Investigation of Photonically Assisted Microwave Frequency Multiplication Based on External Modulation

Wangzhe Li, *Student Member, IEEE*, and Jianping Yao, *Senior Member, IEEE*

***Abstract*—Microwave frequency multiplication based on external modulation using two cascaded Mach–Zehnder modulators (MZMs) has been considered an effective solution for high-frequency and frequency-tunable microwave signal generation. Different techniques have been demonstrated recently, but no generalized approach has been developed. In this paper, a generalized approach to achieving microwave frequency multiplication using two cascaded MZMs is presented. A theoretical analysis leading to the operating conditions to achieve frequency quadrupling, sextupling, or octupling is developed. The system performance in terms of phase noise, tunability, and stability is also investigated.**

***Index Terms*—Microwave photonics, microwave frequency multiplication, Mach–Zehnder modulator (MZM), microwave, terahertz wave.**

I. INTRODUCTION

GENERATION of a low phase-noise, high-frequency, and frequency-tunable microwave signal in the optical domain has been intensively studied in the last few years. Compared with the conventional electronic approaches, the generation of a microwave signal in the optical domain offers distinct advantages such as wide frequency tunability and high spectral purity [1]. In addition, since the microwave signals are generated in the optical domain, the signals can be easily distributed over optical fiber without the need for additional electrical to optical conversion. The fundamental principle to generate a high-frequency and low-phase-noise microwave signal is to heterodyne two optical waves at a photodetector (PD). To ensure that the generated microwave signal has a low phase noise, the two optical waves must be phase correlated. Various techniques have been proposed to generate two optical waves with high phase correlation. These techniques can be generally classified into three categories [2]: 1) optical injection locking (OIL) [3]; 2) optical phase-lock loop (OPLL) [4], [5]; and 3) external modulation [6]–[20].

An OIL system usually consists of a master laser and two slave lasers. The master laser is usually directly modulated by a low-frequency microwave signal. Due to the frequency modulation in the master laser, multiple spectral lines corresponding to different orders of sidebands would be generated. If the free-running wavelengths of the slave lasers are close to two wavelengths of the spectral lines (say, +second-order and –second-order sidebands), the injection of the multiple spectral lines into the slave lasers would make the output wavelengths of the slave lasers be locked. The beating of the two wavelengths from the slave lasers would generate a low-phase-noise microwave signal with the frequency that is four times the frequency of the microwave drive signal.

Two wavelengths with phase correlation can also be achieved using an OPLL. In an OPLL, the two wavelengths from two laser sources are sent to a PD to generate a beat note. The beat note is sent to a phase detector that consists of an electrical mixer and a low-pass filter. A microwave reference is sent to the mixer with its phase to be compared with that of the beat note. A signal with a voltage that is proportional to the phase difference of the reference and the beat note is generated at the output of the low-pass filter and is sent to one laser to control its phase. Once phase locked, two phase-correlated optical waves are generated. The major difficulty in implementing an OPLL is that the loop length should be controlled short, which is essential to ensure a successful locking of the phase terms of the two optical waves [4]. The use of two laser sources with narrow linewidth could ease the requirement for a short loop length, but at a higher cost. Another solution is to use a hybrid system that combines the two techniques of optical injection locking and optical phase-lock loop [5].

The generation of a microwave signal can also be done using external modulation. The key significance of using external modulation is the system simplicity, frequency tunability, and operation stability. O'Reilly *et al.* first proposed and demonstrated a frequency doubling system using a single Mach–Zehnder modulator (MZM) that was biased at the minimum transmission point (MITP) to eliminate all the even-order sidebands. If the modulation signal is small, then the higher order sidebands are small and are ignored. Therefore, only the two first-order sidebands would be present at the output of the MZM. The beating of the two sidebands at a PD would generate a microwave signal with a frequency that is twice that of the sinusoidal drive signal [6].

To achieve a higher multiplication factor, O'Reilly *et al.* demonstrated an approach to achieving frequency quadrupling using an MZM biased at the maximum transmission point (MATP) to suppress all the odd-order sidebands [7]. By incorporating a Mach–Zehnder interferometer (MZI) to select the +second-order and –second-order sidebands, a frequency-quadrupled microwave signal was generated. However, the frequency tunability of the generated microwave signal was limited due to the fixed free spectral range (FSR) of the MZI. To

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The authors are with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, ON, Canada K1N 6N5 (e-mail: jpyao@site.uottawa.ca).

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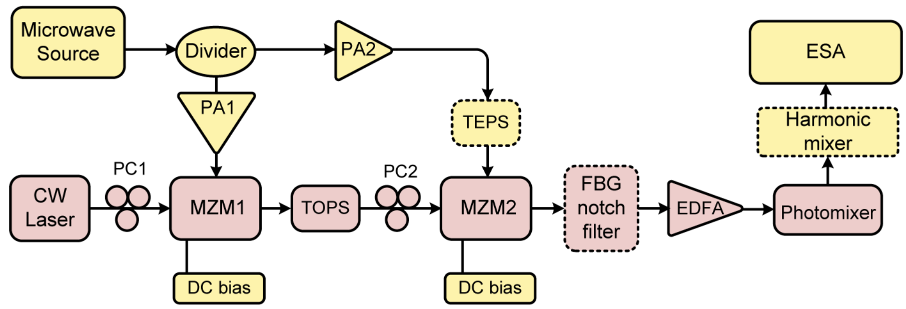


Fig. 1. Schematic diagram of a generalized microwave frequency multiplication system using two cascaded MZMs. The TOPS can be replaced by a TEPS shown in the dotted box. A wavelength-fixed FBG notch filter may be incorporated to remove the optical carrier. A harmonic mixer may also be added to down-convert the generated microwave frequency to make it measurable by the ESA. CW: continuous wave. MZM: Mach–Zehnder modulator. TOPS: tunable optical phase shifter. FBG: fiber Bragg grating. EDFA: erbium-doped fiber amplifier. TEPS: tunable electrical phase shifter. PA: power amplifier.

avoid using an MZI, Qi *et al.* proposed to use a narrow-bandwidth fiber Bragg grating (FBG) to remove the optical carrier [8]. Since the FBG has a narrow bandwidth and its central wavelength is not required to be tunable, the system provides good frequency tunability. The use of a phase modulator to achieve microwave frequency quadrupling has also been proposed [9]. The key advantage of using a phase modulator is the better long-term stability, since a phase modulator is not biased, which makes the system free from dc bias drift.

The low optical extinction ratio of an MZM caused by the imperfect optical division at the input Y-splitter would cause an imperfect elimination of unwanted optical sidebands, which would degrade the optical sideband suppression ratio (OSSR) and the electrical spurious suppression ratio (ESSR). In order to realize a higher optical extinction ratio, Kawanishi *et al.* proposed a specially designed MZM with an optical extinction ratio as high as 70 dB [10]. Two dc-driven sub-MZMs as two active optical intensity trimmers were incorporated in the two arms of the main MZM to perfectly balance the light intensity travelling through the arms to improve the extinction ratio. However, since this special modulator requires the control of three dc bias voltages, an extra care must be paid to avoid the bias fluctuations which would cause the appearance of the undesired sidebands and the degradation of the phase noise performance of the generated microwave signal. An alternative solution is to use an AlGaAs/GaAs-waveguide-based polarization modulator (PolM) [11], [12]. A PolM is a special phase modulator that supports both TE and TM modes with opposite phase modulations. By connecting the PolM with a polarizer, an intensity-modulated signal is generated. Since no dc bias is needed, the PolM-based system is free from bias drift which guarantees an operation with long term stability.

To generate a microwave signal with a higher multiplication factor, a configuration that employs two cascaded MZMs may be used. The multiplication factor can be as high as eight, which enables the generation of a high-frequency microwave or terahertz signal using a low-frequency microwave drive signal. Different techniques have been proposed for the generation of a frequency-quadrupled [13]–[15], sextupled [16]–[18], or octupled [19]–[21] microwave signal. All these approaches were implemented by biasing the MZMs at the MATP or the MITP in conjunction with the use of an optical or microwave phase shifter and an optical filter, but no generalized approach has been reported. In this paper, a generalized approach to achieving microwave frequency multiplication using two cascaded MZMs is presented. The significance of the configuration is that different microwave frequency multiplication factors of four, six, and eight can be implemented. In addition, the system is compact and simple with large frequency tunability and good operation stability.

For two cascaded MZMs, there are four possible bias combinations: 1) MATP, MATP; 2) MITP, MITP; 3) MATP, MITP; and 4) MITP, MATP, with each combination corresponding to a specific multiplication factor under different operation conditions. A theoretical analysis leading to the operating conditions to achieve frequency quadrupling, sextupling and octupling is developed. Experimental verifications are then provided. The performance of the system in terms of phase noise, tunability and stability is discussed.

II. Principle

A generalized system using two cascaded MZMs to achieve microwave multiplication is shown in Fig. 1. The system consists of a continuous-wave (CW) laser source, two MZMs, a tunable optical phase shifter (TOPS), two polarization controllers (PCs), an erbium-doped fiber amplifier (EDFA), and a photomixer. A low-frequency microwave drive signal from a microwave source is divided into two paths by a power divider, amplified by two microwave power amplifiers (PAs), and applied to the two MZMs. A tunable electrical phase shifter (TEPS) can be used between one PA and the corresponding MZM to replace the TOPS. The functions of the TOPS and the TEPS are the same, which will be explained further in this section. The two PCs are used to minimize the polarization-dependent losses of the two MZMs. A wavelength-fixed FBG notch filter may also be incorporated in the system to remove the optical carrier, which will be explained later. A harmonic mixer may also be incorporated to down-convert the generated microwave frequency to make it measurable by an electrical spectrum analyzer (ESA).

In the system, each of the two MZMs is biased at either the MATP or the MITP to suppress the odd- or the even-order sidebands. The cascade of two MZMs would lead to four bias combinations: 1) MATP, MATP; 2) MITP, MITP; 3) MATP, MITP; and 4) MITP, MATP. By properly controlling the powers of the microwave drive signals applied to the two MZMs and the phase shift introduced by the TOPS or the TEPS, only two dominant sidebands would be generated at the output of the second MZM

(MZM_2). Depending on the bias combinations, the frequency spacing of the two sidebands could be four, six, or eight times the frequency of the microwave drive signal. By beating the two sidebands at the photomixer, a frequency quadrupled, sextupled, or octupled microwave signal is generated.

We start our analysis from a general expression of the electrical field at the output of an MZM driven by a low-frequency microwave signal with a small phase modulation index (PMI). The optical extinction ratio of the MZM is assumed to be infinite. When the incident light wave is $E_0\cos(\omega_o t)$, the electrical field $E(t)$ at the output of the MZM can be expressed as in (1), shown at the bottom of the page, where E_0 is the electrical amplitude of the incident light wave, ω_o and ω_m are respectively the angular frequencies of the light wave and the microwave drive signal, $J_i(\beta)$ is the ith-order Bessel function of the first kind, ϕ is the initial phase of the microwave drive signal applied to the MZM, Φ is an additional phase difference between the two optical signals from the two arms of the MZM which is introduced by the bias voltage, β is the PMI, which is equal to $\pi V/2V_\pi$, where V is the amplitude of the microwave drive signal, and V_π is the half-wave voltage of the MZM.

From (1), we can see that if Φ is 0, the MZM is biased at the MATP and all the odd-order sidebands would be suppressed and; if Φ is π, the MZM is biased at the MITP and all the even-order sidebands would be suppressed. As long as the PMI is small, the high-order sidebands are small and negligible, and only the optical carrier and the second-order sidebands would be considered for the MATP case and the first-order sidebands for the MITP case. In the following, we will perform a thorough theoretical analysis for the setup shown in Fig. 1 for four different bias combinations.

A. MATP, MATP

The two MZMs are both biased at the MATP, that is, the additional phase difference between the two optical signals from the two arms of the ith MZM is zero, $\Phi_i = 0$ for $i = 1, 2$. According to (1), the signal $E_1(t)$ at the output of the first MZM (MZM_1) can be written as

$$\begin{aligned} E_1(t) \propto\ & E_0 J_0(\beta_1)\cos(\omega_o t) \\ & - E_0 J_2(\beta_1)\cos((\omega_o - 2\omega_m)t - 2\phi_1) \\ & - E_0 J_2(\beta_1)\cos((\omega_o + 2\omega_m)t + 2\phi_1) \end{aligned} \tag{2}$$

where β_1 is the PMI of MZM_1 and ϕ_1 is the initial phase of the microwave drive signal applied to MZM_1. When the light wave is traveling through the TOPS, a phase difference φ between the two adjacent even-order sidebands would be introduced and the electrical field $E_{11}(t)$ at the output of the TOPS can be written as

$$\begin{aligned} E_{11}(t) \propto\ & E_0 J_0(\beta_1)\cos(\omega_o t + 2\varphi) \\ & - E_0 J_2(\beta_1)\cos((\omega_o - 2\omega_m)t - 2\phi_1 + \varphi) \\ & - E_0 J_2(\beta_1)\cos((\omega_o + 2\omega_m)t + 2\phi_1 + 3\varphi). \end{aligned} \tag{3}$$

$E_{11}(t)$ is then sent to MZM_2. The electrical field $E_2(t)$ at the output of MZM_2 is given

$$\begin{aligned} E_2(t) \propto E_0 \{ & J_2(\beta_1)J_2(\beta_2)\cos((\omega_o - 4\omega_m)t \\ & + \varphi - 2\phi_1 - 2\phi_2) \\ & - J_2(\beta_1)J_0(\beta_2)\cos((\omega_o - 2\omega_m)t + \varphi - 2\phi_1) \\ & - J_0(\beta_1)J_2(\beta_2)\cos((\omega_o - 2\omega_m)t + 2\varphi - 2\phi_2) \\ & + J_2(\beta_1)J_2(\beta_2)\cos(\omega_o t + \varphi - 2\phi_1 + 2\phi_2) \\ & + J_0(\beta_1)J_0(\beta_2)\cos(\omega_o t + 2\varphi) \\ & + J_2(\beta_1)J_2(\beta_2)\cos(\omega_o t + 3\varphi + 2\phi_1 - 2\phi_2) \\ & - J_0(\beta_1)J_2(\beta_2)\cos((\omega_o + 2\omega_m)t + 2\varphi + 2\phi_2) \\ & - J_2(\beta_1)J_0(\beta_2)\cos((\omega_o + 2\omega_m)t + 3\varphi + 2\phi_1) \\ & + J_2(\beta_1)J_2(\beta_2) \\ & \times \cos((\omega_o + 4\omega_m)t + 3\varphi + 2\phi_1 + 2\phi_2) \} \end{aligned} \tag{4}$$

where β_2 is the PMI for MZM_2 and ϕ_2 is the initial phase of the drive signal applied to MZM_2. If two conditions, $\varphi + 2\phi_1 - 2\phi_2 = (2k+1)\pi$, k is an integer, and $\beta_1 = \beta_2 = \beta$ are satisfied, we have $J_0(\beta_1)J_2(\beta_2) = J_0(\beta_2)J_2(\beta_1)$ and (4) can be simplified into

$$\begin{aligned} E_2(t) \propto E_0 \{ & J_2^2(\beta)\cos((\omega_o - 4\omega_m)t + \varphi - 2\phi_1 - 2\phi_2) \\ & + \left[J_0^2(\beta) - 2J_2^2(\beta)\right]\cos(\omega_o t + 2\varphi) \\ & + J_2^2(\beta)\cos((\omega_o + 4\omega_m)t + 3\varphi + 2\phi_1 + 2\phi_2) \}. \end{aligned} \tag{5}$$

As can be seen only the carrier and the fourth-order sidebands are present. If $J_0^2(\beta) = 2J_2^2(\beta)$, then the optical carrier will be suppressed and only the fourth-order sidebands will be

$$\begin{aligned} E(t) \propto\ & E_0 \{\cos[\omega_o t + \beta\cos(\omega_m t + \phi) + \Phi] + \cos[\omega_o t - \beta\cos(\omega_m t + \phi)]\} \\ =\ & E_0\cos(\Phi/2)\Big\{\cos(\omega_o t + \Phi/2)J_0(\beta) + \sum_{n=1}^{\infty}(-1)^n J_{2n}(\beta)[\cos(\omega_o t + 2n(\omega_m t + \phi) + \Phi/2) \\ & + \cos(\omega_o t - 2n(\omega_m t + \phi) + \Phi/2)]\Big\} \\ & + E_0\sin(\Phi/2)\left\{\sum_{n=1}^{\infty}(-1)^n J_{2n-1}(\beta)[\cos(\omega_o t + (2n-1)(\omega_m t + \phi) + \Phi/2) + \cos(\omega_o t - (2n-1)(\omega_m t + \phi) + \Phi/2)]\right\} \end{aligned} \tag{1}$$

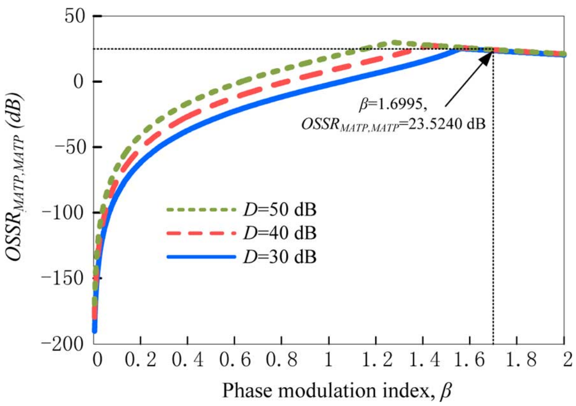


Fig. 2. Relationship between $\mathrm{OSSR}_{\mathrm{MATP,MATP}}$ and the phase modulation index β when a FBG notch filter with a notch depth of D is used.

present at the output of MZM_2. Note that to meet the condition $J_0^2(\beta) = 2J_2^2(\beta)$, β should be equal to 1.6995. By beating the two fourth-order sidebands at the photomixer, an electrical signal with a frequency that is eight times the frequency of the microwave drive signal will be generated; thus frequency octupling is achieved. The frequency multiplication factor (FMF) is eight.

In addition to the dominant fourth-order sidebands, the second largest sidebands are the sixth-order sidebands. From (4), the power of the fourth-order sidebands is proportional to $J_2(\beta)J_2(\beta)$. Similarly, we can easily obtain the power of the sixth-order sidebands which is proportional to $J_4(\beta)J_2(\beta)$. Therefore, in the optical domain, the optical sideband suppression ratio, $\mathrm{OSSR}_{\mathrm{MATP,MATP}}$, is given by

$$\mathrm{OSSR}_{\mathrm{MATP,MATP}} = 20\log_{10}\frac{J_2(\beta)J_2(\beta)}{J_4(\beta)J_2(\beta)} = 23.52\ (\mathrm{dB}). \tag{6}$$

To satisfy the condition $J_0^2(\beta) = 2J_2^2(\beta)$, the PMI should be very large, which is not easy to realize since a large microwave drive signal is needed. When $\beta = 1.6995$, for a MZM with a V_π of 7.5 V, the voltage of the microwave drive signal should be 8.11 V, which corresponds to a microwave power of 29 dBm. To obtain such a high microwave power, a large power RF amplifier is required. To avoid using a large microwave drive signal, one may use a wavelength-fixed notch filter to remove the optical carrier. As shown in Fig. 1, the notch filter is a FBG. Assume a FBG notch filter with a notch depth of D dB is used to remove the residual optical carrier, then the optical sideband suppression ratio, $\mathrm{OSSR}_{\mathrm{MATP,MATP}}$, would be given by

$$\begin{aligned}\mathrm{OSSR}_{\mathrm{MATP,MATP}} = {} & 20\log_{10}[J_2(\beta_2)J_2(\beta_1)] \\ & - \mathrm{Max}\left\{20\log_{10}[J_4(\beta)J_2(\beta)],\right. \\ & \left. 20\log_{10}\left[J_0^2(\beta) - 2J_2^2(\beta)\right] - D\right\} \end{aligned} \tag{7}$$

where $\mathrm{Max}()$ denotes the maximum value in the parentheses.

According to (7), the relationship between the $\mathrm{OSSR}_{\mathrm{MATP,MATP}}$ and the PMI is evaluated by numerical computations, with the results shown in Fig. 2. As can be seen three different values of D are provided. The $\mathrm{OSSR}_{\mathrm{MATP,MATP}}$ will increase first and then decrease as the PMI increases. As the value of D increases, the value of β needed to achieve a maximum $\mathrm{OSSR}_{\mathrm{MATP,MATP}}$ decreases. In the electrical domain, undesired harmonics would be generated due to the beating between the two fourth-order sidebands with the optical carrier or with the two sixth-order sidebands. Thus, the $\mathrm{ESSR}_{\mathrm{MATP,MATP}}$ would be no less than $\mathrm{OSSR}_{\mathrm{MATP,MATP}} - 10\log_{10} 2$.

B. MITP, MITP

The MZMs are both biased at the MITP, that is, $\Phi_i = \pi$ for $i = 1, 2$. According to (1), the signal at the output of MZM_1 can be written as

$$\begin{aligned}E_1(t) \propto {} & E_0 J_1(\beta_1)\sin((\omega_\mathrm{o} - \omega_\mathrm{m})t - \phi_1) \\ & + E_0 J_1(\beta_1)\sin((\omega_\mathrm{o} + \omega_\mathrm{m})t + \phi_1). \end{aligned} \tag{8}$$

If a phase difference φ between the two sidebands is introduced by the TOPS, we have

$$\begin{aligned}E_{11}(t) \propto {} & E_0 J_1(\beta_1)\sin((\omega_\mathrm{o} - \omega_\mathrm{m})t - \phi_1 + \varphi) \\ & + E_0 J_1(\beta_1)\sin((\omega_\mathrm{o} + \omega_\mathrm{m})t + \phi_1 + 2\varphi). \end{aligned} \tag{9}$$

The optical signal is then sent to MZM_2. The electrical filed at the output of MZM_2 is

$$\begin{aligned}E_2(t) \propto {} & E_0 J_1(\beta_1)J_1(\beta_2) \\ & \times \{\cos((\omega_\mathrm{o} - 2\omega_\mathrm{m})t + \varphi - \phi_1 - \phi_2) \\ & + \cos(\omega_\mathrm{o} t + \varphi - \phi_1 + \phi_2) \\ & + \cos(\omega_\mathrm{o} t + 2\varphi + \phi_1 - \phi_2) \\ & + \cos((\omega_\mathrm{o} + 2\omega_\mathrm{m})t + 2\varphi + \phi_1 + \phi_2)\}. \end{aligned} \tag{10}$$

If the phase condition $\varphi + 2\phi_1 - 2\phi_2 = (2k+1)\pi$ is satisfied, (10) can be simplified into

$$\begin{aligned}E_2(t) \propto {} & E_0 J_1(\beta_1)J_1(\beta_2)\{\cos((\omega_\mathrm{o} - 2\omega_\mathrm{m})t + \varphi - \phi_1 - \phi_2) \\ & + \cos((\omega_\mathrm{o} + 2\omega_\mathrm{m})t + 2\varphi + \phi_1 + \phi_2)\}. \end{aligned} \tag{11}$$

As can be seen only the second-order sidebands are generated at the output of MZM_2. By beating the second-order sidebands at the photomixer, a frequency-quadrupled signal would be generated [13], [14]; thus frequency quadrupling is achieved. The FMF is four.

In addition to the dominant second-order sidebands, the second largest sidebands are the fourth-order sidebands. From (11), the power of the second-order sidebands is proportional to $J_1(\beta_1)J_1(\beta_2)$. Similarly, we can easily obtain the power of the fourth-order sidebands which is proportional to $J_1(\beta_1)J_3(\beta_2)$. Therefore, the optical sideband suppression ratio, $\mathrm{OSSR}_{\mathrm{MITP,MITP}}$, is given by

$$\mathrm{OSSR}_{\mathrm{MITP,MITP}} = 20\log_{10}\frac{J_1(\beta_1)J_1(\beta_2)}{J_1(\beta_1)J_3(\beta_2)} = 20\log_{10}\frac{J_1(\beta_2)}{J_3(\beta_2)}\ (\mathrm{dB}). \tag{12}$$

If the phase condition is not fully satisfied, the optical carrier would appear which can be removed by a wavelength-fixed notch filter.

C. MATP, MITP

If MZM_1 is biased at the MATP with $\Phi_1 = 0$, and MZM_2 is biased at the MITP with $\Phi_2 = \pi$, only the third-order side-

TABLE I
CONDITIONS FOR GENERATING ONLY TWO OPTICAL SIDEBANDS USING TWO MZMS BIASED AT DIFFERENT MODES

Bias modes \ Conditions	PMI	Phase	FMF
MATP+MATP	$\beta_1=\beta_2=\beta\approx 1.6995$	$\varphi+2\phi_1-2\phi_2=(2k+1)\pi$	8
MITP+MITP	NONE	$\varphi+2\phi_1-2\phi_2=(2k+1)\pi$	4
MATP+MITP	$J_0(\beta_1)=J_2(\beta_1)$, $\beta_1\approx 1.8412$	$\varphi+2\phi_1-2\phi_2=2k\pi$	6
MITP+MATP	$J_0(\beta_2)=J_2(\beta_2)$, $\beta_2\approx 1.8412$	$\varphi+2\phi_1-2\phi_2=2k\pi$	6

bands would be generated and frequency sextupling would be achieved.

The electrical fields at the outputs of MZM_1 and the TOPS are identical to (2) and (3). The electrical filed at the output of MZM_2 can be expressed as

$$\begin{aligned} E_2(t) \propto & E_0 J_1(\beta_2) \\ & \times \{J_2(\beta_1)\sin((\omega_o-3\omega_m)t+\varphi-2\phi_1-\phi_2) \\ & +J_2(\beta_1)\sin((\omega_o-\omega_m)t+\varphi-2\phi_1+\phi_2) \\ & -J_0(\beta_1)\sin((\omega_o-\omega_m)t+2\varphi-\phi_2) \\ & -J_0(\beta_1)\sin((\omega_o+\omega_m)t+2\varphi+\phi_2) \\ & +J_2(\beta_1)\sin((\omega_o+\omega_m)t+3\varphi+2\phi_1-\phi_2) \\ & +J_2(\beta_1)\sin((\omega_o+3\omega_m)t+3\varphi+2\phi_1+\phi_2)\}. \end{aligned} \tag{13}$$

If the PMI condition $J_0(\beta_1) = J_2(\beta_1)$ and phase condition $\varphi-2\phi_1+\phi_2+2k\pi = 2\varphi-\phi_2, 3\varphi+2\phi_1-\phi_2 = 2\varphi+\phi_2+2k\pi$, or $\varphi+2\phi_1-2\phi_2 = 2k\pi$ are satisfied, then (13) can be simplified to

$$\begin{aligned} E_2(t) \propto E_0 \{ & J_2(\beta_1)J_1(\beta_2)\sin((\omega_o-3\omega_m)t+\varphi-2\phi_1-\phi_2) \\ & +J_2(\beta_1)J_1(\beta_2)\sin((\omega_o+3\omega_m)t \\ & +3\varphi+2\phi_1+\phi_2)\}. \end{aligned} \tag{14}$$

As can be seen only the third-order sidebands are generated. By beating the third-order sidebands at the photomixer, a frequency-sextupled signal is generated; thus frequency sextupling is achieved. The FMF is six.

Note that to satisfy the PMI condition $J_0(\beta_1) = J_2(\beta_1)$, the value of β_1 should be 1.8412. Considering the fact that $\beta_1 \approx 1.8412$ is very large, the fourth-order sidebands at the output of MZM_1 would have a relatively high power and would generate the fifth-order sidebands at the output of MZM_2, which would contribute to the generation of a frequency-doubled and a frequency-octupled signals at the output of the photomixer. It is theoretically calculated that the optical sideband suppression ratio, $OSSR_{MATP,MITP}$, would be approximately equal to $20\log_{10}[J_2(\beta_1)/J_4(\beta_1)] \approx 21.97$ dB, and the electrical spurious suppression ratio, $ESSR_{MATP,MITP}$, would be $21.9669 - 10\log_{10} 2 \approx 18.96$ dB.

D. MITP, MATP

If MZM_1 is biased at the MITP with $\Phi_1 = \pi$, and MZM_2 is biased at the MATP with $\Phi_2 = 0$, only the third-order sidebands would be generated and frequency sextupling would be achieved.

The electrical fields at the outputs of MZM_1 and the TOPS are identical to (8) and (9). The electrical fieid at the output of MZM_2 can expressed as

$$\begin{aligned} E_2(t) \propto & E_0 J_1(\beta_1) \\ & \times \{J_2(\beta_2)\sin((\omega_o-3\omega_m)t+\varphi-\phi_1-2\phi_2) \\ & -J_0(\beta_2)\sin((\omega_o-\omega_m)t+\varphi-\phi_1) \\ & +J_2(\beta_2)\sin((\omega_o-\omega_m)t+2\varphi+\phi_1-2\phi_2) \\ & -J_2(\beta_2)\sin((\omega_o+\omega_m)t+\varphi-\phi_1+2\phi_2) \\ & +J_0(\beta_2)\sin((\omega_o+\omega_m)t+2\varphi+\phi_1) \\ & +J_2(\beta_2)\sin((\omega_o+3\omega_m)t+2\varphi+\phi_1+2\phi_2)\}. \end{aligned} \tag{15}$$

If the PMI condition $J_0(\beta_2) = J_2(\beta_2)$, i.e., $\beta_2 \approx 1.8412$, and phase condition $2\varphi+\phi_1-2\phi_2 = \varphi-\phi_1+2k\pi$, $\varphi-\phi_1+2\phi_2+2k\pi = 2\varphi+\phi_1$, i.e., $\varphi+2\phi_1-2\phi_2 = 2k\pi$, are satisfied, (15) can be simplified to

$$\begin{aligned} E_2(t) \propto & E_0 J_1(\beta_1) \\ & \times \{J_2(\beta_2)\sin((\omega_o-3\omega_m)t+\varphi-\phi_1-2\phi_2) \\ & +J_2(\beta_2)\sin((\omega_o+3\omega_m)t+2\varphi+\phi_1+2\phi_2)\}. \end{aligned} \tag{16}$$

As can be seen only the third-order sidebands are kept and the other sidebands are suppressed. By beating the two third-order sidebands at the photomixer, a frequency-sextupled signal would be generated. Again, the FMF is six.

Similar to the case where MZM_1 and MZM_2 are respectively biased at the MATP and the MITP, a frequency-doubled signal and a frequency-octupled signal at the output of the photomixer would be also generated due to the existence of the fifth-order sidebands. The theoretically calculated optical sideband suppression ratio, $OSSR_{MITP,MATP}$, and the electrical spurious suppression ratio, $ESSR_{MITP,MATP}$, would also be as same as those in the previous case.

The conditions required for the generation of only two dominant optical sidebands using two MZMs are summarized in Table I.

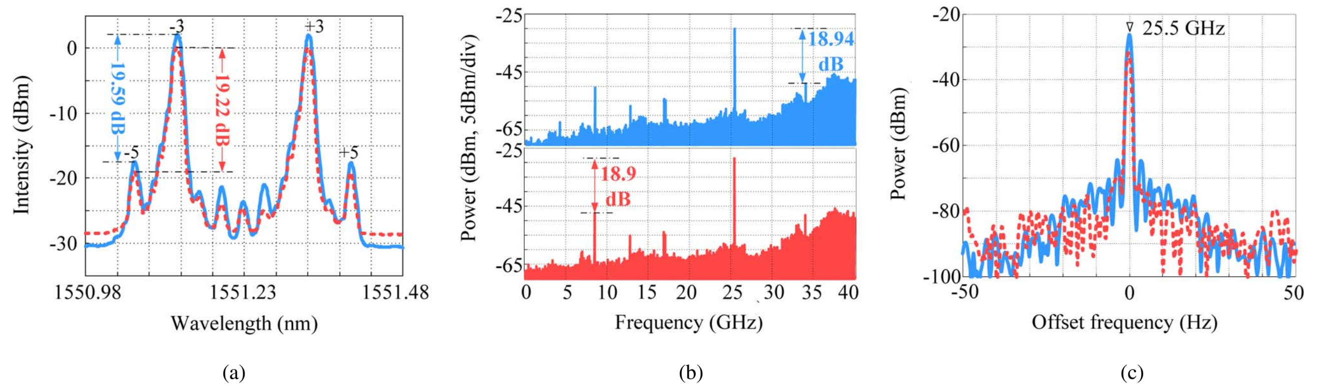


Fig. 3. Frequency-sextupled signal generation when MZM_1 and MZM_2 are respectively biased at the MITP and the MATP. (a) Measured optical spectra (dotted) with and (solid) without fiber transmission. The third-order sidebands are dominant. (b) Measured electrical spectra. (Lower) After 20-km transmission. (Upper) Without transmission. (c) Zoom-in views of the electrical spectra (dotted) with and (solid) without transmission.

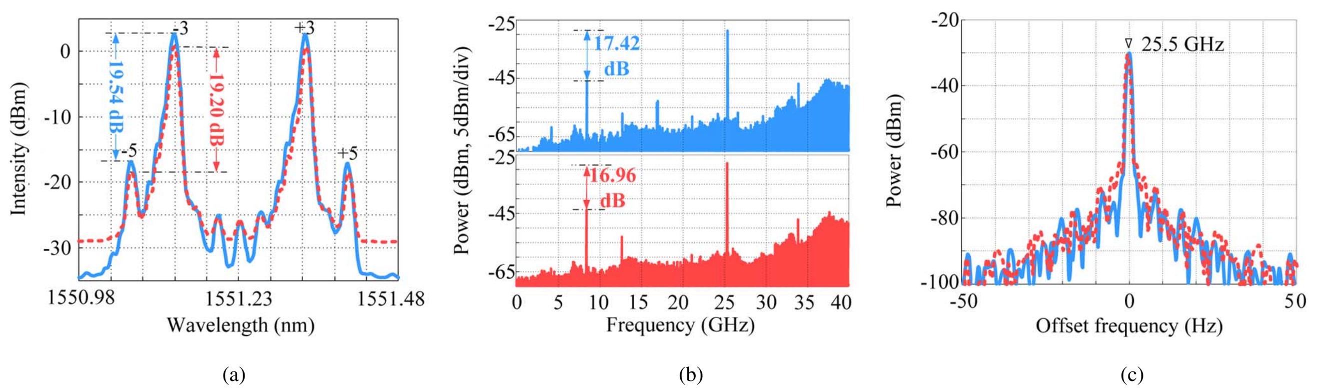


Fig. 4. Frequency-sextupled signal generation when MZM1 and MZM2 are respectively biased at the MATP and the MITP. (a) Measured optical spectra (dotted) with and (solid) without fiber transmission. The third-order sidebands are dominant. (b) Measured electrical spectra. (Lower) After 20-km transmission. (Upper) Without transmission. (c) Zoom-in views of the electrical spectra (dotted) with and (solid) without transmission.

For the four cases discussed above, the phase condition $\varphi + 2\phi_1 - 2\phi_2 = (2k+1)\pi$ or $\varphi + 2\phi_1 - 2\phi_2 = 2k\pi$ can be realized using a TOPS. As a matter of fact, it can also be satisfied by using a tunable optical delay line to change φ or a TEPS mentioned before to change ϕ_1 or ϕ_2. Therefore, the functions of the TOPS and the TEPS are the same.

III. Experimental Results and Discussion

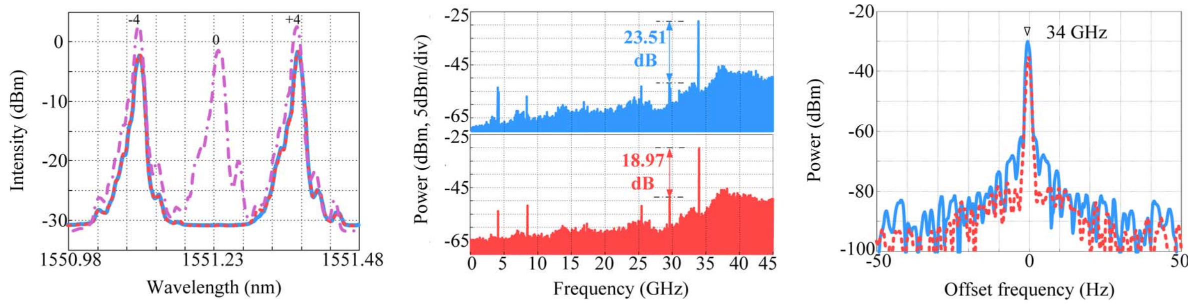
Experiments based on the setup shown in Fig. 1 are performed, and the generation of photonic frequency-sextupled and frequency-octupled signals is conducted. The frequency of the drive signal is set at 4.25 GHz. Both the optical spectra at the output of MZM_2 and the electrical spectra of the generated signals at the output of the photomixer are recorded. We also transmit the optical signals at the output of MZM_2 through a 20-km single-mode fiber and compare the corresponding optical and electrical spectra of the remote signals to evaluate the transmission performance of the system. To evaluate the phase noise performance, the single-side-band phase noise of the generated local and remote signals is measured. In addition, the frequency tunability and the system stability are also investigated. The key advantage of using the technique is that a high-frequency signal can be generated using a low-frequency microwave drive signal. To demonstrate this conclusion, the generation of a subterahertz signal based on the frequency octupling is demonstrated.

A. *Microwave Signal Generation*

In the first experiment, the generation of a frequency-sextupled signal is demonstrated. To do so, MZM_1 and MZM_2 are respectively biased at the MITP and the MATP. Fig. 3(a) shows the measured optical spectra of the generated third-order sidebands at the output of MZM_2 and after 20-km fiber transmission. During the measurement, an EDFA is incorporated to compensate for the fiber loss due to the 20-km fiber transmission.

We can clearly see that the two third-order sidebands are dominant in the optical spectra and experience no significant degradation after 20-km fiber transmission. The electrical spectra of the generated 25.5-GHz signal measured with and without fiber transmission are shown in Fig. 3(b). Fig. 3(c) gives zoom-in views of the electrical spectra. As can be seen the generated microwave signal at the remote side exhibits the same spectral quality as that without fiber transmission. The power of the 25.5-GHz signal is approximately 18.9 dB greater than that of the next largest component, which agrees well with the theoretical value of 18.96 dB. The linewidth of the generated microwave signal is only a few Hz.

The same experiment is repeated, but with MZM_1 and MZM_2 being respectively biased at the MATP and the MITP. Fig. 4 shows the experimental results. Again, a frequency-sextupled microwave at 25.5 GHz is generated. The quality of the generated microwave signal with or without fiber transmission is



(a) (b) (c)

Fig. 5. Frequency-octupled signal generation. (a) Measured optical spectra at the output of (dash-dotted line) MZM2 and the notch filter (dotted line: with fiber distribution, solid line: without fiber transmission). (b) Measured electrical spectra. (Lower) After 20-km transmission. (Upper) Without transmission. (c) Zoom-in views of the electrical spectra (dotted) with and (solid) without transmission.

identical to that generated by biasing the two MZMs at the MITP and the MATP.

In the second experiment, both MZMs are biased at the MATP to suppress all the odd-order sidebands. Therefore, frequency octupling would be achieved. To eliminate the optical carrier, the condition $J_0^2(\beta) = 2J_2^2(\beta)$ or equivalently $\beta \approx 1.6995$ must be satisfied, which can be done using a high-power microwave drive signal. In the experiment, instead of using a high-power microwave drive signal to eliminate the optical carrier, a FBG notch filter is used to filter out the residual optical carrier. The notch depth D of the FBG notch filter is about 40 dB, and the PMI $\beta \approx 1.43$. According to (7), the maximum optical sideband suppression ratio, $\mathrm{OSSR}_{\mathrm{MATP,MATP}}$, is approximately equal to 26.79 dB, and the electrical spurious suppression ratio, $\mathrm{ESSR}_{\mathrm{MATP,MATP}}$, is approximately equal to 23.78 dB when the PMI β is equal to 1.43. From Fig. 5(a), we can clearly see that at the output of MZM_2 there are two dominant fourth-order sidebands as well as the residual optical carrier, which is then removed by the FBG notch filter. After 20-km fiber transmission, the optical spectrum experiences negligible degradation. The electrical spectra of the generated 34-GHz signal measured with and without fiber transmission are shown in Fig. 5(b). Fig. 5(c) gives the zoom-in views of the spectra. The power of the frequency-octupled local signal is 23.51 dB greater than that of the next largest component, which agrees well with the theoretical value of the $\mathrm{ESSR}_{\mathrm{MATP,MATP}}$, which is 23.78 dB.

B. Phase Noise Performance

The phase noise performance of the generated microwave signals with and without fiber transmission is evaluated.

The power spectrum of the phase noise in the generated frequency-multiplied signal based on external modulation can be expressed [22]

$$10\log_{10}[S(f)] = 10\log_{10}[S_{\mathrm{res}}(f)] + 10\log_{10}\left[m^2 \cdot S_{\mathrm{e}}(f)\right] \tag{17}$$

where m is the FMF, $S_{\mathrm{e}}(f)$ and $S_{\mathrm{res}}(f)$ are the power spectra of the microwave drive signal and the residual phase noise of the system, respectively. Therefore, the phase noise of the drive signal and the residual phase noise of the system both contribute to the total phase noise of the generated signal. If $S_{\mathrm{res}}(f) \ll m^2 \cdot S_{\mathrm{e}}(f)$ (Condition 1), the first term in the right-hand side of (17) can be neglected and the phase noise of the generated signal is approximately equal to that of the microwave drive source plus $20\log_{10}(m)$. If $m^2 \cdot S_{\mathrm{e}}(f) \ll S_{\mathrm{res}}(f)$ (Condition 2), the second term in the right-hand side of (17) can be neglected and the phase noise of the generated signal is approximately equal to the residual phase noise of the system.

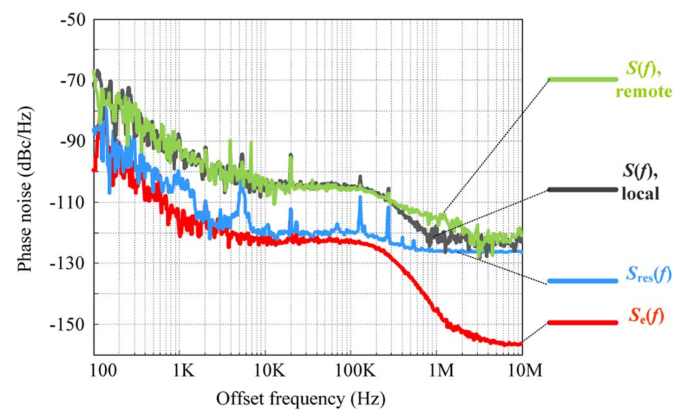


Fig. 6. Measured phase noise of (green line: remote; gray line: local) the generated 34-GHz signal, (blue line) the residual noise of the system, and (red line) the phase noise of the drive signal.

To evaluate the phase noise performance, we measure the single-side-band phase noise of the 34-GHz frequency-octupled signal with and without fiber transmission using a signal source analyzer (Agilent E5052B). As a comparison, the phase noise of the microwave drive signal at 4.25 GHz and the residual phase noise of the system are also measured and plotted in Fig. 6.

The generated 34-GHz signal has a phase noise as low as -89.35 dBc/Hz at an offset frequency of 1 kHz. By observing the phase noise curves in Fig. 6 more closely, we find that when the offset frequency is lower than 1 MHz, Condition 1 is satisfied and the phase noise of the 34-GHz signal is resulted from the phase noise of the microwave drive signal, with a value increased by $20\log_{10}(10) \approx 18$ dB; when the offset frequency is higher than 1 MHz, Condition 2 is satisfied and the phase noise of the 34-GHz signal is mainly contributed by the residual phase noise of the system. From Fig. 6 we also see that the phase noise of the generated microwave signal after 20-km fiber transmission is kept unchanged. This conclusion shows that the fiber transmission would introduce negligible phase noise to the microwave signal.

According to (17), the phase noise of the frequency-multiplied signal can be decreased by using a microwave drive signal source with smaller phase noise or a system with less residual phase noise. The residual phase noise of the experimental system is mainly attributed from the dc power suppliers. A direct solution to reduce the residual phase noise is to use high-quality dc suppliers. Another solution is to replace the MZMs by two PolM-based intensity modulators [11], [12]. Since a PolM is not biased by a dc voltage, the phase noise resulted from the dc bias would be eliminated. In fact, in a PolM-based intensity modulator, the bias is actually controlled by a polarization controller, since a PC is a passive device, it will introduce negligible phase noise to the generated signal. Therefore, the phase noise performance of the generated signal would be also enhanced.

C. Tunability and Stability

One important feature of the technique is the large frequency tunability. The frequency of the generated microwave signal can be continuously tunable by changing the frequency of the microwave drive signal. In achieving the frequency tuning, two conditions should always be satisfied: the PMI condition and the phase condition. The power of the drive signal should be controlled to meet the PMI condition, while the additional phase introduced by the TOPS or the TEPS should also be adjusted to meet the phase condition. Since we can sweep the frequency of the microwave drive signal and adjust the TOPS or the TEPS correspondingly, it is possible to scan the frequency of the generated signal. The scan speed is determined by the frequency sweeping speed of the microwave drive signal and the phase sweeping speed of the TOPS or the TEPS. The frequency tuning range of the generated signal is the product of the multiplication factor and the frequency tuning range of the microwave drive signal. The tuning step of the generated signal is the product of the multiplication factor and the frequency tuning step of the microwave drive signal.

To evaluate the tunability, in the frequency sextupling experiment, the frequency of the microwave drive signal is tuned from 2 to 4 GHz with an interval of 0.5 GHz, a frequency-sextupled signal from 12 to 24 GHz is thus generated, as shown in Fig. 7(a). In the frequency octupling experiment, the frequency of the microwave drive signal is tuned from 3.4 to 3.8 GHz with an interval of 0.1 GHz, a frequency-octupled signal from 27.2 to 30.4 GHz is thus generated, as shown in Fig. 7(b). In such a system, the tunable range is only limited by the operation bandwidths of the MZMs, the microwave amplifiers and the photomixer.

Another important feature of the technique is the excellent short-term stability. Since the two sidebands are generated from the same CW laser source which is modulated by the same microwave source and the modulated signal goes through the same optical path, the two sidebands are always phase-correlated and the system has an excellent short-term stability. The long-term stability is mainly affected by the bias drift of the two MZMs. Theoretically, the bias conditions are only determined by the value of Φ. Although the value of Φ barely depends on the frequencies of the optical carrier and of the optical sidebands, it does experience a very tiny change when the frequencies of the optical carrier and the optical sidebands change. Therefore, the bias voltages need a small adjustment when the microwave drive frequency is tuned. The long-term stability is mainly affected by the fluctuations of the bias conditions. To improve the long-term stability, the bias voltages should be controlled by a bias controller. Another solution to improve the long-term stability is to replace the two MZMs by two PolM-based intensity modulators [11], [12]. The bias conditions for a PolM-based intensity modulator are mainly determined by the polarization conditions of the input light wave. To improve the long-term stability, polarization maintaining devices may be used. Another advantage of using PolM-based intensity modulators is that the extinction ratio can be controlled large by adjusting the PC, which would provide a significantly increased optical sideband suppression ratio.

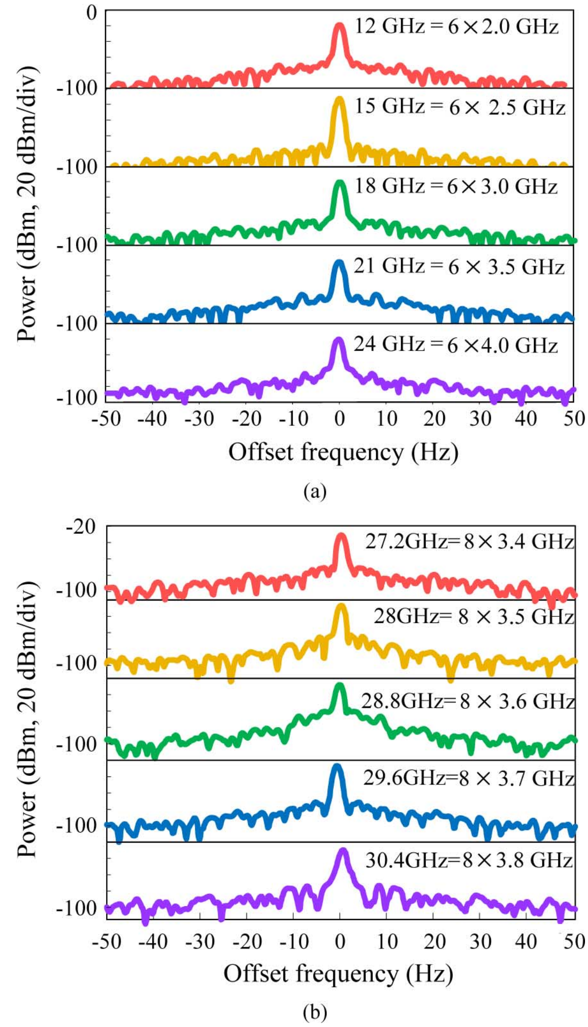
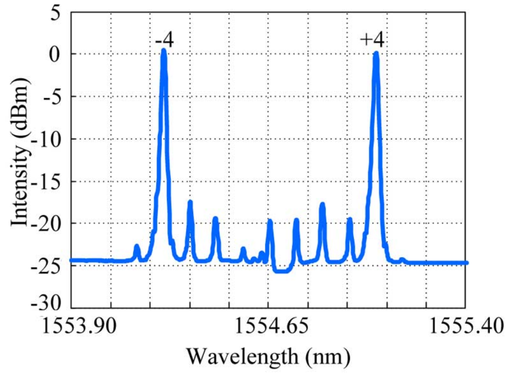


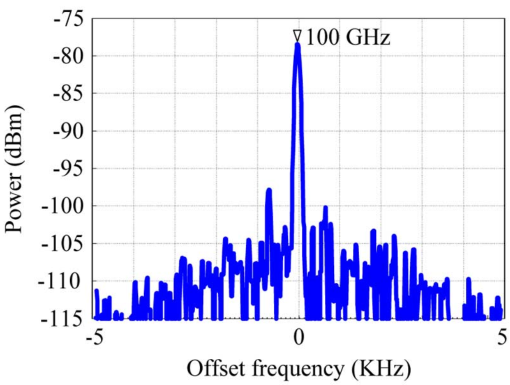
Fig. 7. Frequency tunability of the system. (a) Measured electrical spectra of the frequency-sextupled signal with its frequency tuned from 12 to 24 GHz with a tuning step of 0.5 GHz. (b) Measured electrical spectra of the frequency-octupled signal with its frequency tuned from 27.2 to 30.4 GHz with a tuning step of 0.1 GHz.

D. Subterahertz Generation

Frequency multiplication based on external modulation facilitates the generation of high-frequency electrical signals using a relatively low-frequency microwave drive signal. An important example to advocate the advantage is to use the technique to generate a sub-THz signal. Assume the system



(a)



(b)

Fig. 8. THz generation based optical frequency octupling. (a) Measured optical spectrum at the output of MZM_2, two dominant fourth-oder sidebands are observed. (b) Measured electrical spectrum of the generated 0.1-THz signal.

in Fig. 1 is configured to achieve frequency octupling. To generate a sub-THz signal at 0.1 THz, a microwave drive signal at 12.5 GHz is needed. Fig. 8(a) shows the measured optical spectrum at the output of MZM_2, in which the two fourth-order sidebands spaced by approximately 0.8 nm (corresponding to 0.1 THz) are observed. By beating the two wavelengths at a high-speed photomixer (U2T, 100-GHz photodetector), a 0.1-THz signal is generated.

Note that the fourth-order sidebands in Fig. 8(a) are dominant and other sidebands including the optical carrier are greatly suppressed. The appearance of the residual sidebands and the optical carrier is caused by the following reasons: 1) the PMI at 12.5 GHz is not large enough. Based on our measurement, the PMI is approximately 1.3, which is smaller than that value of 1.6995 to ensure a complete suppression of the optical carrier. 2) The extinction ratio of the MZMs used is not large enough to effectively suppress all odd-order sidebands. As discussed earlier, the use of PolM-based intensity modulators would significantly reduce the unwanted sidebands.

Considering that MZMs with a bandwidth up to 100 GHz are now commercially available, if such MZMs are used, the generation of a THz signal with a frequency greater than 1 THz is feasible. For example, if the microwave drive signal is 40 or 100 GHz, the frequency of the generated terahertz signal based on frequency octupling is 0.64 or 1.6 THz.

The bandwidth of a commercially available photomixer or a photoconductive antenna can be as high as 1 THz. Therefore, it is feasible to generate a terahertz wave by employing the microwave frequency multiplication technique. The key limitation of the approach, however, is the poor efficiency of the photomixer or photoconductive antenna. In general, the power of a generated terahertz signal is only in the order of μW or even less, which can barely meet the demands for practical applications.

IV. Conclusion

A generalized approach to achieving photonically assisted frequency multiplication using two cascaded MZMs was investigated. A theoretical analysis was performed, which led to the operating conditions, including the phase condition and the PMI condition, to achieve frequency quadrupling, sextupling, or octupling. The theoretical results were verified by experiments. The performance of the system in terms of phase noise with or without fiber transmission, frequency tunability, and operation stability was evaluated. The technique features large tunability and good stability. An important application of the technique is to generate a high-frequency electrical signal using a low-frequency microwave source, such as THz generation. In the paper, a sub-THz signal with a frequency at 0.1 THz was generated based on frequency octupling, in which a microwave drive signal at 12.5 GHz was employed.

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Wangzhe Li (S’08) received the B.Eng. degree in electronic science and technology from Xi’an Jiaotong University, Xi’an, China, in 2004, and the M.Sc. degree in optoelectronics and electronic science from Tsinghua University, Beijing, China, in 2007. He is currently working toward the Ph.D. degree in electrical engineering in the School of Information Technology and Engineering, University of Ottawa, Ottawa, ON, Canada.

His current research interests include photonic generation of microwave and THz signals.

Jianping Yao (M’99-SM’01) received the Ph.D. degree in electrical engineering in 1997 from the Université de Toulon, Toulon, France.

He joined the School of Information Technology and Engineering, University of Ottawa, Ottawa, ON, Canada, in 2001, where he is currently a Professor, Director of the Microwave Photonics Research Laboratory, and Director of the Ottawa-Carleton Institute for Electrical and Computer Engineering. From 1999 to 2001, he held a faculty position with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. He holds a Yongqian Endowed Visiting Chair Professorship with Zhejiang University, China. He spent three months as an Invited Professor in the Institut National Polytechnique de Grenoble, France, in 2005. His research has focused on microwave photonics, which includes all-optical microwave signal processing, photonic generation of microwaves, millimeter-wave and teraherz, radio-over-fiber, ultrawideband-over-fiber, fiber Bragg gratings for microwave photonics applications, and optically controlled phased array antennas. His research interests also include fiber lasers, fiber-optic sensors, and biophotonics. He is an author or coauthor of over 280 papers, including over 160 papers in peer-reviewed journals and 120 papers in conference proceeding. He is an Associate Editor of the *International Journal of Microwave and Optical Technology*.

Dr. Yao is on the editorial board of IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES. He received the 2005 International Creative Research Award of the University of Ottawa. He was the recipient of the 2007 George S. Glinski Award for Excellence in Research. He was named University Research Chair in Microwave Photonics in 2007. He was a recipient of an NSERC Discovery Accelerator Supplements award in 2008. He is a Registered Professional Engineer of Ontario. He is a Fellow of the Optical Society of America and a Senior Member of the IEEE Photonics Society and the IEEE Microwave Theory and Techniques Society.