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Coupled frequency-doubling optoelectronic oscillator based on polarization modulation and polarization multiplexing

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ABSTRACT

A coupled frequency-doubling optoelectronic oscillator (OEO) is proposed and experimentally demonstrated, which is constructed based on the perfect combination of polarization modulation and polarization multiplexing. A fundamental microwave signal at 9.95 GHz or a frequency-doubled microwave signal at 19.9 GHz is generated with a wavelength-independent sidemode-suppression ratio (SMSR) as high as 78 dB obtained. The phase noise of the generated 19.9-GHz signal is −103.45 dBc/Hz at 10-kHz frequency offset, indicating a good short-term stability. The proposed scheme is simple and flexible, which can find applications in radars and wireless communications.

1. Introduction

Optoelectronic oscillator (OEO) has attracted great interests recently for microwave or millimeter-wave generation and signal processing in various RF and optical systems, such as radars, wireless communications, and modern instrumentation [1,2]. The hybrid optical-electronic scheme with a frequency of tens of gigahertz has shown distinctive advantages of high spectral purity, high RF stability and low phase noise. However, the maximal achievable frequency is limited principally by the bandwidth of the electro-optical modulators and electronic components in the cavity. To expand the range of frequency, frequency-doubling OEOs have been proposed [3–6]. However, the frequency-doubling OEOs either need a high-bandwidth frequency divider or two lasers at designed wavelengths, which is costly and complicated. Recently, Tsuchida and we respectively suggested a frequency-doubling OEO based on a polarization modulator [5,6]. The proposed approach is simple and compact since no high-speed devices, active modulator bias control, and an extra laser diode (LD) are needed. However, the phase noise of the generated fundamental or frequency-doubled microwave signals was high, resulting in poor short-term frequency stability. In addition, the spectral purity was low since several sidemodes around the oscillating signal were still observable. On the other hand, coupled OEOs with multiple loops can effectively improve the phase noise performance and suppress the sidemodes [7–9], but two or more photodiodes (PDs) are always required, which not only demand for more driving circuits, but also increase the power consumption and noise. In addition, the electrically combining of the multiple loops would introduce additional power losses because the electrical power combiner has an intrinsic 3-dB loss. To solve the above problem, an optical domain coupled OEO is proposed [10], but it can only achieve an oscillation at the fundamental frequency.

In this letter, a coupled frequency-doubling OEO based on polarization modulation and polarization multiplexing is proposed and demonstrated. In the OEO, a polarization modulator (PolM) in conjunction with a polarization controller (PC) and a polarization beam splitter (PBS) is used to perform intensity modulation (IM) biased at either the quadrature transmission point or the minimum transmission point [5]. The PBS is also served as a power splitter to form two paths. Each path has a section of single-mode fiber (SMF) and a PC. The two paths are combined by a second PBS. Two polarization-multiplexed loops are thus formed in the OEO. The incorporation of polarization modulation and polarization multiplexing in the OEO not only generates flexibly the fundamental or frequency-doubling microwave signal, but also effectively suppresses the undesirable sidemodes. The key advantage of the proposed approach is that only a single PD is used, which reduces the noise of the generated signal and the cost of the scheme. In addition, the polarization multiplexing would not introduce the 3-dB combining loss, which lowers the gain requirement of an electrical amplifier (EA) in the OEO loop. Besides, the net gain of each loop can be adjusted easily by tuning the PC in each path, making the system flexible.

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2. Principle

The schematic diagram of the coupled frequency-doubling OEO is shown in Fig. 1. A lightwave from a LD is sent to a PolM, and then splits into two branches by an optical coupler. One branch is used to form a feedback loop to generate a fundamental oscillation signal, and the other branch is adjusted to achieve either a fundamental or a frequency-doubling microwave signal [5]. Mathematically, the output of the PolM along with the two polarization axes can be expressed as

$$E_{x,y} = exp[j\omega_c t \pm j\beta sin\omega_m t] \tag{1}$$

where ω_c is the angular frequency of the optical carrier, β is the phase modulation index, and ω_m is the angular frequency of the OEO oscillation frequency. Introduce the signal into a PBS, where the principle axes of the PBS are aligned to have a 45° to one principle axis of the PolM, we have

$$E_1 = \sqrt{2}cos\left(\beta sin\omega_m t - \frac{\pi}{4}\right)e^{j\omega_c t + j\frac{\pi}{4}} \tag{2a}$$

$$E_2 = \sqrt{2}sin\left(\beta sin\omega_m t - \frac{\pi}{4}\right)e^{j\omega_c t + j\frac{3\pi}{4}} \tag{2b}$$

In obtaining Eq. (2), we assume that a PC is inserted before the PBS, which introduces a phase difference of $\pi/2$ between E_x and E_y. From Eqs. (1) and (2), we can see that the PBS simultaneously serves as a polarization-modulation-to-IM converter and a power splitter, which divides the signal into two optical paths with orthogonal polarization states and complementary intensity modulation.

After transmission over fibers with different lengths, the signals in the two paths are combined by a second PBS. Two PCs are inserted in the two paths. Since the PBS has a high selectivity of polarization state in each path, the PCs can be adjusted to introduce optical losses, which equivalently modify the net gain of the loops. The combined signal is sent to a PD. Because the polarizations of the optical lightwaves from the two paths are orthogonal after multiplexing in the second PBS, they would not interfere with each other. The generated electrical signal is amplified, filtered and then fed back to the PolM. The recursive relation of the signal at the output of PD can be written as

$$V_i(\omega_m) = \left(g_1 e^{j\omega_m\tau_1} - g_2 e^{j\omega_m\tau_2}\right)V_{i-1}(\omega_m) \tag{3}$$

where g_1 and g_2 are the complex gains of the two loops, respectively, τ_1 and τ_2 are the time delays, which are mainly determined by the lengths of the fibers in the two loops. The total output at any instant time is the summation of all circulating fields,

$$V_{out}(\omega_m) = \frac{V_0}{1-(g_1 e^{j\omega_m\tau_1} - g_2 e^{j\omega_m\tau_2})} \tag{4}$$

The corresponding microwave power $P(\omega_m)$ is given by

$$P(\omega_m) = \frac{|V_0|^2/2R}{1+|g_1|^2+|g_2|^2-2|g_1||g_2|cos(\varphi_1-\varphi_2)-2(|g_1|cos\varphi_1-|g_2|cos\varphi_2)} \tag{5}$$

where $\varphi_i = \omega_m\tau_i + \theta_i$ $(i=1,2)$, and θ_i is the phase factor of the complex gain g_i. The coupled OEO will oscillate only when the oscillation frequency and microwave power satisfy

$$f_{osc} = k/\tau_1 = (m+1/2)/\tau_2 \tag{6a}$$

$$P(\omega_{osc}) = max\{P(\omega_m)\} \tag{6b}$$

where k and m are integers. Thus, we have

$$\varphi_1 = 2k\pi \tag{7a}$$

$$\varphi_2 = (2m+1)\pi \tag{7b}$$

$$\varphi_1 - \varphi_2 = [2(k-m)+1]\pi \tag{7c}$$

It should be noted that a π-phase is introduced in Eq. (7b) to maximize the signal in the path. Substituting Eq. (7) into Eq. (5) and applying the condition in Eq. (6b), we have

$$1+\left|g_1\right|^2+\left|g_2\right|^2+2\left|g_1\right|\left|g_2\right|-2\left(\left|g_1\right|+\left|g_2\right|\right)=0 \tag{8}$$

which can be simplified to

$$|g_1|+|g_2| = 1 \tag{9}$$

As can be seen, an oscillation mode will start from noise transient when the gains satisfy the condition in Eq. (9) and the phases satisfy the condition in Eq. (7). These strict conditions would result in an oscillation with high SMSR.

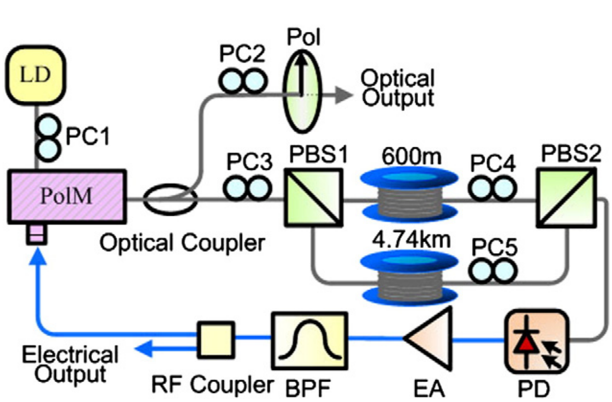

Fig. 1. Schematic diagram of the proposed coupled frequency-doubling OEO based on polarization modulation and polarization multiplexing.

3. Experiment

An experiment based on the setup shown in Fig. 1 is performed. The parameters of the key components are as follows. The wavelength of the LD is 1550 nm; the PolM has a 3-dB bandwidth of 40 GHz; the PD has a responsivity of 0.88 A/W and a 3-dB bandwidth of 10 GHz; the gain of the low-noise EA is 40 dB when operating at 8–18 GHz; the 3-dB bandwidth of the high-Q bandpass filter (BPF) is 11.34 MHz centered at 9.95 GHz; the lengths of the two loops are 600 m and 4.74 km, respectively. To evaluate the performance of the coupled OEO, a second PD with a responsivity of 0.65 A/W and a bandwidth of 40 GHz is used to convert the fundamental or frequency-doubling optical microwave signal into the electrical domain. The electrical spectrum and the single-sideband (SSB) phase noise spectrum are measured by an electrical spectrum analyzer (Agilent E4447AU).

Fig. 2 shows the electrical spectra and phase noise spectra when the OEO is operated at the fundamental frequency, e.g. 9.95 GHz. When the loop with 4.74-km SMF is disabled, the SMSR is less than 60 dB, and the maximal SSB phase noise at the locations of the sidemodes is −90.7 dBc/Hz, as shown in Fig. 2(a) and (b). Fig. 2(c) and (d) shows the case when the loop with 600-m SMF is disabled. Serious multimode oscillation is observed. The phase noise at the locations of the sidemodes reaches −60 dBc/Hz. Fig. 2(e) and (f) shows the performance when both loops enabled. The multimode oscillation almost

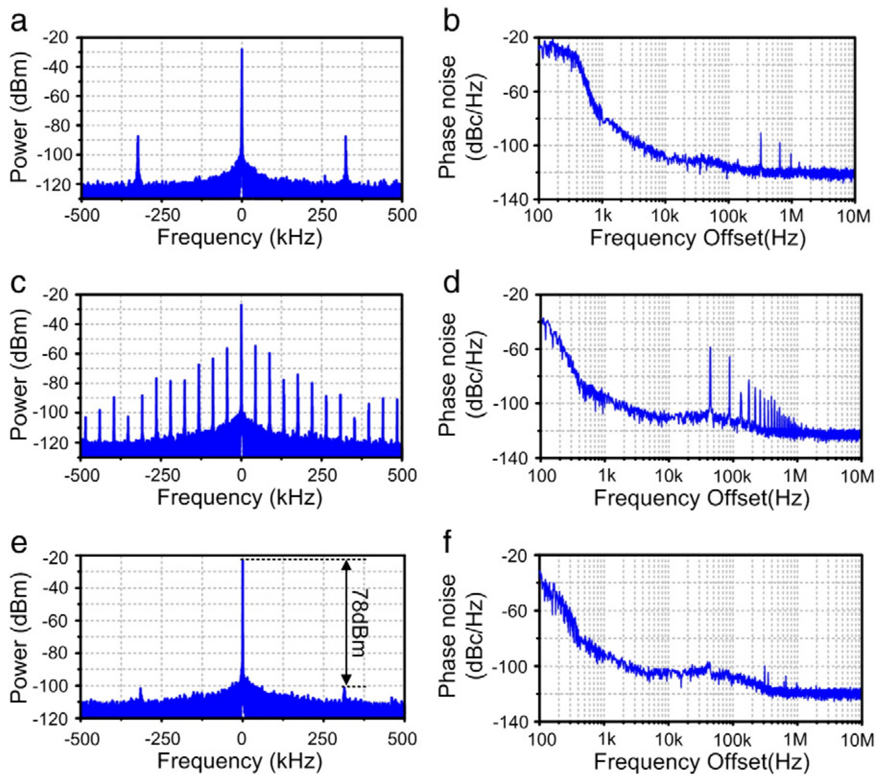

Fig. 2. Electrical spectra and phase noise spectra (a),(b) when the loop with 600-m SMF is enabled; (c),(d) when the loop with 4.74-km SMF is enabled; (e),(f) when both loops are enabled. (a),(c),(e) The electrical spectra with a span of 1 MHz and a RBW of 100 Hz. (b),(d),(f) The phase noise spectra.

disappears. A SMSR as large as 78 dB is achieved. Fig. 3 shows the measured SMSR as a function of the laser wavelength. In the experiment, the wavelength is tuned from 1531 to 1563 nm while other configurations are kept unchanged. As can be seen, all the SMSRs are greater than 71 dB, indicating the operation of the polarization modulation and polarization multiplexing is almost independent on laser wavelength.

The phase noise performance is evaluated when the system is configured to generate a frequency-doubled microwave signal at 19.9-GHz. As shown in Fig. 4, the phase noise of the 19.9-GHz signal is −103.45 dBc/Hz at 10-kHz frequency offset. The maximal phase noise at the locations of the sidemodes is reduced to be −95.4 dBc/Hz. The stability of the frequency-doubled signal in term of phase noise is also studied. Fig. 5 shows the repeated phase noise measurement for about 2 min. The phase noise at 10-kHz frequency offset fluctuates within ±0.4 dBc/Hz, showing that the short-term stability is very good. It should be noted that the phase noise measurement based on the electrical spectrum analyzer would be seriously affected by intensity noise, so the actual phase noise performance should be better than the measured cases.

4. Conclusion

The combination of polarization modulation and polarization multiplexing was introduced to an OEO, to generate a fundamental or frequency-doubling microwave signal, and in the same time to effectively suppress the undesirable sidemodes. Feasibility of the proposed scheme was demonstrated by both theoretical analysis and a proof of concept experiment. A 9.95- and 19.9-GHz microwave signal was generated with a wavelength-independent SMSR as high as 78 dB and a phase noise smaller than −103 dBc/Hz at 10-kHz frequency offset obtained.

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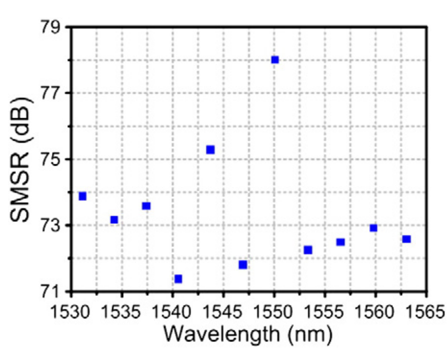

Fig. 3. SMSR as a function of the laser wavelength.

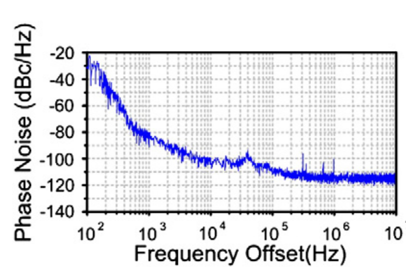

Fig. 4. Phase noise spectrum of the generated 19.9-GHz signals.

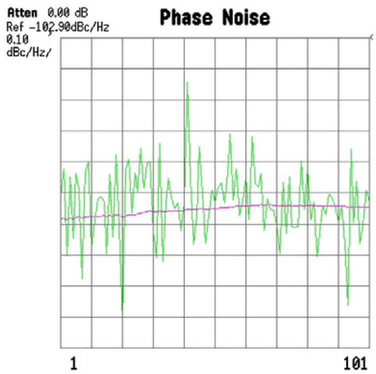

Fig. 5. Repeated phase noise measurement of the frequency-doubled signal at 10-kHz frequency offset.

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