Microwave Generation Based on Optical Domain Microwave Frequency Octupling

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***Abstract*—A novel approach to achieving microwave frequency octupling in the optical domain is proposed and demonstrated. The proposed system consists of two cascaded Mach–Zehnder modulators (MZMs) that are both biased at the maximum transmission point, with a tunable optical phase shifter connected in between to introduce a phase shift. An input microwave signal is applied to the MZMs with its power adjusted to ensure the two MZMs having an identical phase modulation index. A theoretical analysis that leads to the conditions for achieving frequency octupling is provided. The approach is verified by experiments. The phase noise performance and the frequency tunability are also experimentally investigated.**

***Index Terms*—Microwave generation, microwave photonics.**

I. Introduction

PHOTONIC generation of microwave, millimeter-wave, and terahertz wave has been a topic of interest in the last few years which can find numerous applications, such as wireless communications systems, radar, medical imaging, and modern instrumentation. The key advantages of using optics to generate a high-frequency electrical signal are the broad bandwidth and large tunability offered by optics, which is difficult to realize using an electrical system [1]. Various techniques have been proposed to generate high-frequency electrical signals in the optical domain. These techniques can be classified into four categories [2]: 1) optical injection locking [3], 2) optical phase-lock loop [4], 3) microwave generation based on external modulation [5]–[10], and 4) microwave generation using a dual-wavelength laser source [11]. Among these techniques, external modulation has been considered an attractive solution due to the frequency range, excellent system stability, and high spectral purity of the generated signal. In addition, an external-modulator-based system has a simpler configuration with lower system cost. In [5], frequency doubling was realized using a single Mach–Zehnder modulator (MZM) which was biased at the minimum transmission point (MITP) to produce two dominant sidebands with a wavelength spacing corresponding to two times the frequency of the drive sinusoidal signal. In [6], [7], frequency quadrupling was realized using an MZM biased at the maximum transmission point (MATP) to suppress all odd order sidebands. By incorporating an optical notch filter to remove the optical carrier, a frequency quadrupled microwave was generated. The use of two MZMs that are biased at the MITP would also generate a frequency quadrupled microwave, but without the need for an optical notch filter [8]. Microwave frequency sextupling can also be realized by using two cascaded MZMs. In [9], frequency sextupling was implemented using two dual-electrode MZMs that were biased at the MITP and the MATP. Two electrical π-phase shifters were used to introduce a π-phase shift to the input microwave signal that was applied to one of the electrodes of each of the MZMs. Microwave frequency sextupling can also be realized using a phase modulator and an MZM [10]. Since the use of a phase modulator would generate many optical sidebands, the output from the photodetector (PD) would have many other frequency components which are not expected for most of the applications. To generate a frequency-sextupled microwave signal without other frequency components, we recently proposed to bias two MZMs at the MITP and the MATP [12]. The two MZMs were connected by a tunable optical phase shifter (TOPS). If the power of the microwave signal applied to the second MZM and the phase shift introduced by the TOPS were properly set, an optical output with only the $\pm$3rd-order sidebands was obtained. By beating the $\pm$3rd-order sidebands at a PD, a frequency sextupled signal was generated.

Although the generation of a frequency doubled, quadrupled or sextupled microwave signal has been well studied; the generation of a frequency octupled microwave signal has not been reported. In this letter, we propose and investigate the generation of a frequency octupled microwave signal using two MZMs. Although the setup is similar to the previously reported systems where two MZMs were used, the operation conditions for the frequency octupling are completely different. Specifically, to achieve frequency octupling, the two MZMs must be biased at the MATP. A TOPS must be incorporated between the two MZMs to introduce a proper phase shift. The phase modulation indices of the two MZMs must also be properly controlled. A theoretical analysis that leads to the operation conditions is provided. Experiments are then performed. The frequency tunability and the phase noise of the generated signal are also studied.

II. Principle of Operation

The proposed system is shown in Fig. 1, which consists of a continuous-wave (CW) laser source, two MZMs that are connected by a TOPS, and a PD. A low-frequency microwave signal from a microwave source is amplified by a microwave power amplifier (PA), and then divided into two signals by a power divider and applied to the two MZMs. Both of the MZMs are biased at the MATP to suppress the odd-order sidebands. By properly adjusting the phase shift introduced by the TOPS and the powers of the drive signals, only the 4th-order sidebands are

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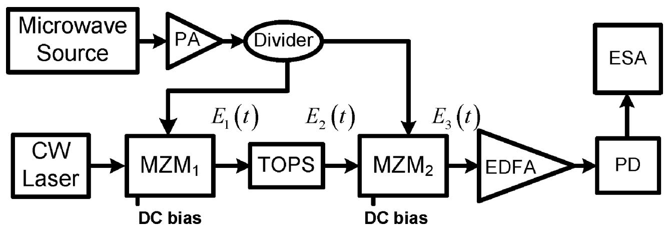

Fig. 1. Schematic diagram of the proposed microwave frequency octupling system using two cascaded MZMs. EDFA: erbium-doped fiber amplifier; ESA: electrical spectrum analyzer.

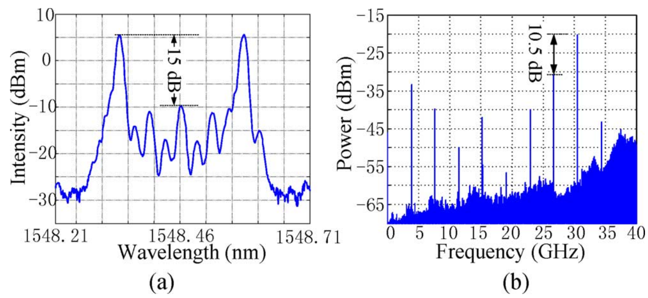

Fig. 2. (a) Measured optical spectrum at the output of MZM_2. (b) Measured electrical spectrum of the optical signal after heterodyning at the PD.

generated. By beating the ±4th-order sidebands at the PD, a frequency-octupled microwave signal is generated.

Mathematically, the electrical field $E_1(t)$ at the output of the first MZM (MZM_1) can be expressed as

$$\begin{aligned} E_1(t) \approx\, & 2E_0 J_0(\beta_1)\cos(\omega_o t) \\ & - 2E_0 J_2(\beta_1)\cos[(\omega_o - 2\omega_m)t - 2\varphi_1] \\ & - 2E_0 J_2(\beta_1)\cos[(\omega_o + 2\omega_m)t + 2\varphi_1] \end{aligned} \tag{1}$$

where E_0 is the amplitude of the incident light wave to each arm of the MZM, ω_o and ω_m are, respectively, the angular frequencies of the light wave and the input microwave signal, J_n is the nth-order Bessel function of the first kind, β_1 and φ_1 are, respectively, the phase modulation index (PMI) and the initial phase of the microwave signal applied to MZM_1. Due to the small PMI, the higher even-order sidebands are too small and can be ignored. When the light wave is traveling through the TOPS, a phase difference ϕ between two adjacent even-order sidebands would be introduced and the electrical field $E_2(t)$ at the output of the TOPS can be written as

$$\begin{aligned} E_2(t) \approx\, & 2E_0 J_0(\beta_1)\cos(\omega_o t + 2\phi) \\ & - 2E_0 J_2(\beta_1)\cos[(\omega_o - 2\omega_m)t - 2\varphi_1 + \phi] \\ & - 2E_0 J_2(\beta_1)\cos[(\omega_o + 2\omega_m)t + 2\varphi_1 + 3\phi]. \end{aligned} \tag{2}$$

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

$$\begin{aligned} E_3(t) & \\ \approx KE_0\{ & J_2(\beta_1)J_2(\beta_2)\cos[(\omega_o - 4\omega_m)t + \phi - 2\varphi_1 - 2\varphi_2] \\ & - J_2(\beta_1)J_0(\beta_2)\cos[(\omega_o - 2\omega_m)t + \phi - 2\varphi_1] \\ & - J_0(\beta_1)J_2(\beta_2)\cos[(\omega_o - 2\omega_m)t + 2\phi - 2\varphi_2] \\ & + J_2(\beta_1)J_2(\beta_2)\cos[\omega_o t + \phi - 2\varphi_1 + 2\varphi_2] \\ & + J_0(\beta_1)J_0(\beta_2)\cos[\omega_o t + 2\phi] \\ & + J_2(\beta_1)J_2(\beta_2)\cos[\omega_o t + 3\phi + 2\varphi_1 - 2\varphi_2] \\ & - J_0(\beta_1)J_2(\beta_2)\cos[(\omega_o + 2\omega_m)t + 2\phi + 2\varphi_2] \\ & - J_2(\beta_1)J_0(\beta_2)\cos[(\omega_o + 2\omega_m)t + 3\phi + 2\varphi_1] \\ & + J_2(\beta_1)J_2(\beta_2)\cos \\ & \cdot[(\omega_o + 4\omega_m)t + 3\phi + 2\varphi_1 + 2\varphi_2]\} \end{aligned} \tag{3}$$

where K is a constant which is determined by the total loss of the system, β_2 and φ_2 are, respectively, the PMI and the initial phase of the microwave signal applied to MZM_2. If the following two conditions, $\phi + 2\varphi_1 - 2\varphi_2 = \pi$, and $\beta_1 = \beta_2 = \beta$ are satisfied, we would have $J_0(\beta_1)J_2(\beta_2) = J_0(\beta_2)J_2(\beta_1)$, and (3) can be simplified

$$\begin{aligned} E_3(t) \approx KE_0\{ & J_2^2(\beta)\cos[(\omega_o - 4\omega_m)t + \phi - 2\varphi_1 - 2\varphi_2] \\ & + [J_0^2(\beta) - 2{J_2}^2(\beta)]\cos(\omega_o t + 2\phi) \\ & + J_2^2(\beta)\cos[(\omega_o + 4\omega_m)t + 3\phi + 2\varphi_1 + 2\varphi_2]\}. \end{aligned} \tag{4}$$

As can be seen, only the carrier and the ±4th-order sidebands are present. Note that the condition $\phi + 2\varphi_1 - 2\varphi_2 = \pi$ can also be satisfied by changing ϕ using an optical delay line, or by changing φ_1 or φ_2 using a microwave phase shifter.

If a third condition $J_0^2(\beta) = 2J_2^2(\beta)$ is satisfied, where β should be equal to 1.699, then the optical carrier is also suppressed. Since the output from MZM_2 consists of only the ±4th-order sidebands, the beating of the two sidebands at the PD would generate a frequency-octupled microwave signal.

III. Experiments

Two experiments based on the setup shown in Fig. 1 are performed. In the first experiment, the PMIs are set at 1.699 to make $J_0^2(\beta) = 2J_2^2(\beta)$; therefore, the optical carrier is eliminated. In the second experiment, to avoid having large PMIs to make $J_0^2(\beta) = 2J_2^2(\beta)$ which requires large microwave drive powers, a fixed optical notch filter is used to filter out the optical carrier.

In the first experiment, the frequency of the microwave drive signal is 3.8 GHz. The microwave power and the phase difference introduced by the TOPS are properly adjusted to satisfy the three conditions, i.e., the phase condition $\phi + 2\varphi_1 - 2\varphi_2 = \pi$, and the PMI conditions $\beta_1 = \beta_2 = \beta$ and $J_0^2(\beta) = 2J_2^2(\beta)$. The optical spectrum of the signal at the output of MZM_2 and the electrical spectrum of the beat note at the output of the PD are shown in Fig. 2. From Fig. 2(a), we can clearly see that only two sidebands at the ±4th-order are generated and other sidebands are suppressed. Fig. 2(b) shows the spectrum of the signal at the output of the PD. A frequency-octupled microwave signal is generated. Due to the incomplete suppression of the other sidebands, the powers of the other harmonics are relatively high. However, the frequency-octupled component has a power 10.5 dB greater than the next largest component which is the seventh harmonic.

To completely eliminate the optical carrier without using high PMIs, in the second experiment, a fixed fiber Bragg grating (FBG) notch filter is incorporated between MZM_2 and the PD, to remove the optical carrier. The optical spectra at the outputs of MZM_2 and the optical notch filter are shown in Fig. 3(a) and (b), respectively. It can be clearly seen that the optical carrier is effectively removed. Since the condition $J_0^2(\beta) = 2J_2^2(\beta)$ is not required, we have more flexibility

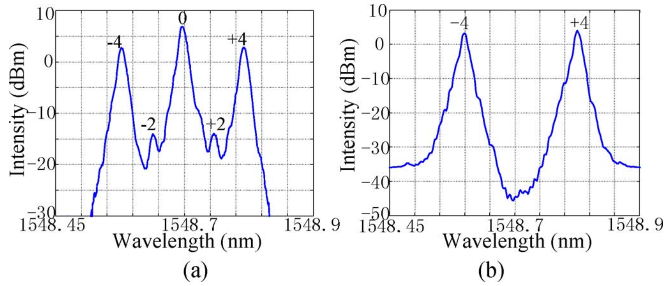

Fig. 3. (a) Measured optical spectrum at the output of MZM_2. (b) Measured optical spectrum at the output of the notch filter.

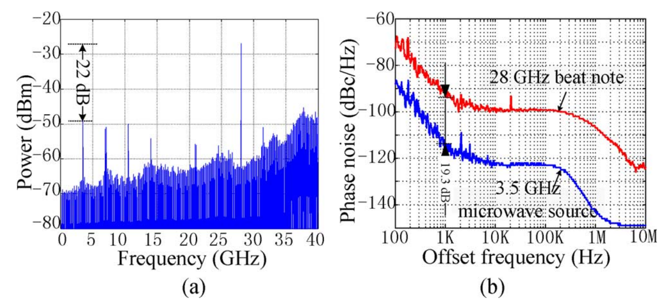

Fig. 4. (a) Measured electrical spectrum of the frequency-octupled signal at the output of the PD. (b) Measured single-sideband phase noise of the generated 28-GHz signal. The phase noise of the 3.5-GHz microwave drive signal is also shown for comparison.

in tuning the PMIs to have a better suppression of the undesired sidebands. As can be seen from Fig. 3(b), only the two ±4th-order sidebands are observed.

In the second experiment, the frequency of the microwave drive signal is 3.5 GHz. By beating the two ±4th-order sidebands at the PD, a frequency-octupled microwave at 28 GHz is generated. As can be seen from Fig. 4(a), the generated microwave has a power 22 dB greater than the next largest component (the first-order harmonic).

To evaluate the phase noise performance, we measure the single-sideband phase noise of the generated signal, as shown in Fig. 4(b). As can be seen, the generated signal has a phase noise of -96.5 dBc/Hz at an offset of 1 KHz. As a comparison, the phase noise of the microwave drive signal at 3.5 GHz is also shown in Fig. 4(b). As expected, the phase noise of the frequency-octupled signal is increased by about 19.3 dB, which is in good agreement with the theoretical prediction of 18.1 dB, calculated by $20\log_{10} 8 \approx 18.1$ dB.

The frequency of the generated signal can be continuously tuned by changing the frequency of the drive signal and adjusting the TOPS. The tunable range is only limited by the bandwidth of the MZMs and the PD. Fig. 5 shows the generation of a frequency tunable microwave signal: the frequency of the microwave drive signal is tuned from 3.4 to 3.8 GHz with a tuning step of 0.1 GHz; a frequency-octupled signal with its frequency tunable from 27.2 to 30.4 GHz is thus generated.

IV. Conclusion

An approach to achieving frequency octupling in the optical domain was proposed and experimentally demonstrated. By

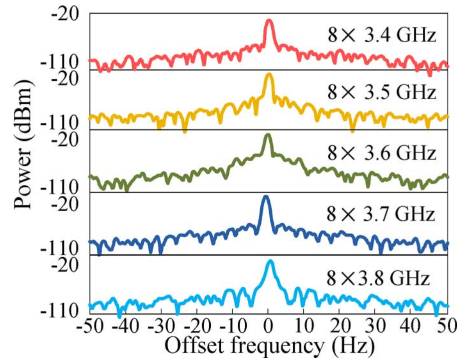

Fig. 5. Spectra of the generated frequency-octupled microwave signal with a 100-Hz spectral span when the frequency of the microwave drive signal is tuned from 3.4 to 3.8 GHz with a 0.1-GHz interval.

properly controlling the input microwave power and the phase shift introduced by the TOPS to satisfy the three conditions, only the ±4th-order sidebands would be generated with the optical carrier and the other sidebands suppressed. By beating the two ±4th-order sidebands at a PD, a frequency-octupled signal was generated. To avoid using large PMIs, we could also use a fixed FBG notch optical filter to filter out the optical carrier. A comprehensive theoretical analysis was presented, which was verified by the experiments. The phase noise performance and the frequency tunability were also experimentally investigated.

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