Frequency-Multiplying Optoelectronic Oscillator With a Tunable Multiplication Factor

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***Abstract*—A frequency-multiplying optoelectronic oscillator (OEO) with a tunable multiplication factor to generate a frequency-quadrupled, sextupled, or octupled microwave signal without using an optical filter is proposed and experimentally demonstrated, for the first time to the best of our knowledge. In the proposed OEO, a polarization modulator (PolM), a polarization controller (PC), and an optical polarizer (Pol) function jointly as a Mach–Zehnder modulator (MZM). Microwave oscillation is achieved in the OEO by feedbacking the intensity-modulated signal to the PolM after photodetection, and the oscillation frequency is determined by the center frequency of an electrical bandpass filter (EBPF) in the loop. A frequency-multiplied microwave signal is generated by a joint use of the PolM and a second modulator to generate two sidebands at the ±second, ±third, or ±fourth orders with the sidebands at other orders fully suppressed. By beating the two sidebands at a second photodetector (PD), a frequency-quadrupled, sextupled, or octupled microwave signal is generated. An experiment is performed. A fundamental microwave signal at 9.957 GHz is generated in the OEO loop, which is multiplied to generate a frequency-quadrupled, sextupled, or octupled microwave signal at 39.828, 59.742, or 79.656 GHz, respectively. The phase-noise performance of the frequency-multiplying microwave signal is also investigated.**

***Index Terms*—Frequency multiplication, microwave generation, microwave photonics, optoelectronic oscillator (OEO).**

I. Introduction

PHOTONIC generation of microwave, millimeter-wave (mm-wave), and terahertz waves has been a topic of interest in the last several years, which can find numerous applications, such as in wireless communications, radar, imaging, and modern instrumentation. Conventionally, a high-frequency microwave signal is generated using a low-frequency electronic oscillator followed by many stages of frequency multiplying circuits to up-convert a low frequency to a high frequency. The system is complicated, and the generated microwave signal has poor spectrum purity due to the existence of many harmonics [1]–[4]. The generation of a microwave signal in the optical domain offers distinct advantages, such as high frequency, high spectrum purity, and large tunability [5]. In addition, since the microwave signal is generated in the optical domain, it can be directly distributed over an optical fiber by taking advantage of the low loss and wide bandwidth offered by the state-of-the-art optical fibers, with no additional electrical to optical conversion needed.

The fundamental technique to generate a microwave signal in the optical domain is to heterodyne two phase-correlated wavelengths at a photodetector (PD). Numerous techniques have been proposed to generate two optical wavelengths that are locked in phase, such as optical phase-locked loop [6] and optical injection locking [7]. Two phase-correlated optical wavelengths can also be generated based on optical nonlinear effects such as four-wave mixing (FWM) [8] and stimulated Brillouin scattering (SBS) [9]. The generation of two phase-correlated optical wavelengths based on external optical modulation using Mach–Zehnder modulators (MZMs) [10], [11] or a phase modulator [12] has been demonstrated.

Frequency multiplication is an effective solution to generate a high-frequency microwave signal from a low-frequency reference source. In the past few years, numerous approaches have been proposed. For example, a frequency-quadrupled [13]–[15], sextupled [16], or octupled [17] microwave signal could be generated using two cascaded MZMs. However, these approaches need a reference microwave source. To generate a low-phase-noise microwave signal, a low-phase-noise reference source is needed.

On the other hand, a low-phase noise microwave signal can be generated using an optoelectronic oscillator (OEO) [18], [19]. An OEO usually consists of a laser source, a modulator, a PD, a microwave or optical amplifier, and a microwave bandpass filter. Due to the low loss, a long optical fiber (loss 0.2 dB/km) can be incorporated in an OEO loop to make the loop have a high Q factor, thus a microwave signal with low phase noise can be generated. To generate a high-frequency microwave signal, the optoelectronic and microwave devices in the loop, such as the modulator, the PD, the microwave amplifier, and the microwave bandpass filter, should operate at high frequency, which would increase the cost of the system. Recently, a few techniques have been proposed to generate frequency-doubled or quadrupled microwave signal using an OEO operating at a low frequency [20]–[23]. Since the oscillation frequency in the OEO loop is two or four times lower, the system cost is significantly reduced. The major limitation of the techniques in [20]–[23] is

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that the multiplication factor is limited to 4. In addition, for a frequency-quadrupling OEO, a narrowband optical filter is always needed to filter out the optical carrier. Thus, the system is complicated, especially for frequency tuning, where the minimum tunable frequency is limited by the bandwidth of the optical filter.

In this paper, we propose a new technique to implement a frequency-multiplying OEO with a tunable multiplication factor up to 8 without using an optical filter. To the best of our knowledge, this is the first time an OEO is demonstrated with a tunable multiplication factor up to 8. The fundamental principal of the approach is to use the OEO to generate a low-frequency reference source and a frequency-multiplied microwave signal is generated by a joint use of the modulator in the OEO loop and a second modulator outside the loop to produce two sidebands at the ±second, ±third, or ±fourth orders with the sidebands at other orders fully suppressed. The modulator in the OEO loop has two functions: to form an OEO loop to generate a low-frequency reference source and to form a frequency multiplier to generate a frequency multiplied microwave signal, which is the key contribution of the work. By beating the two sidebands at a PD, a frequency-quadrupled, sextupled, or octupled microwave signal is generated. A theoretical analysis is performed, which is verified by an experiment. A fundamental oscillation signal with a frequency at 9.957 GHz is generated in the OEO loop, which is multiplied to get a frequency-quadrupled, sextupled, or octupled microwave signal at 39.828, 59.742, or 79.656 GHz. The phase-noise performance of the generation at different multiplication factors is also investigated.

II. Principle of Operation

Fig. 1 shows the schematic of the proposed frequency-multiplying OEO. A linearly polarized light wave from a laser diode (LD) is fiber coupled to a polarization modulator (PolM) via a polarization controller (PC1). The polarization of the incident light wave to the PolM is adjusted to have an angle of 45° relative to one principal axis of the PolM. The signal at the output of the PolM is split into two parts by an optical coupler (OC), with one part sent to a polarizer (Pol1) via a second PC (PC2), and the other part sent to a second modulator, which is an MZM. The joint operation of the PolM, PC2, and Pol1 is equivalent to an MZM (called equivalent MZM or e-MZM1) [21]. The optical signal at the output of Pol1 is sent to a long fiber before being detected by a PD (PD1). The electrical signal at the output of PD1 is amplified by two electronic amplifiers (EA1 and EA2) and then applied to a high-Q electrical bandpass filter (EBPF) before being sent back to the PolM to form the OEO loop. A fundamental microwave signal with a frequency determined by the center frequency of the EBPF is generated by the OEO. The frequency multiplication operation is performed by a joint use of the PolM and the MZM. As can be seen, the optical signal from the PolM is sent to the MZM via a third PC (PC3) and a second polarizer (Pol2). The MZM is driven by the fundamental microwave signal from the output of the EBPF using a 3-dB electrical coupler. An electrical phase shifter is incorporated between the output port of the electrical coupler and the RF port of the MZM. By tuning the bias point of the MZM, the phase shift of the phase shifter, and the static phase of PC3, two sidebands at the ±second, ±third, or ±fourth orders are generated with the sidebands at other orders fully suppressed. By beating the two sidebands at a second PD (PD2), a frequency-quadrupled, sextupled, or octupled microwave signal is generated.

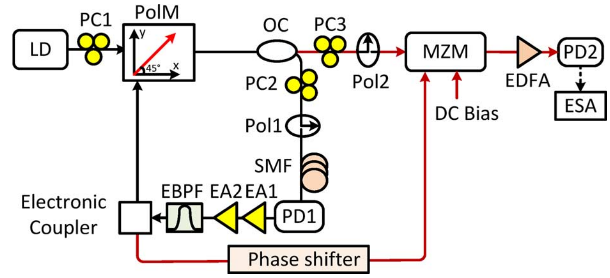

Fig. 1. Schematic of the proposed frequency-multiplying OEO. LD: laser diode; PC: polarization controller; Pol: Polarizer; SMF: single-mode fiber; EA: electrical amplifier; EBPF: electrical bandpass filter; EDFA: erbium-doped fiber amplifier; ESA: electrical spectrum analyzer; OC: optical coupler.

We assume that the optical field of the light wave from the LD is

$$E_0(t) = E_0 \exp(j\omega_c t + j\varphi_0) \tag{1}$$

where E_0, ω_c, and φ_0 are the amplitude, the angular frequency, and the initial phase of the optical carrier, respectively. PC1 is used to adjust the polarization direction of the incident light wave to have an angle of 45° with respect to one principal axis of the PolM. When the OEO starts oscillation, the optical field at the output of the PolM along the two principle axes (x and y) can be expressed as

$$\begin{bmatrix} E_x(t) \\ E_y(t) \end{bmatrix} = \frac{\sqrt{2}}{2}\alpha E_0 \begin{bmatrix} \exp(j\omega_c t + jm\sin\omega_s t + j\varphi_0) \\ \exp(j\omega_c t - jm\sin\omega_s t + j\varphi_0) \end{bmatrix} \tag{2}$$

where ω_s is the oscillating frequency and V_0 is its amplitude, m is the phase modulation index given by $m = \pi V_0/V_{\pi 1}$, $V_{\pi 1}$ is the half-wave voltage of the PolM, and $1-\alpha^2$ is the insertion loss of the PolM. Part of the two signals are obtained from one output port of the OC and are applied to Pol1 via PC2 with its principal axis oriented at an angle of 45° to one principle axis of the PolM, we have

$$E_1(t) = \frac{\sqrt{2}}{2}\left[E_x(t) + E_y(t)\, e^{-j\theta_0}\right] \tag{3}$$

where θ_0 is the static phase term introduced by PC2. The joint operation of the PolM, PC2, and Pol1 is equivalent to an MZM (e-MZM1) that is biased at the maximum transmission point (MATP) for $\theta_0 = 0$, at the quadrature transmission point (QTP) for $\theta_0 = \pi/2$, or at the minimum transmission point (MITP) for $\theta_0 = \pi$. In the OEO loop, e-MZM1 is biased at the QTP by tuning PC2 to generate a fundamental microwave signal with its frequency determined by the center frequency of the EBPF.

The frequency-multiplying operation is performed by a joint use of the PolM and the MZM. As can be seen, the PolM operates jointly with PC3 and Pol2 to form another equivalent MZM (e-MZM2), with the bias point set by tuning PC3, which operates with the second modulator (the MZM) to form a frequency-multiplying module to generate a frequency-multiplied microwave signal with the tunable multiplication factor determined by the bias point of the MZM, the phase shift of the phase shifter and the static phase shift of PC3.

Specifically, when the phase shift introduced by the phase shifter is $\pi/2$, and e-MZM2 and the MZM are both biased at the MITP, only two $\pm$second-order sidebands are generated at the output of the second MZM with the sidebands at other orders fully suppressed. By beating the two sidebands at PD2, a frequency-quadrupled microwave signal is generated.

When the phase shift introduce by the phase shifter is 0, e-MZM2 is biased at the MATP, the MZM is biased at the MITP, and $m = \beta = 1.9154$, where β is the phase modulation index of the MZM, only two $\pm$third-order sidebands are generated at the output of the MZM with the sidebands at other orders fully suppressed. By beating the two sidebands at PD2, a frequency-sextupled microwave signal is generated. The condition $m = \beta = 1.9154$ is satisfied by increasing the powers of the fundamental microwave signal to the two modulators. Note that the condition $m = \beta = 1.9154$ is required if we consider the sidebands at the outputs of the two modulators up to the fourth order. In fact, the condition can be loosened by only letting m equals to 1.9154, and choosing a relatively lower value for β, if we only consider the sidebands up to the second order. In this case, the condition to realize frequency sextupling is independent of β.

When the phase shift introduced by the phase shifter is $\pi/2$, e-MZM2 and the MZM are both biased at the MATP, and $m = \beta = 1.7005$, only two $\pm$fourth-order sidebands are generated at the output of the MZM with the sidebands at other orders fully suppressed. By beating the two sidebands at PD2, a frequency-octupled microwave signal is generated. Furthermore, when the phase shift is $\pi/4$, e-MZM2 and the MZM are both biased at the MATP, and $m = \beta = 2.2650$, again only two $\pm$fourth-order sidebands are generated with the sidebands at other orders fully suppressed, thus a frequency-octupled microwave signal can also be generated. Note that the two conditions ($m = \beta = 1.7005$ and $m = \beta = 2.2650$) are required if we consider the sidebands up to the fourth order at the outputs of the two modulators. Fig. 2 shows the distributions of the optical carrier, the second-order sidebands and the fourth-order sidebands as a function of the modulation indices. By comparing Fig. 2(a) and (b), we can see that the $\pm$fourth-order sidebands are dominant when the phase shift is $\pi/4$ (the modulation index is 2.2650), which is more than five times greater than that when the phase shift is $\pi/2$ (the modulation index is 1.7005). Thus, the case when the phase shift is $\pi/4$ has a better tolerance to modulation index deviation. However, based on the Bessel function property, a greater modulation index would lead to greater power distributions of the sidebands with orders higher than 4 which is not desirable since the spectrum purity may be deteriorated. Compared with the case when the phase shift is $\pi/4$, the modulation index is 1.7005 for a phase shift of $\pi/2$, which is much lower, and thus the influence caused by sidebands higher than the fourth order is much smaller, which is easy to be seen in the experimental results.

A detailed discussion on the conditions for the generation of a frequency-quadrupled, sextupled, and octupled microwave signal using two cascaded MZMs can be found in [10].

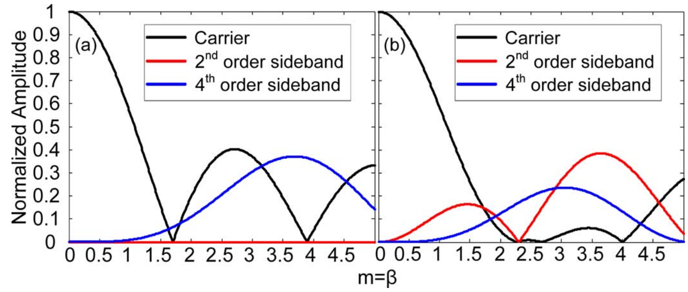

Fig. 2. Variations of the amplitudes of the desired fourth-order sidebands and undesired carrier and second-order sidebands versus m and β for a phase shift of the phase shifter is (a) $\pi/2$ and (b) $\pi/4$.

III. Experiment and Discussion

An experiment based on the setup shown in Fig. 1 is performed. A linearly polarized light wave at 1550.34 nm with a power of 13 dBm from a tunable laser source (Agilent N7714A) is sent to the PolM (Versawave) via PC1. The polarization of the light wave is adjusted by tuning PC1 to have an angle of 45° relative to one principal axis of the PolM. The PolM has a bandwidth of 40 GHz and an insertion loss of 3 dB. A PD with a bandwidth of 10 GHz is used in the OEO loop (PD1). The total length of the OEO loop is about 440 m. EA1 in in the OEO loop is a low-noise microwave amplifier (Anvanteck) with a bandwidth 10 GHz from 8 to 18 GHz and a signal gain of about 40 dB. EA2 is a high-power amplifier (Lucix) with a bandwidth of 12 GHz from 6 to 18 GHz and a gain of 34 dB. The fundamental oscillation frequency is determined by the EBPF in the OEO loop which has a 3-dB bandwidth of 30 MHz centered at 9.957 GHz. The MZM for frequency multiplication is a 20-GHz MZM (JDS-U) with an insertion loss of about 6 dB. To compensate for the insertion loss, an EDFA (MPB EFA-R35/130) with a gain of 27 dB is connected at the output of the MZM. The frequency-multiplied signal is generated at PD2, which is a 50-GHz PD for frequency quadrupling (with a responsivity of 0.65 A/W) or a 100-GHz PD (with a responsivity of 0.5 A/W) for frequency sextupling and octupling.

A. OEO Loop

In the OEO loop, PC2 is adjusted to let $\theta_0 = \pi/2$ to make e-MZM1 biased at the QTP. When the loop is closed, a fundamental microwave signal is generated. The spectrum measured by an electrical spectrum analyzer (ESA, Agilent E4448A) is shown in Fig. 3. The oscillation frequency is 9.957 GHz, which is determined by the center frequency of the EBPF. The second-order harmonic also appears in the electrical spectrum, but it is much smaller (39.1 dB) than the fundamental frequency.

B. Frequency Quadrupling

The fundamental microwave signal is then sent to the MZM for frequency-multiplied microwave generation. As discussed in Section II, the PolM, PC3, and Pol2 jointly operate as an equivalent MZM (e-MZM2) with the bias determined by the static phase shift introduced by PC3. To achieve frequency quadrupling, PC3 is tuned to introduce a static phase shift of $\theta_0 = \pi$ to make e-MZM2 biased at the MITP. Thus, a double-sideband with suppressed carrier (DSB-SC) modulation is achieved, as shown in Fig. 4(a), where two first-order sidebands are clearly shown. The DSB-SC optical signal is injected into the MZM, which is also biased at the MITP. The electrical phase shifter is tuned to introduce a $\pi/2$ phase shift between the two paths

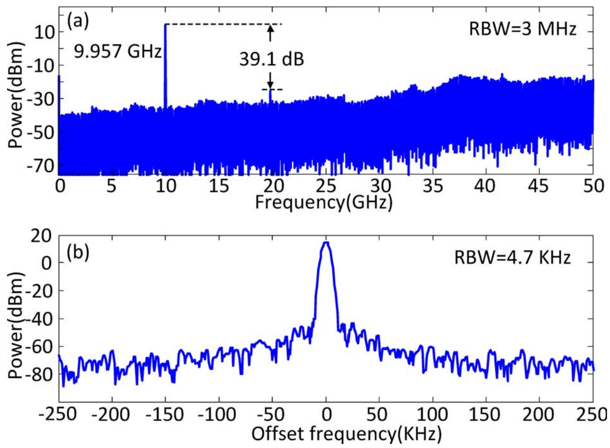

Fig. 3. Fundamental microwave signal generated by the OEO. (a) Electrical spectrum of the generated signal at 9.957 GHz. (b) Zoom-in view of the spectrum.

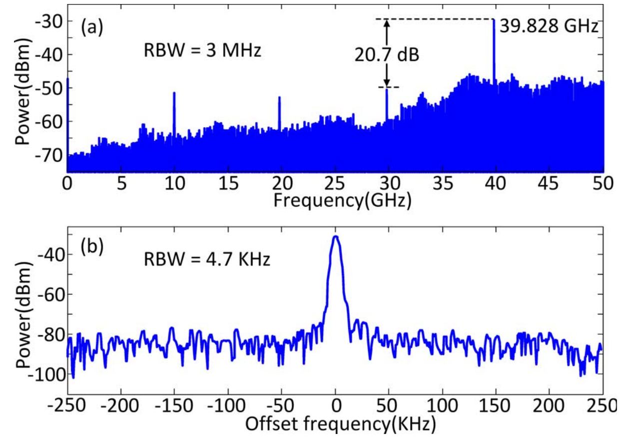

Fig. 5. (a) Electrical spectrum of the generated frequency-quadrupled signal at 39.828 GHz. (b) Zoom-in view of the spectrum.

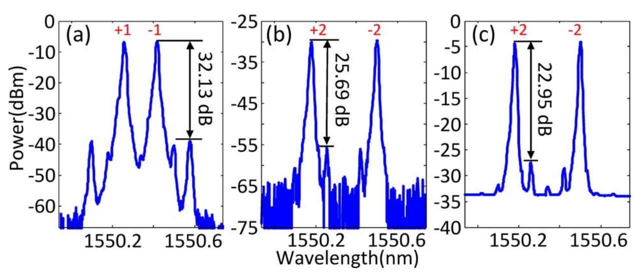

Fig. 4. Optical spectra for frequency quadrupling. (a) Optical spectrum at the output of Pol2. (b) Optical spectrum at the output of the MZM. (c) Optical spectrum at the output of EDFA.

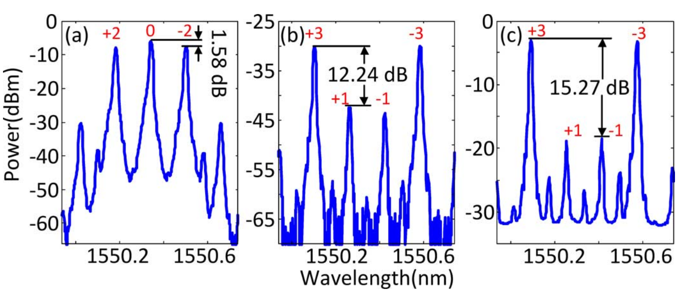

Fig. 6. Optical spectra for frequency sextupling. (a) Optical spectrum at the output of Pol2. (b) Optical spectrum at the output of the MZM. (c) Optical spectrum at the output of the EDFA.

of the electrical signals applied to the PolM and the MZM. The optical spectrum at the output of the MZM is shown in Fig. 4(b), where the ±second-order sidebands are dominant, and the ±first-order sidebands are 25.69 dB smaller than the ±second-order sidebands. The optical signal is amplified by the EDFA with the amplified optical spectrum shown in Fig. 4(c). The amplified optical spectrum is applied to PD2. A frequency quadrupled microwave signal at 39.828 GHz is thus generated. The spectrum is shown in Fig. 5. As can be seen, the power of the frequency-quadrupled signal has a power 20.7 dB greater than the third harmonic, which is the next highest harmonic in this experiment.

C. Frequency Sextupling

As discussed in Section II, if we only consider the sidebands up to the 2nd order at the outputs of the two modulators, the condition to realize frequency sextupling is $m = 1.9154$ and β can have an arbitrary value. In the experiment, we set the modulation index m of the PolM at 1.9154 and use a smaller modulation index β of the MZM. In the experiment, PC3 is tuned to make $\theta_0 = 0$ such that the equivalent MZM (e-MZM2) is biased at MATP. The spectrum of the generated optical signal at the output of Pol2 is shown in Fig. 6(a), where the optical carrier and the second-order sidebands are generated with the odd-order sidebands suppressed. Then, the optical signal is injected into the MZM, which is biased at the MITP. The fundamental microwave signal from the electrical coupler is applied to the MZM via the electrical phase shifter. The phase shift is adjusted to make the fundamental microwave signals applied to the PolM and the MZM with no phase difference. The optical spectrum at the output of the MZM is shown in Fig. 6(b). Fig. 6(c) shows the optical spectrum after amplification by the EDFA. As can be seen the largest undesired sidebands are the ±first-order sidebands, which are 15.27 dB smaller than the desired ±third-order sidebands. The amplified optical signal is injected into the 100-GHz PD. A frequency-sextupled microwave signal is generated and its spectrum is shown in Fig. 7. Since the frequency of the generated microwave signal exceeds the measurement range of the ESA, a waveguide mixer (Tektronix WM 490U) is used jointly with the ESA to measure the electrical spectrum.

D. Frequency Octupling

Again, as discussed in Section II, to realize frequency octupling, the modulation indices should be $m = \beta = 1.7005$ with a phase shift of $\pi/2$ or $m = \beta = 2.2650$ with a phase shift of $\pi/4$. Since the MZM available for the experiment has a much larger half-wave voltage compared with the PolM, to simplify the implementation, a second PolM (PolM2) having an identical half-wave voltage with that of the first PolM (PolM1) is used to replace the MZM. The schematic of the system is shown in Fig. 8, in which PolM2 operating jointly with PC4, PC5 and Pol3 is equivalent to the MZM.

When the phase shift introduced by the phase shifter is $\pi/2$, the two equivalent MZMs are both biased at the MATP, and $m = \beta = 1.7005$, only two ±fourth-order sidebands are generated at

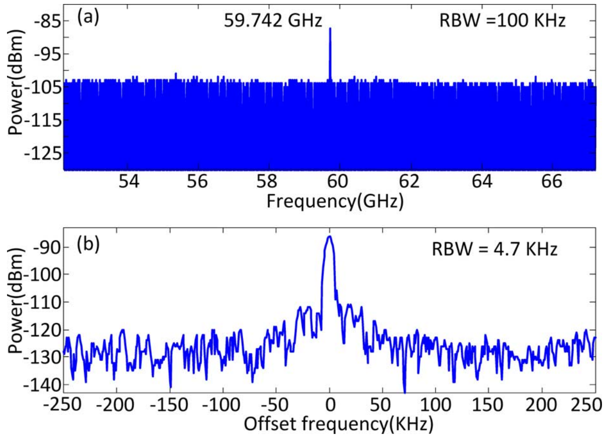

Fig. 7. (a) Electrical spectrum of the frequency-sextupled microwave signal at 59.742 GHz. (b) Zoom-in view of the spectrum.

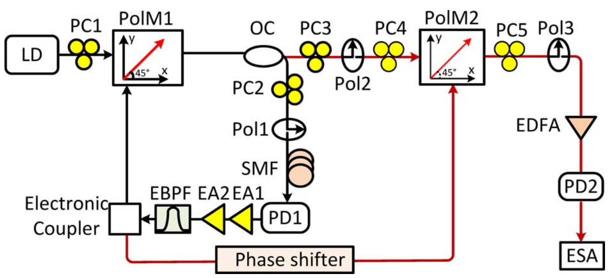

Fig. 8. Schematic of the proposed frequency-octupling OEO using two PolMs.

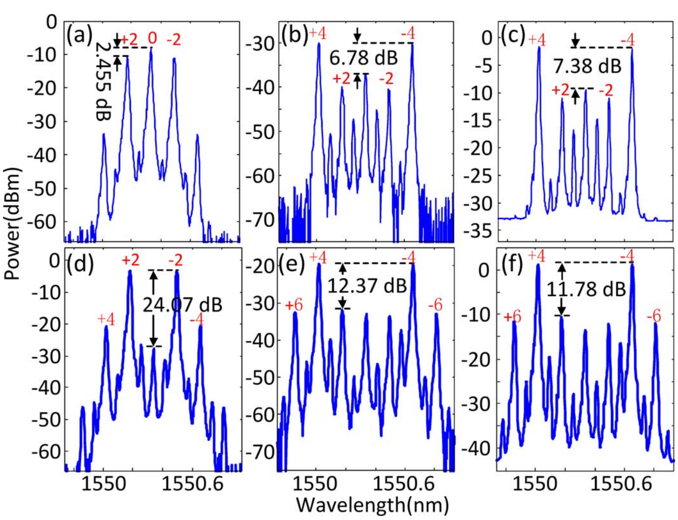

Fig. 9. Optical spectra for frequency octupling when $m = \beta = 1.7005$. (a) Optical spectrum at the output of Pol2. (b) Optical spectrum at the output of Pol3 (c) Optical spectrum at the output of the EDFA. Optical spectra for frequency octupling when $m = \beta = 2.2650$. (d) Optical spectrum at the output of Pol2. (e) Optical spectrum at the output of Pol3. (f) Optical spectrum at the output of the EDFA.

the output of Pol3 with the sidebands at other orders suppressed. The optical spectra are shown in Fig. 9(a)–(c).

When the phase shift is $\pi/4$, the two equivalent MZMs are both biased at the MATP, and $m = \beta = 2.2650$, again only two $\pm$fourth-order sidebands are generated at the output of Pol3 with the sidebands at other orders suppressed. The optical spectra are shown in Fig. 9(d)–(f).

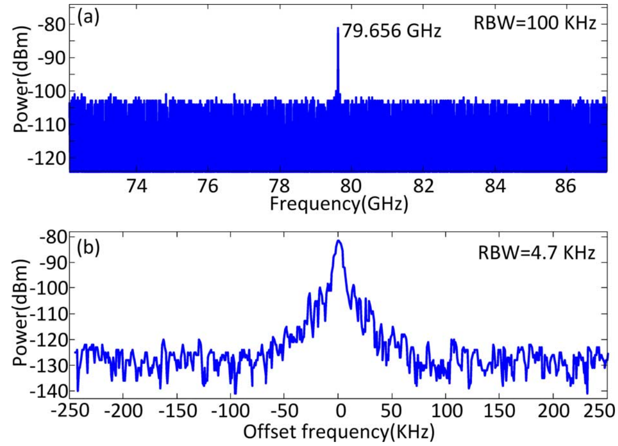

Fig. 10. (a) Electrical spectrum of the generated frequency-octupled signal at 79.656 GHz. (b) Zoom-in view of the spectrum.

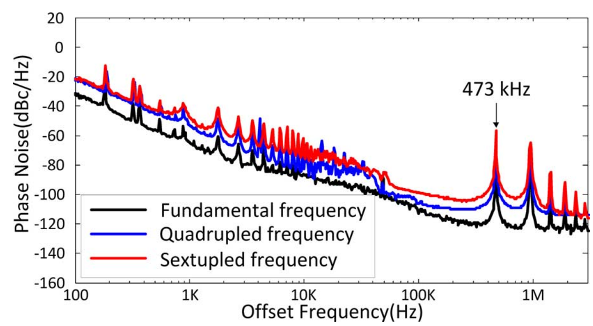

Fig. 11. Phase-noise measurements for the fundamental (9.957 GHz), frequency-quadrupled (39.828 GHz), and sextupled (59.742 GHz) microwave signals.

By beating the two fourth-order sidebands, shown in Fig. 9(f), at PD2, a frequency-octupled microwave signal at 79.656 GHz is generated. The spectrum of the signal is shown in Fig. 10.

E. Stability and Phase Noise Performance

The stability of the proposed OEO-based microwave generation scheme is investigated. Since no optical filter is employed, the system is not sensitive to the wavelength drifts of the LD. Thus, a good stability is maintained. In the experiment, the system is allowed to operate in a room environment for 20 min. No significant changes in the spectrum of the generated microwave signal are observed. We should note that the configuration is polarization-dependent since polarization-dependent components are employed, such as the PolM, the MZM, the PCs, and the Pols. To avoid instability caused by the drifts of the polarizations, in the experiment, the polarization states are well controlled to ensure that the polarization states stay fixed.

The phase-noise performance of at the generated microwave signals with different multiplication factors is also evaluated, which is done by using a signal source analyzer (Agilent E5052B) with a microwave down converter (Agilent E5053A) and a waveguide harmonic mixer (Agilent 11970A or 11970U). The phase-noise measurements of the fundamental, frequency-quadrupled, and sextupled signals at 9.957, 39.828, and 59.742 GHz are shown in Fig. 11. The phase noises at the 100-kHz offset frequency are, respectively, -113, -106, and -98.8 dBc/Hz. The phase noise of the frequency-octupled

TABLE I
COMPARISON OF DIFFERENT MICROWAVE GENERATION SYSTEMS

<table>
<tr><th colspan="2"></th><th>RF source free</th><th>Frequency multiplication factor</th><th>Size</th><th>Stability</th><th>Harmonic suppression</th><th>Phase noise performance</th></tr>
<tr><td colspan="2">Our system</td><td rowspan="3">Yes</td><td>Medium</td><td rowspan="3">Large</td><td rowspan="2">Good</td><td rowspan="4">Good</td><td rowspan="3">Excellent</td></tr>
<tr><td rowspan="2">Other OEOs</td><td>Without optical filtering [20-21]</td><td>Very small</td></tr>
<tr><td>With optical filtering [22-23]</td><td>Small</td><td>Fair</td></tr>
<tr><td colspan="2">Optical external modulation [10-17]</td><td rowspan="2">No</td><td>Large</td><td>Medium</td><td>Very good</td><td rowspan="2">Determined mainly by the RF source</td></tr>
<tr><td colspan="2">RFICs [1-4]</td><td>Very large</td><td>Small</td><td>Excellent</td><td>Poor</td></tr>
</table>

*Optical microwave generation systems are all implemented based on discrete components. The size can be greatly reduced and the stability can be greatly improved by RF and photonics integration [26].

signal at 79.656 GHz is not measured because the frequency exceeds the measuring range of the instrument.

Some peaks at integral multiples of 473 kHz are observed, this is due to the eigenmodes in the OEO loop which are separated by the free spectral range (FSR) of the loop, which is 473 kHz. From 1 to 10 kHz, some peaks with frequency spacing of about 900 Hz are also observed, which are caused by the tunable laser source (Agilent N7714A). The phase noise performance can be improved if a high quality laser source with an ultra-low linewidth [24] and low relative intensity noise (RIN) [25] is employed, since the phase noise and the RIN can be converted to the microwave phase noise via dispersion and nonlinearities in the optical link.

To have a better understanding of the characteristics of the microwave generation techniques, a comparison is made in which the proposed system, other optical microwave generation systems and radio-frequency integrated circuits (RFICs) are considered, which is shown in Table I.

IV. CONCLUSION

A frequency-multiplying OEO with a tunable multiplication factor was proposed and experimentally demonstrated. The fundamental concept of the technique was the use of an OEO to generate a fundamental microwave signal at a relatively low frequency and then a joint use of the first modulator in the OEO loop and a second modulator to generate a frequency multiplied microwave signal. The key contribution of the work is the dual use of the modulator in the OEO which functions to generate a fundamental microwave signal and to perform frequency multiplication. The proposed technique has two major advantages: 1) the multiplication factor is tunable and 2) no optical filter is employed. Since no optical filter was employed, the system stability was significantly improved. An experiment was performed. A fundamental microwave signal at 9.957 GHz and its frequency-quadrupled, sextupled, and octupled signals at 39.828, 59.742, and 79.656 GHz were generated. The phase-noise performance of the generated microwave signals was also evaluated. The proposed system has a potential to generate sub-terahertz wave if PD2 is replaced by a PD with wider bandwidth.

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