# Optical Millimeter-Wave Signal Generation Using Frequency Quadrupling Technique and No Optical Filtering

Chun-Ting Lin, Po-Tsung Shih, Jason (Jyehong) Chen, Wen-Qiang Xue, Peng-Chun Peng, and Sien Chi

***Abstract*—This letter demonstrates a novel method to generate high-purity optical millimeter-wave signals with carrier suppression by using a frequency quadrupling technique. To the authors' knowledge, this is the first time that a frequency quadrupling system requires only a single integrated Mach–Zehnder modulator without a narrowband optical filter to remove undesired optical sidebands. Since no optical filter is needed, fast frequency tuning is straightforward and this approach will be particularly attractive for optical up-conversion in wavelength-division-multiplexing radio-over-fiber systems. This letter provides both theoretical analysis and experimental demonstration. The generated optical millimeter-wave signals have very high quality with an optical carrier and harmonic distortion suppression ratio of more than 38 and 36 dB at 40 and 72 GHz, respectively.**

***Index Terms*—Mach–Zehnder modulator (MZM), optical frequency multiplication, optical millimeter-wave, radio-over-fiber (RoF).**

## I. INTRODUCTION

WITH THE accelerated development of wireless communications, efficient and cost-effective methods of generating and transmitting microwave/millimeter-wave signals are of utmost importance. The generation and transmission of microwave/millimeter-wave signals over an optical fiber have been intensively investigated for various applications, such as broadband wireless access networks, phase-array antennas, optical sensors, antenna remoting, and radars [1]–[7]. The advantages of using optical fiber as a millimeter-wave signal transmission medium lie in the almost unlimited bandwidth and very low propagation loss. However, the generation of optical millimeter-wave signals at frequencies above 40 GHz remains a major challenge which is limited by the frequency response of an $\mathrm{LiNbO_3}$ Mach–Zehnder modulator (MZM), typically less than 40 GHz, or phase modulator (PM). Additionally, the electrical components and equipments at frequencies over 40 GHz, such as amplifiers, mixers, and synthesizers, are very expensive. Therefore, a cost-effective way of generating of optical millimeter-wave signals beyond 40 GHz is of great interest.

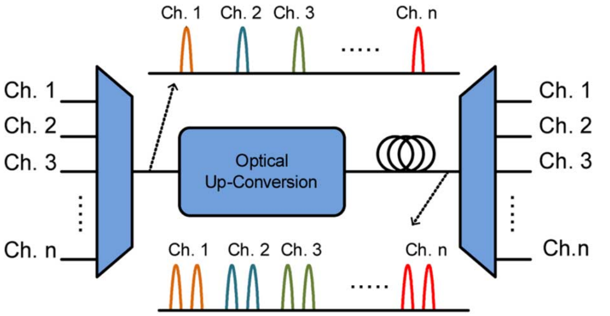

Fig. 1. Optical up-conversion using a frequency multiplication technique for WDM RoF systems.

Numerous optical millimeter-wave signal generation schemes using an MZM or PM to achieve frequency multiplication have been recently demonstrated [1]–[7], [9]. However, these proposed systems need either more than one optical filter to remove undesired optical sidebands [2]–[7], [9] or two cascaded external modulators [7], which significantly increase system complexity and cost. Additionally, the unavoidable optical filtering severely hinders the implementation of optical up-conversion in wavelength-division-multiplexer (WDM) radio-over-fiber (RoF) systems, as shown in Fig. 1 and [8]. Therefore, the frequency quadrupling technique without optical filters is of great interest.

This letter demonstrates a novel frequency quadrupling approach that can generate a carrier-suppressed optical millimeter-wave signal by using only one external modulator without optical filtering. The optical carrier and harmonic distortion suppression ratio (OCHDSR) of the 40- and 72-GHz millimeter-wave signals which are generated by using 10- and 18-GHz driving signal can exceed 38 and 36 dB, respectively. Since the optical carrier and harmonic distortion are highly suppressed, the high-purity two-tone millimeter-wave light wave does not suffer from impairment due to fiber dispersion.

## II. THEORETICAL ANALYSIS

Fig. 2 shows a conceptual diagram of optical carrier-suppressed millimeter-wave signal generation using a frequency quadrupling technique without any optical filter. An external integrated MZM that consists of three sub-MZMs

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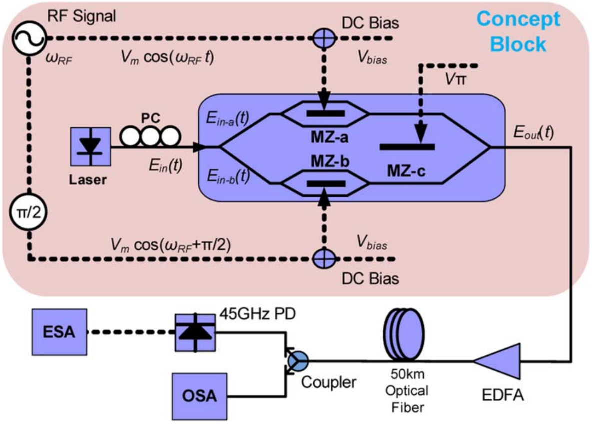

Fig. 2. Optical up-conversion using a frequency multiplication technique for WDM RoF systems. (MZ: Mach–Zehnder modulator; EDFA: erbium-doped fiber amplifier; OSA: optical spectrum analyzer; ESA: electrical spectrum analyzer).

is key to generating optical millimeter-wave signals [7]. One sub-MZM (MZ-a or MZ-b) is embedded in each arm of the main modulator (MZ-c). The optical field at the input of the integrated MZM is defined as

$$E_{\text{in}}(t) = E_o\cos(\omega_o t) \tag{1}$$

where $E_o$ is the amplitude of the optical field and $\omega_o$ is the angular frequency of the optical carrier. MZ-a and MZ-b are both biased at the full point. Electrical driving modulation signals sent into MZ-a and MZ-b are $V_a(t) = V_m\cos(\omega_{\text{RF}}t)$ and $V_b(t) = V_m\cos(\omega_{\text{RF}}t + (\pi/2))$, respectively. In addition, the MZ-c is biased at the null point. Therefore, the optical field at the output of the integrated MZM can be expressed as

$$\begin{aligned} E_{\text{out}}(t) = &\frac{1}{2}\cdot E_o\cdot\{\cos(\omega_o t)\cdot\cos[m\cdot\cos(\omega_{\text{RF}}t)] \\ &- \cos(\omega_o t)\cdot\cos[m\cdot\cos(\omega_{\text{RF}}t+\pi/2)]\} \end{aligned} \tag{2}$$

where the phase modulation index $m$ is $\pi \mathrm{V}_m/2V_\pi$. Expanding the $\cos[m\cdot\cos(\omega_{\text{RF}}t)]$ and $\cos[m\cdot\cos(\omega_{\text{RF}}t+(\pi/2))]$ using a Bessel function, the output optical field can be rewritten as

$$\begin{aligned} E_{\text{out}}(t) = &-E_o\sum_{n=1}^{\infty}J_{4n-2}(m) \\ &\times\{\cos[(\omega_o+(4n-2)\omega_{\text{RF}})t]+\cos[(\omega_o-(4n-2)\omega_{\text{RF}})t]\} \end{aligned} \tag{3}$$

where $J_n$ is the Bessel function of the first kind of order $n$. Within the typical modulation range of $0 \le m \le \pi$, the Bessel function $J_{4n-2}$ monotonically decreases with $m$. At $m = \pi$, the corresponding values of $J_2(m), J_6(m), J_{10}(m)$, and $J_{14}(m)$ are 0.4854, 0.0145, $2.0095\times10^{-5}$, and $5.4133\times10^{-9}$, respectively. Therefore, the optical sidebands with the order higher than $J_6$ can be ignored without significant errors, and the optical field can be further simplified to

$$\begin{aligned} E_{\text{out}}(t) = -E_o\{&J_2(m)\cos[(\omega_o+2\omega_{\text{RF}})t] \\ &+J_2(m)\cos[(\omega_o-2\omega_{\text{RF}})t] \\ &+J_6(m)\cos[(\omega_o+6\omega_{\text{RF}})t] \\ &+J_6(m)\cos[(\omega_o-6\omega_{\text{RF}})t]\}. \end{aligned} \tag{4}$$

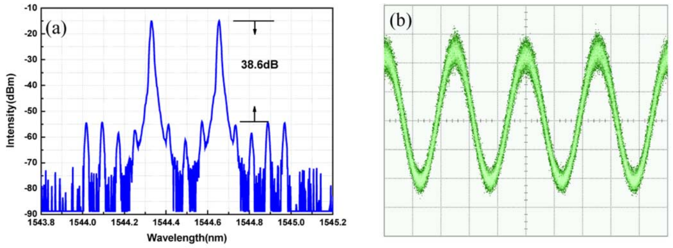

Fig. 3. Experimental results of 40-GHz optical millimeter-wave signal. (a) Optical spectrum. The resolution is 0.01 nm. (b) Optical waveform (313 uW/div; 10 ps/div).

After square-law detection using a photodiode (PD), the photocurrent can be expressed as

$$i(t) = R\cdot|E(t)|^2 \tag{5}$$

where $R$ is the 45-GHz photodetector's responsivity. The cross terms of (5) will generate the desired millimeter-wave signal and its harmonic distortion signals.

## III. EXPERIMENTAL RESULTS AND DISCUSSION

To verify the proposed method, the experimental setup is illustrated in Fig. 2. The external integrated MZM is a commercially available $\text{LiNbO}_3$ modulator with 3-dB bandwidth of 20 GHz. The optical carrier generated by the distributed-feedback laser with wavelength of 1544.5 nm is applied to the integrated MZM via a polarization controller (PC). The frequency of the microwave signal is set at 10 or 18 GHz. The generated optical millimeter-wave signal is amplified with an erbium-doped fiber amplifier (EDFA) to compensate the MZM loss and then transmitted over 50-km single-mode fiber (SMF). The optical power is normalized to 1 dBm before PD detection.

Fig. 3(a) shows the measured spectrum of the optical 40-GHz millimeter-wave signal using 10-GHz driving signal before transmission. As can be seen, the optical carrier is effectively suppressed, and the power of the two second-order sidebands which are converted into 40-GHz electrical millimeter-wave signal after PD detection is 38 dB higher than that of the other order sidebands. Besides the second and sixth order sidebands, the other harmonic sidebands are observed due to the imbalanced y-junction splitting ratio of the MZM. However, the suppression of the undesired harmonic sidebands can achieve more than 38 dB and induces a negligible influence on the performance of the optical millimeter-wave signal. Fig. 3(b) shows the waveform of the optical millimeter-wave signal with 50% duty cycle due to high OCHDSR.

Fig. 4 shows the electrical spectrum of the generated millimeter-wave signal with 40-GHz span and 30-kHz resolution bandwidth. A strong electrical output signal with frequency four times that of the driving signal is observed, and the first, second, and third terms of the electrical signal are totally suppressed. Fig. 5(a) shows that the linewidth of the generated 40-GHz signal is quite small and almost equal to that of the 10-GHz driving signal. After transmission over 50 km of SMF, no linewidth broadening of the electrical 40-GHz signal due to fiber dispersion is observed, as shown in Fig. 5(b). Limited by the bandwidth of available RF amplifier in our laboratory, the

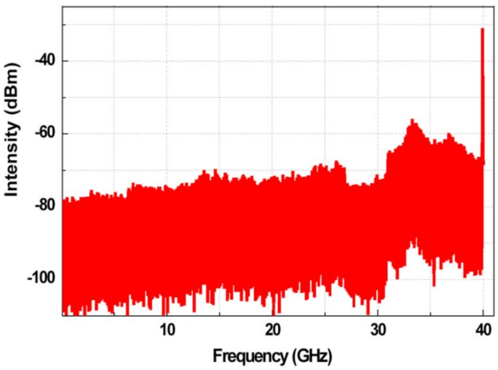

Fig. 4. Electrical spectrum of the generated 40-GHz millimeter-wave signal.

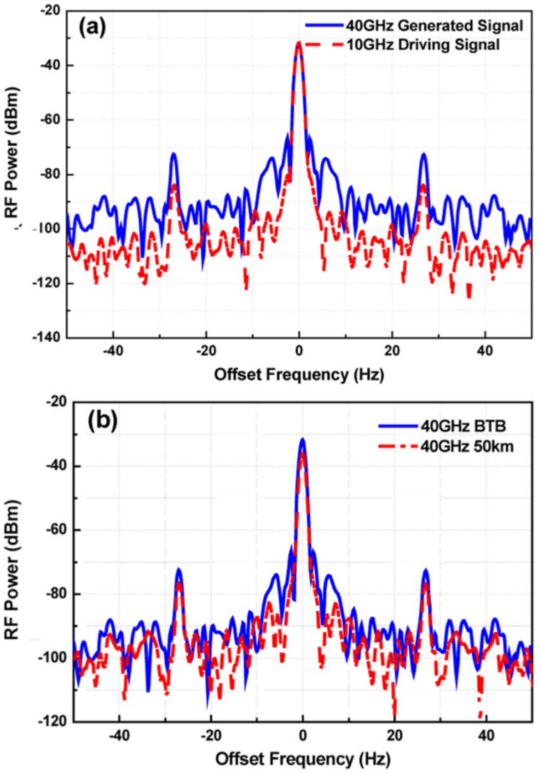

Fig. 5. Electrical spectrum of the generated 40-GHz millimeter-wave signal with 100-Hz span. (a) Comparison of generated 40-GHz signal and 10-GHz driving signal. (b) Comparison of generated BTB and following 50-km SMF transmission 40-GHz signal. The resolution bandwidth is 1 Hz.

optical 72-GHz millimeter-wave signal is also demonstrated using an 18-GHz driving signal. Fig. 6 shows that the optical power of the two second sidebands is 36 dB higher than that of the other sideband, which is good enough for most practical applications.

## IV. CONCLUSION

In this letter, a novel frequency quadrupling technique for optical millimeter-wave generation is proposed. A two-tone light wave with frequency separation of four times the modulation frequency can be generated using only one external modulator without optical filtering. Optical millimeter-wave signals of 40 and 72 GHz are generated from 10- and 18-GHz driving signals, respectively. The OCHDSR of these optical millimeter-wave signals can reach more than 36 dB. Since no optical filter is needed, the proposed scheme can be utilized in WDM RoF and continuously tunable millimeter-wave signal generation systems. Since the state-of-the-art MZM has an upper-limit frequency response around 40 GHz [7], the proposed method is capable of generating optical millimeter-wave signals up to 160 GHz.

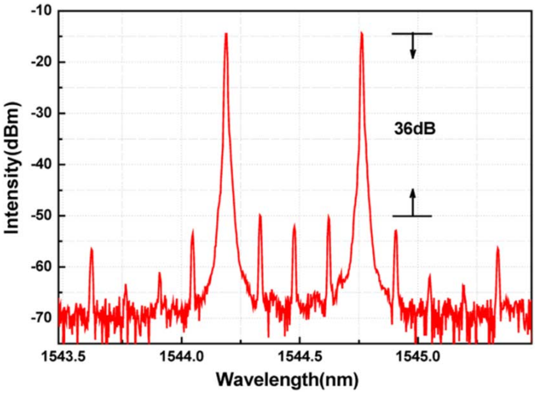

Fig. 6. Optical spectrum of the generated 72-GHz millimeter-wave signal using 18-GHz driving signal.

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