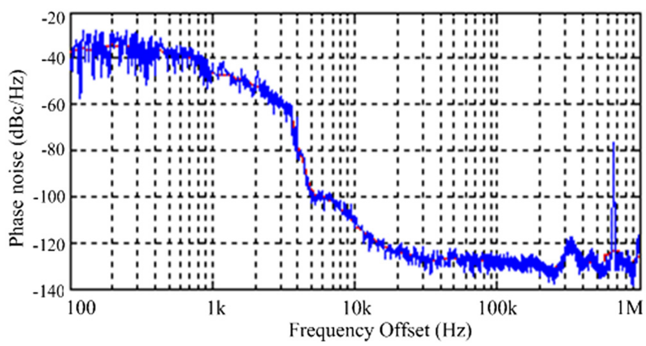

Fig. 5 The phase noise spectrum of the generated microwave signal.

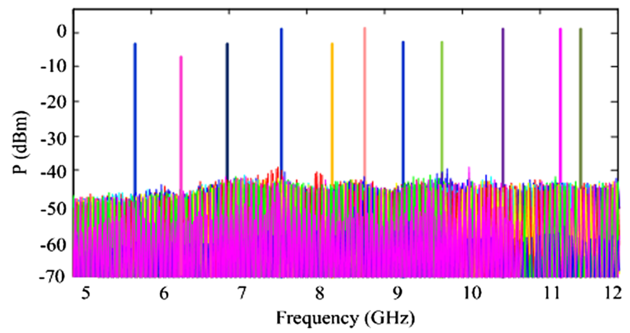

Fig. 6 Electrical spectra of the generated microwave signal under different bias voltages.

generated microwave signal is −112.6 dBc/Hz at 10-kHz frequency offset. It should be noted that the phase noise measurement based on the electrical spectrum analyzer would be affected by the intensity noise, so the actual phase noise performance should be better. Compared with the other tunable OEO schemes,[7–10] the phase noise of the generated microwave is decreased because the longer fiber is adopted. As we know, the phase noise of OEO is mainly dependent on the fiber length[15] in proportion to the fiber length L^2.[16] So the phase noise performance can be further improved if a longer loop is employed. But once the longer fiber is adopted, the fiber dispersion and the nonlinearity of fiber will introduce into the other noise and will worsen the phase noise of generated microwave signal. As the fiber is susceptible to outer temperature, the stability of generated microwave frequency will decrease with the increase of fiber length.

The tunability of the OEO is realized by adjusting the bias voltage of the DMZM. Figure 6 shows the spectrum of the generated microwave signal. The frequency can be tuned from 5.8 to 11.8 GHz. During the frequency tuning, only the bias voltage to the DMZM is adjusted with all other parameters kept unaltered. It should be noted that the voltage source can have very high resolution, so the tuning of the frequency can achieve high accuracy.

The stability of the frequency is also investigated in the lab environment. The frequency drifts about 20 kHz in half an hour. If the temperature of the fiber in the system keeps unchanged, the stability of the frequency will be improved.

4 Conclusion

A novel approach to achieving a frequency-tunable OEO using a chirped MZM and a CFBG was proposed and experimentally demonstrated. A tunable microwave signal from 5.8 to 11.8 GHz was achieved. The frequency of the generated microwave signal could be easily tuned by tuning the bias voltage. The generated microwave signal exhibited a phase noise as low as −112.6 dBc/Hz at an offset of 10 kHz. The phase noise performance can be further improved if a longer loop is employed.

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