A Frequency-Doubling Optoelectronic Oscillator Using a Polarization Modulator

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***Abstract*—A novel realization of a frequency-doubling optoelectronic oscillator (OEO) using a polarization modulator (PolM) is proposed and experimentally demonstrated. In the proposed system, the PolM in combination with two optical polarizers connected via two polarization controllers (PCs) is operating as a two-output intensity modulator. One output of the intensity modulator is connected to the radio-frequency port of the PolM, to form an optoelectronic loop for the generation of a microwave signal with the fundamental frequency determined by the center frequency of a narrowband electronic filter. The other output of the intensity modulator provides a fundamental or frequency-doubled optically modulated microwave signal depending on the static phase term introduced by the PC before the polarizer. The proposed OEO is experimentally demonstrated. A fundamental microwave signal at 10 GHz or a frequency-doubled microwave signal at 20 GHz is generated. The phase noise performance of the generated microwave signal is also investigated.**

***Index Terms*—Optoelectronic oscillator (OEO), optical microwave generation, clock recovery, polarization modulation.**

I. INTRODUCTION

OPTOELECTRONIC oscillators (OEOs) have shown high performance in microwave and millimeter-wave generation [1], [2] for applications in wireless and optical communications. For example, in an optical communication system, an OEO can be used to achieve clock recovery [3], [4] and format conversion [5]. Usually, a conventional OEO can generate a low-phase-noise microwave signal or a low-timing-jitter optical clock at a small frequency range, which is limited mainly by the bandwidth of the electrooptic modulator. To extend the frequency range, several approaches have been proposed [6]–[8]. Sakamoto *et al.* suggested a frequency-doubling OEO by biasing a $\mathrm{LiNbO_3}$ Mach–Zehnder modulator (MZM) at the minimum transmission point (MITP) [6]. This frequency-doubling OEO was further applied for optical clock recovery [7], showing a potential solution to extract an optical prescaled clock from a high-repetition-rate data signal using only low-frequency devices. The major limitation of the approaches in [6] and [7] is that a high-speed photodetector (PD), a high-frequency electrical amplifier (EA), and an electrical frequency divider are needed to obtain the feedback signal required for the optoelectronic oscillation, which makes the OEO operate only at a relatively low frequency. By using the wavelength-dependent nature of the half-wave voltage of a $\mathrm{LiNbO_3}$ MZM, Shin *et al.* proposed an approach to generating a frequency-doubled microwave signal using an OEO [8]. In the system, two continuous-wave (CW) lasers at 1550 and 1310 nm were used. The bias voltage was carefully adjusted such that the modulation was performed at the quadrature transmission point (QTP) for the wavelength at 1310 nm to produce a low-frequency feedback signal, and the modulation was performed at the MITP for the wavelength at 1550 nm to generate a frequency-doubled signal. The key limitation associated with the operation of an MZM at the MITP is the bias drifting problem, which reduces the system stability or a sophisticated control circuit is needed to stabilize the operation. In addition, for an MZM it is difficult to achieve an ideal 50/50 splitting ratio in the Y-splitter due to the fabrication tolerances. Therefore, a poor suppression of the odd- or even-order sidebands would be resulted, which will degrade the spectral purity of the generated microwave signals. Moreover, two optical sources at two wavelengths are needed, which makes the system more complicated and costly.

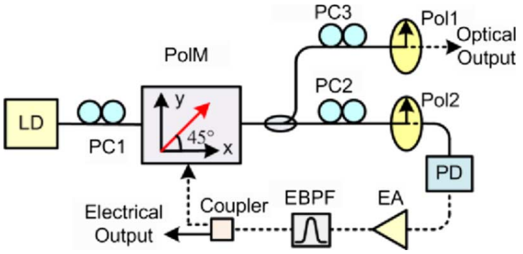

Fig. 1. Schematic diagram of the frequency-doubling OEO. LD: laser diode; Pol: polarizer; EBPF: electrical bandpass filter.

In this letter, we propose a novel and simple frequency-doubling OEO without the need for high frequency electrical devices and an additional optical light source. In the proposed system, a CW light wave from a laser diode is sent to a polarization modulator (PolM), which is connected by two optical polarizers via two polarization controllers (PCs). The PolM is a special phase modulator that can support both transverse-electric and transverse-magnetic modes with however opposite phase modulation indices [9]. When a linearly polarized incident lightwave oriented with an angle of 45° to one principle axis of the PolM is sent to the PolM, a pair of complementary phase-modulated signals are generated along the two principle axes. Applying the two phase-modulated signals to a polarizer with its principal axis oriented at an angle of 45° to one principle axis of the PolM via tuning the PC, the phase-modulated signals will be combined

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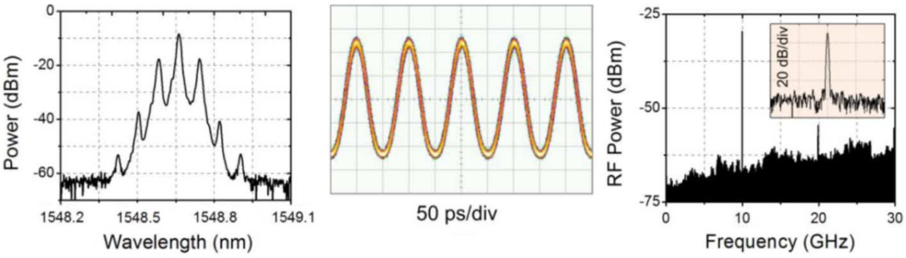


(a) (b) (c)

Fig. 2. Generation of 10-GHz signal using the proposed frequency-doubling OEO. (a) Optical spectrum. (b) Electrical waveform. (c) Electrical spectrum at SPAN 30 GHz and RBW 3 MHz. Inset: the electrical spectrum at SPAN 1 MHz and RBW 9.1 kHz.

to generate an intensity-modulated signal. Depending on the static phase term introduced by the PC, the intensity modulator is operating at either the QTP or the MITP. Therefore, a PolM followed by two polarizers with the polarization directions of the incident light wave to the polarizers adjusted at 45° is equivalent to an intensity modulator with two outputs, to generate two microwave signals at ω_m or $2\omega_m$. In our proposed system, the PC in one branch is adjusted to obtain an optically modulated microwave signal at ω_m, which is fed back to the PolM to enable the optoelectronic oscillation, while the PC in the other branch is adjusted to produce a microwave signal at either ω_m or 2 ω_m. As a result, the system can generate a microwave with a frequency at either the fundamental or the second-harmonic frequency, which enables the extraction of both prescaled and line-rate clocks from a high-speed optical data signal using only low-frequency devices [3], [4], [7]. In addition, since no dc bias is actually required, the system is free from bias drift, ensuring a stable operation.

II. PRINCIPLE

The schematic diagram of the proposed frequency-doubling OEO is shown in Fig. 1. A light wave from a laser diode is fiber coupled to a PolM via a PC (PC1). The PolM is connected by two polarizers via two PCs (PC2 and PC3), which is equivalent to a two-output-port intensity modulator. One output of the intensity modulator is fed back to the radio-frequency port of the PolM to form an OEO loop. A PD is used in the OEO loop to perform optical-to-electrical conversion. To ensure the loop gain is higher than unity which is the condition required to guarantee oscillation, an EA is incorporated. An electrical narrowband bandpass filter (EBPF) is also incorporated in the loop, to select the oscillation frequency.

The normalized optical field at the output of the PolM along the principle axes (x and y) can be expressed as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} \exp[j\omega_c t + j\beta \sin \omega_m t] \\ \exp[j\omega_c t - j\beta \sin \omega_m t] \end{bmatrix} \tag{1}$$

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 oscillating signal. Applying the two signals to a polarizer with its principal axis oriented at an angle of 45° to one principle axis of the PolM, we have

$$E_o = \frac{\sqrt{2}}{2}[E_x + E_y \cdot e^{-j\phi_0}] \tag{2}$$

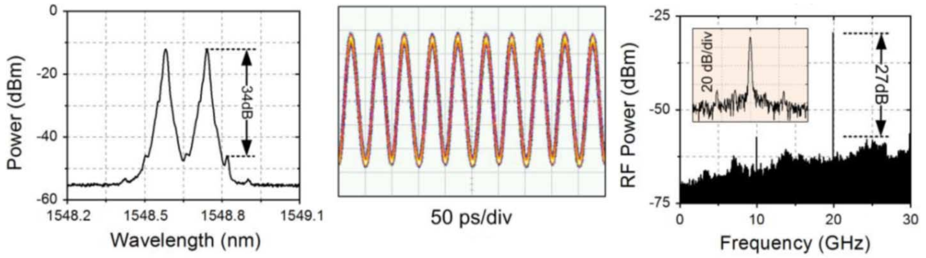
where ϕ_0 is a static phase term introduced by the PC. As can be seen, the obtained optical field is equivalent to an output of an MZM biased at the QTP when $\phi_0 = -\pi/2$, or at the MITP when $\phi_0 = \pi$. By choosing $\phi_0 = -\pi/2$ via tuning PC2 in the OEO loop, the feedback signal at ω_m for optoelectronic oscillation is obtained. Then, PC3 is adjusted to generate optical microwave signals at ω_m or $2\omega_m$.

III. EXPERIMENTAL RESULTS

An experiment is performed based on the setup shown in Fig. 1. The key device in the proposed system is the PolM, which is a commercially available 40-Gb/s GaAs-based PolM from Versawave Technologies [9]. The parameters of the OEO used in the experiment are as follows: the PD has a 3-dB bandwidth of 45 GHz and a responsibility of 0.4 A/W. The bandwidth of the EBPF is 50 MHz centered at 9.95328 GHz. The power gain of the EA is about 55 dB. The phase modulation index of the modulator is around 0.4π. The free spectral range (FSR) of the OEO is measured to be 4.24 MHz. To evaluate the performance of the generated microwave signal, a second 45-GHz PD is used to convert the optical signal to a microwave signal. The waveform is observed by a high-speed sampling oscilloscope (Agilent 86116A) and the spectrum is measured by an electrical spectrum analyzer (Agilent E4448A). In addition, an optical spectrum analyzer (Ando AQ 6317B) with a resolution of 0.01 nm is employed to monitor the optical spectrum.

To generate a 10-GHz optical microwave signal, we adjust PC3 in the output port to let $\phi_0 = -\pi/2$, with the results shown in Fig. 2. Fig. 2(a) shows the optical spectrum, which is a double-sideband modulated optical signal with a wavelength spacing of 0.08 nm or 10 GHz between two neighboring wavelengths. By applying the optical signal at the PD, a microwave signal at 10 GHz is generated, as shown in Fig. 2(b). Fig. 2(c) gives the spectrum of the generated signal. Since PC3 is tuned to generate the fundamental microwave signal, the spectral component of the 10-GHz signal is 25-dB higher than that of its second harmonic. The inset in Fig. 2(c) provides a zoom-in view of the spectral component at 10 GHz.

To generate a frequency-doubled microwave signal at 20-GHz, PC3 is adjusted such that $\phi_0 = \pi$. Fig. 3(a) shows the optical spectrum, which is an intensity-modulated signal with suppressed even-order sidebands. As can be seen, the two first-order sidebands are 34 dB higher than the optical carrier and the second-order sidebands. Excellent even-order sideband suppression is confirmed. The wavelengths of the two first-order sidebands are at 1548.582 and 1548.742 nm, giving



(a) (b) (c)

Fig. 3. Generation of 20-GHz signal using the proposed frequency-doubling OEO. (a) Optical spectrum. (b) Electrical waveform. (c) Electrical spectrum at SPAN 30 GHz and RBW 3 MHz. Inset: the electrical spectrum at SPAN 1 MHz and RBW 9.1 kHz.

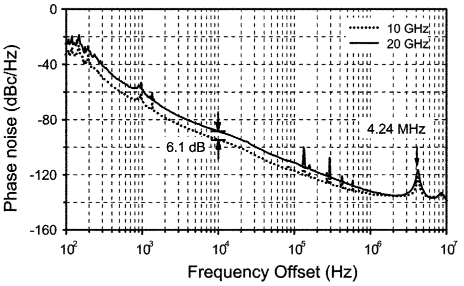


Fig. 4. Phase noise measurement for the generated 10- and 20-GHz signals.

a wavelength spacing of 0.16 nm or 20 GHz. Fig. 3(b) shows the generated microwave signal at 20 GHz. The electrical spectrum of the 20-GHz signal is shown in Fig. 3(c). Although the first and third-order harmonics in the generated microwave signal are observed in the spectrum, they are 27-dB lower than that of the frequency-doubled component. The inset of Fig. 3(c) provides a zoom-in view of the electrical spectrum of the 20-GHz signal.

The key feature of this technique is that no dc bias is needed, which makes the system very stable. To verify this conclusion, we allow the system to operate in a room environment for a period of 60 min; no significant changes in the optical spectrum and the temporal waveform are observed. Since the 10- and 30-GHz components are very small, they are more sensitive to the environmental variations. However, during the entire 60-min period, a 24-dB suppression ratio is always maintained.

The phase noise performance of the generated electrical signals is also studied. Fig. 4 shows the single-sideband (SSB) phase noise spectra of the generated 10- and 20-GHz signals, which are measured by an Agilent E5052B signal source analyzer incorporating an Agilent E5053A downconverter. The phase noises of the 10- and 20-GHz signals are -94.6 and -88.5 dBc/Hz, respectively, at 10-kHz offset frequency. The 20-GHz signal has a 6.1-dB phase noise degradation compared with the 10-GHz signal. Theoretically, the phase noise of a frequency-doubled signal should have a phase noise degradation of about $10\log_{10} 2^2 = 6$ dB. The measurement is consistent with the theoretical prediction. A peak at 4.24 MHz offset frequency, corresponding to the FSR of the OEO resulted from the nonoscillating sidemodes, is shown in the SSB phase noise spectra with a phase noise of -116 dBc/Hz. Considering the resolution bandwidth of the measurement (80 kHz at 4.24-MHz offset), we calculate that the sidemode is suppressed to below -67 dBc.

IV. DISCUSSION AND CONCLUSION

A simple and novel frequency-doubling OEO using a PolM has been proposed and experimentally demonstrated. Compared with the previously reported approaches using an MZM, the proposed technique has three advantages: 1) the use of lower frequency electrical devices and a single optical light source to achieve the same functionality as demonstrated in [6] and [8]. 2) The system can generate a microwave with a frequency at either the fundamental or the second-harmonic frequency. 3) Since no bias is needed, the system is free from bias drift, a serious problem when an MZM is used for frequency-doubling in which the MZM has to be biased at the minimum or maximum transmission point.

An experiment was performed. A microwave signal at the fundamental frequency of 10 GHz or the second-harmonic frequency of 20 GHz was generated. The phase noise performance of the generated signals was evaluated. The proposed approach features a simple and compact structure with stable operation, which may find applications for microwave generation, optical clock recovery and multiplication, and optical format conversion.

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