# Generation of 60-GHz Optical Millimeter-Wave and 20-GHz Channel-Spaced Optical Multicarrier Using Two Cascaded 10-GHz Modulators

**Qingjiang Chang, Tong Ye, Junming Gao, and Yikai Su**
*State Key Lab of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering*
*Shanghai Jiao Tong University, 800 Dongchuan Rd, Shanghai 200240, China, yikaisu@sjtu.edu.cn*

**Abstract:** We propose and experimentally demonstrate the generation of 60-GHz optical millimeter-wave and 20-GHz channel-spaced optical multicarrier using two cascaded 10-GHz single–drive Mach-Zehnder modulators.

**OCIS codes**: (060.2330) Fiber optics communications; (060.5625) Radio frequency photonics.

## 1. Introduction

The generation of high-speed optical millimeter-wave (MMW) for photonic up-conversion of baseband data is a key technique in radio over fiber (RoF) systems [1]. In addition, the optical MMW can be used as photonic local-oscillators for radio astronomy [2], optical clock for optical signal processing [3], and optical pulse train for carving non return-to-zero (NRZ) signal to produce return-to-zero (RZ) or carrier-suppression RZ format [4]. Therefore, the optical MMW generation technique is receiving increasing attentions. Photonic frequency multiplication (PFM) technique based on external modulator is considered as an attractive approach, since the generated optical MMW has the advantages of simplicity, stability and high spectral purity [1, 5-6]. However, in previous demonstrations, the PFM could only be generated with double [1] or quadruple frequency [5] of the electronic modulating signal. To obtain a frequency multiplication factor higher than four, the methods so far typically depended on four-wave-mixing nonlinear effects combined with optical filters to remove the unwanted harmonic components [6], which could result in complicate structure and high cost.

In this paper, we experimentally demonstrate a new scheme to generate 60-GHz optical MMW based on two cascaded 10-GHz single-drive Mach-Zehnder modulators (SDMZMs). The scheme is scalable in frequency band if higher-speed devices are employed, thus up to 240-GHz optical MMW can be obtained using currently available 40-GHz devices. Moreover, the method can be extended to produce an optical multicarrier consisting of 4 channels with a 20-GHz channel spacing and high spectral flatness, which is very useful in super-dense wavelength-division multiplexed systems [7]. We also demonstrate that the generated optical MMW is used in an RoF system for up-converting 10-Gb/s NRZ to the 60-GHz carrier, the penalty after 25-km transmission is ~1.8-dB.

## 2. Principle

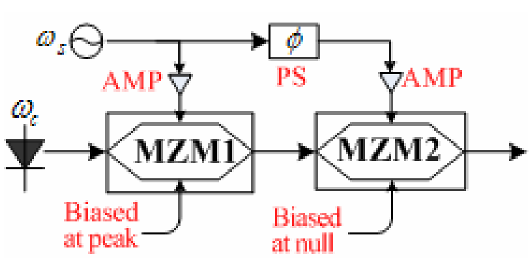


Fig. 1. Schematic diagram of the proposed system

Figure. 1 depicts the schematic diagram of the generation of optical MMW and optical multicarrier based on two cascaded SDMZMs. A radio frequency (RF) signal $V_1(t)=\varepsilon_1 V_\pi+\alpha_1 V_\pi\cos(\omega_s t+\phi_1)$ is used to drive MZM1, where $\varepsilon_1$ and $\alpha_1$ are the bias voltage of the modulator and the driving amplitude of the RF signal normalized to the half-wave voltage $V_\pi$, respectively. $\omega_s$ and $\phi_1$ are the frequency and the phase of the RF signal. The MZM1 is biased at the peak of the transmission curve to suppress the odd-order sidebands. The output field of the MZM1 can be approximately expressed as:

$$E_{out\_1}(t) \approx J_0(\alpha_1 \frac{\pi}{2})\cos(\omega_c t) - J_2(\alpha_1 \frac{\pi}{2})\{\cos[(\omega_c + 2\omega_s)t + \phi_1] + \cos[(\omega_c - 2\omega_s)t - \phi_1]\} \quad (1)$$

Since the amplitudes of the generated tones are proportional to $J_x(\alpha_1 \cdot \pi/2)$, the frequency components at the optical carrier and the two second-order harmonics can achieve the same amplitude while the higher-order sidebands remain negligible by properly controlling the driving voltage, as shown in Fig. 1(a). The output signals of the MZM1 are injected into a following modulator MZM2 of the same type, which is biased at the transmission null to obtain optical carrier suppressed modulation and driven by another RF signal $V_2(t) = \varepsilon V_\pi + \alpha_2 V_\pi \cos(\omega_s t + \phi_2)$, where is a normalized value, and $\phi_2$ is the phase. Thus the output field of the MZM2 can be given by:

$$\begin{aligned} E_{out\_2}(t) \approx & -\{J_0(\alpha_1 \frac{\pi}{2})J_1(\alpha_2 \frac{\pi}{2})\cos[(\omega_c + \omega_s)t + \phi_2] - J_2(\alpha_1 \frac{\pi}{2})J_1(\alpha_2 \frac{\pi}{2})\cos[(\omega_c + \omega_s)t + \phi_1 - \phi_2]\} \\ & -\{J_0(\alpha_1 \frac{\pi}{2})J_1(\alpha_2 \frac{\pi}{2})\cos[(\omega_c - \omega_S)t - \phi_2] - J_2(\alpha_1 \frac{\pi}{2})J_1(\alpha_2 \frac{\pi}{2})\cos[(\omega_c - \omega_s)t - \phi_1 + \phi_2]\} \\ & +\{J_2(\alpha_1 \frac{\pi}{2})J_1(\alpha_2 \frac{\pi}{2})\cos[(\omega_c - 3\omega_s)t - \phi_1 - \phi_2]\} + \{J_2(\alpha_1 \frac{\pi}{2})J_1(\alpha_2 \frac{\pi}{2})\cos[(\omega_c + 3\omega_s)t + \phi_1 + \phi_3]\} \end{aligned} \quad (2)$$

Therefore, the output of MZM2 includes 4 components ($\omega_c \pm \omega_s, \omega_c \pm 3\omega_s$). When the phases satisfy $\phi_2 = \phi_1 - \phi_2$, the tones at the frequency $\omega_c \pm \omega_s$ cancel each other due to the opposite phases and the same amplitude. The phase difference between the two modulating signals is introduced by a phase shifter (PS). Only two tones of the highest and lowest frequencies remain, which are spaced by a six-fold frequency of the electrical driving signal, while other components are greatly suppressed. Fig. 2(b) shows the process of generating the sixfold-frequency optical MMW. When the phases satisfy $\pi - \phi_2 = \phi_2 - \phi_1$ and the driving amplitude of the MZM2 is properly adjusted, one can obtain a multicarrier including 4 tones with frequency-doubled channel spacing and the same optical power from a single seed laser, as shown in Fig. 2(c).

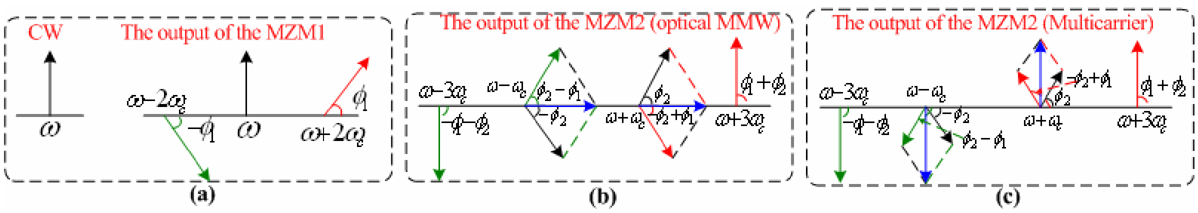


Fig. 2. Principle diagram of the generation of the optical MMW and the optical multicarrier.

### 3. Experimental Setup and Results

We perform an experiment to verify the feasibility of the proposed scheme, as shown in Fig. 1. Two 10-GHz SDMZMs of the same type are biased at the transmission peak and null, respectively. A continues wave signal is fed into the MZM1, which is driven by a 10-GHz RF signal with ~11-V peak-to-peak value to produce three tones including a carrier and two strong second-order harmonics. Fig. 3(a) shows the spectrum, where the three tones have nearly the same amplitudes and other higher-order tones are 20-dB lower. The MZM2 is driven by the same frequency RF signal, and a PS is used to adjust the phase difference of the RF signals applied to the two MZMs. Here, we set a π/6 phase difference between the two modulating signals to generate 60-GHz optical MMW. The

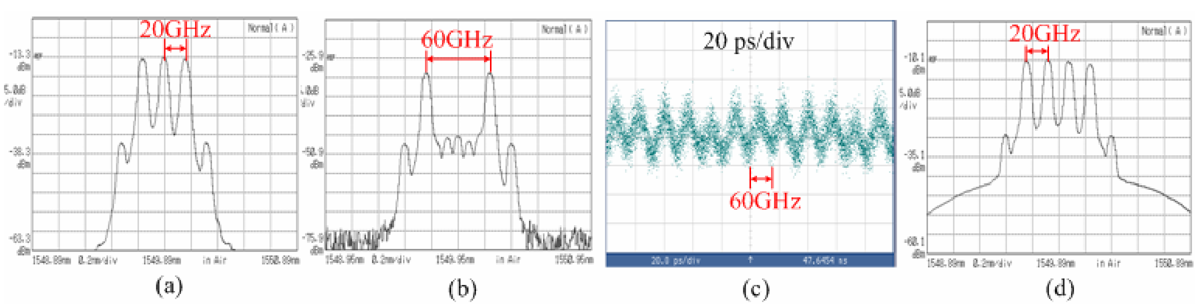


Fig. 3. Optical spectra and eye diagram.

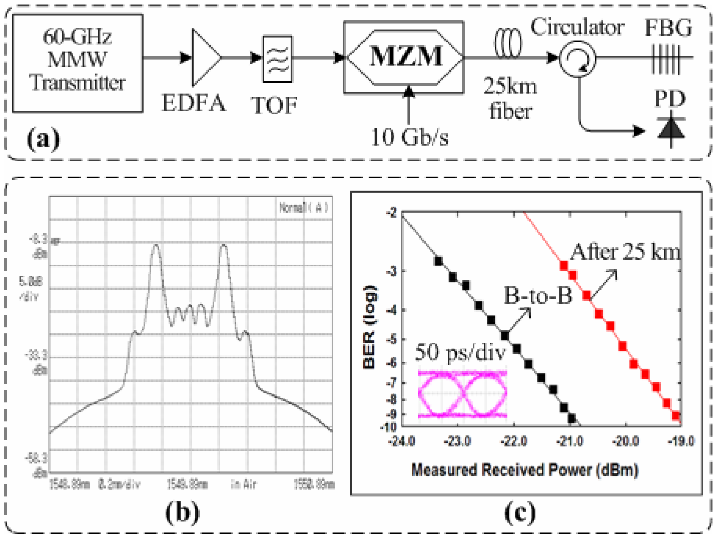


Fig.4. Experimental setup and results for up-converting 10-Gb/s data in RoF systems.

spectrum of the obtained MMW is provided in Fig. 3(b), showing ~18-dB suppression ratio on the residual tones. The optical eye diagram captured by a 40-GHz oscilloscope is shown in Fig. 3(c). When the phase difference equals to π/2 and the amplitude of the modulating signal of the MZM2 is ~5.5-V peak-to-peak voltage, an ultra-flat optical multicarrier including 4 tones with 20-GHz channel spacing is obtained, where the power variation among the tones is less than 0.4 dB, as indicated in Fig. 3(d). The generated optical MMW can be used in RoF systems to up-convert baseband data, an experimental setup is depicted in Fig. 4(a). The amplified 60-GHz optical MMW is mo transmission over a 25-km single mode fibre (SMF), a high-speed photo-detector (PD) is used to convert the optical MMW signal into electrical wireless signal which is supposed to be broadcasted through air. In this experiment, we mainly focus on demonstrating the optical MMW generation; the signal is detected using a similar method in [8]. The BER performance with ~1.8-dB power penalty and the electrical eye diagram are also shown in Fig. 4(c).

## 4. Conclusion

We have experimentally demonstrated the generation of the frequency-sextupled optical MMW and the optical multi-carrier with frequency-doubled channel-spacing by using two cascaded SDMZMs. The 10-Gb/s NRZ is up-converted to the 60-GHz MMW, the transmission penalty is ~1.8-dB through 25-km fiber.

**Acknowledgement**:

This work was supported by the 863 High-Tech Program (2006AA01Z255), and the Fok Ying Tung Fund (101067).

## References:

[1] J. Yu, Z. Jia, L. Yi, Y. Su, G. K. Chang, and T. Wang, "Optical millimeterwave generation or up-conversion using external modulators," *IEEE Photon. Technol. Lett.*, vol. 18, no. 1, pp. 265–267, Jan. 1, 2006.

[2] Ueda, A., Noguchi, T., Asayama, S., Iwashita, H., Sekimoto, Y., Ishiguro, et. al., "Ultra-Low Noise Photonic Local Oscillator at 100 GHz," Jpn. J. *Appl. Phys.*, 42(6B), L704–L705, 2003.

[3] E. Awad, P. Cho, C. J. K. Richardson, N. Moulton, J. Goldhar, "Optical 3R regeneration using a single EAM for all-optical timing extraction with simultaneous re-shaping and wavelength conversion," *IEEE Photon. Technol. Lett.* Vol. 14, no. 9, 1378 – 1380. Sep. 2002.

[4] G. Bosco, A. Carena, V. Curri, R. Gaudino, and P. Poggiolini, "On the use of NRZ, RZ, and CSRZ modulation at 40 Gb/s with narrow DWDM channel spacing," *J. Lightw. Technol.*, vol. 20, no. 9, pp. 1694–1704, Sep. 2002.

[5] T. Kawanishi, H. Kiuchi, M. Yamada, T. Sakamoto, et al, "Quadruple frequency double sideband carrier suppressed modulation using high extinction ratio optical modulators for photonic local oscillators," in *Proc. IEEE Microwave Photonics 2005*, paper PDP-03..

[6] A. Wiberg, P. P-Millan, M. V. Andres, and P. O. Hedekvist., "Microwave-photonic frequency multiplication utilizing optical four-wave mixing and fiber Bragg Gratings," *J. Lightw. Technol.* vol. 24, no. 1, pp. 329-334, Jan. 2006.

[7] M. Fujiwara, M. Teshima, J. Kani, H. Suzuki, et al,"Optical carrier supply module using flattened optical multicarrier generation based on sinusoidal amplitude and phase hybrid modulation,"*J. Lightw. Technol.*, vol. 21, no. 11, pp. 2705–2714, Nov. 2003.

[8] Q. Chang, H. Fu, and Y. Su, "Simultaneous generation and transmission multi-band signals and upstream data in a bidirectional radio over fiber system," *IEEE Photon. Technol. Lett.*. vol. 20, no. 3, pp. 181-183, Feb. 2008.