Simultaneous generation of 3G and millimeter-wave signals using a dual-electrode MZM in ROF systems*

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A novel radio-over-fiber (ROF) scheme to simultaneously generate and transmit the 3rd generation telecommunication (3G) and millimeter-wave (MMW) signals by using a single dual-electrode Mach-Zehnder modulator (MZM) is proposed. There is no apparent nonlinearity induced by the ROF system. By employing this analog ROF signal transmission technique, highly transparent fiber-wireless convergence networks can be realized, which are ideal for multi-standard wireless system operation.

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Radio-over-fiber (ROF) technique has raised great interest in the last decade to provide optical transmission of radio signals for multiple operators[1,2]. In order to reduce the infrastructure cost, the convergence of multi-service access networks over ROF system has been investigated recently[3,4]. Hybrid wireline and wireless signal transmission over a wavelength division multiplexing passive optical network (WDM-PON) has also attracted great interest in the past few years[5,6]. In Ref.[7], optical tunable filtering and polarization de-multiplexing have been used to realize reconfigurable remote access modes for the transmission of 60 GHz millimeter-wave (MMW) and baseband signals. In Ref.[8], a passive optical network architecture supporting ROF and orthogonal frequency division multiple access (OFDMA) signals has been proposed. A WDM-PON system compatible with wired transmission and ultra-wideband (UWB) transmission in the frequency band from 3.1 GHz to 10.6 GHz has been introduced in Refs.[9] and [10]. In Ref.[11], broadband MMW generation and 2.5 Gbit/s baseband transmission are simultaneously realized with two Mach-Zehnder modulators (MZMs).

Recently, multi-band modulation technique based on a single optical modulator is inquired to further reduce the overall system cost. In Ref.[12], a single electro-absorption modulator is employed to realize a multi-band ROF system transmitting wideband code-division multiple access (WCDMA) and baseband signals simultaneously, but the system requires a 60 GHz signal generator and a 60 GHz optical modulator, which means high cost of the infrastructure. A novel modulation approach for simultaneous generation and transmission of optical radio-frequency (RF) wireless vector signal and baseband wireline signal using a single-electrode MZM is presented in Ref.[13], but the two kinds of signals are affected by each other. Ref.[14] demonstrates a cost-effective ROF system for downstream 1 Gbit/s on-off keying/binary phase shift keying (OOK/BPSK) and 2 Gbit/s 16 quadrature amplitude modulation-orthogonal frequency division multiplexing (16QAM-OFDM) signals using only one single-drive MZM by driving both RF and bias ports.

In this paper, a novel ROF scheme to simultaneously generate and transmit the 3rd generation telecommunication (3G) mobile and MMW signals by using a single dual-electrode MZM is proposed. The related theoretical analysis and the experimental results are presented.

The schematic diagram of the proposed ROF scheme is shown in Fig.1. In the central office (CO), a 2.5 Gbit/s baseband signal is mixed with a 30 GHz carrier, which is at half of the local oscillation (LO) frequency. The mixed signal is applied to one electrode of the MZM. The other electrode of the MZM is driven by a 3G mobile signal. The direct current (DC) bias point of the MZM is shown in the inset (i) of Fig.1. As a result, the 2.5 Gbit/s baseband signal is carried on two subcarriers separated by a frequency of LO in the optical domain, while the 3G signal is imposed on the optical carrier. The optical spectra after modulation are depicted in the inset (ii) of Fig.1. At the base station (BS), a fiber Bragg grating (FBG) is utilized to separate these two signals, as shown in the insets (iii) and (iv) of Fig.1, and each signal is transmitted to the corresponding photodetector (PD).

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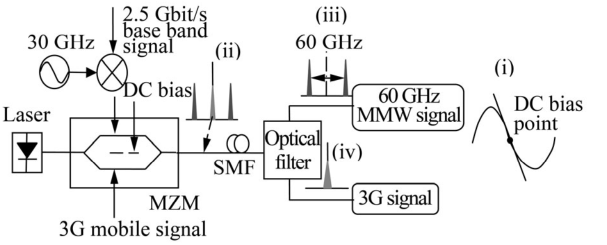


(i) DC bias point of MZM; Spectra of (ii) modulated signal, (iii) 60 GHz MMW signal and (iv) 3G signal

Fig.1 Schematic diagram for simultaneous generation of 3G and MMW signals using a dual-electrode MZM

The optical field at the input of the MZM is given by $E_{\text{in}}(t)=A\exp(\text{j}\omega_{\text{c}}t)$, where A and ω_{c} are the amplitude and angular frequency of the optical field, respectively. The 30 GHz MMW driving signal sent into the MZM is $V_{\text{MM}}(t)\cdot\cos[\omega_{\text{MM}}t+\theta_{\text{MM}}(t)]$, where $V_{\text{MM}}(t)$ and $\theta_{\text{MM}}(t)$ are amplitude and phase information of the MMW driving signal, respectively, and ω_{MM} is the angular frequency of the MMW carrier signal. The 3G driving signal is $V_{3\text{G}}(t)\cdot\cos[\omega_{3\text{G}}t+\theta_{3\text{G}}(t)]$, where $V_{3\text{G}}(t)$ and $\theta_{3\text{G}}(t)$ are amplitude and phase information of the 3G signal, respectively, and $\omega_{3\text{G}}$ is the angular frequency of the 3G carrier signal. The modulated optical signal at the output of the MZM can be expressed as

$$E(t)=\frac{A}{2}\exp(\text{j}\omega_{\text{c}}t)\times$$
$$\left\{\exp\left[\text{j}\gamma\pi+\text{j}m_{3\text{G}}\pi\cos\left(\omega_{3\text{G}}t+\theta_{3\text{G}}(t)\right)\right]+\right.$$
$$\left.\exp\left[\text{j}m_{\text{MM}}\pi\cos\left(\omega_{\text{MM}}t+\theta_{\text{MM}}(t)\right)\right]\right\}, \tag{1}$$

where γ=1/2 is a constant phase shift induced by the DC biased voltage, $m_{3\text{G}}=V_{3\text{G}}(t)/V_\pi$ is the modulation index of 3G signal, $m_{\text{MM}}=V_{\text{MM}}(t)/V_\pi$ is the modulation index of MMW signal, and V_π is the half-wave voltage of the MZM. Using the Jacobi-Anger identity and ignoring high-order Bessel function, the optical field at the output of the MZM can be simplified to

$$E(t)=\frac{A}{2}\exp(\text{j}\omega_{\text{c}}t)\left\{J_0\left[m_{\text{MM}}(t)\pi\right]+\right.$$
$$\left.2\text{j}J_1\left[m_{\text{MM}}(t)\pi\right]\cos\left[\omega_{\text{MM}}t+\theta_{\text{MM}}(t)\right]\right\}+$$
$$\frac{\text{j}A}{2}\exp(\text{j}\omega_{\text{c}}t)\left\{J_0\left[m_{3\text{G}}(t)\pi\right]+\right.$$
$$\left.2\text{j}J_1\left[m_{3\text{G}}(t)\pi\right]\cos\left[\omega_{3\text{G}}t+\theta_{3\text{G}}(t)\right]\right\}, \tag{2}$$

where J_n is the n-order Bessel function of the first kind. The corresponding optical spectrum is illustrated in Fig.2. Two orthogonal components can be observed at the optical carrier. The amplitudes of the two components are determined by MMW and 3G mobile signals, respectively. The MMW signal is carried on two subcarriers separated by a frequency of $2\omega_{\text{MM}}$ in the optical domain, while the 3G signal is imposed on frequencies of $\omega_{\text{c}}\pm\omega_{3\text{G}}$ which are around the optical carrier. Obviously, it's easy to separate MMW and 3G signals by using an FBG.

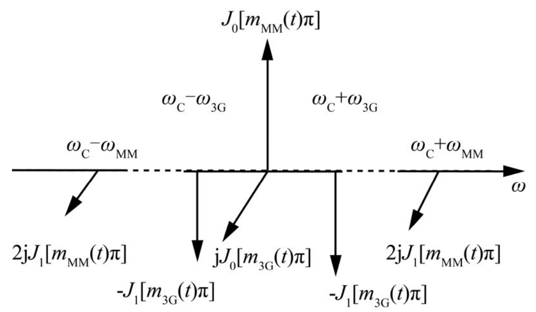


Fig.2 Illustration of the optical spectrum at the output of MZM

After back-to-back transmission, the corresponding output photocurrents of the two PDs can be obtained as

$$i_1=R_1\left|E_{\text{MM}}(t)\right|^2=\frac{R_1A^2}{2}J_1^2\left[m_{\text{MM}}(t)\pi\right]\times$$
$$\left\{1+\cos\left[2\omega_{\text{MM}}t+2\theta_{\text{MM}}(t)\right]\right\}, \tag{3}$$
$$i_2=i_{\text{DC}}-R_2A^2J_0\left(m_{\text{MM}}\pi\right)J_1\left(m_{3\text{G}}\pi\right)\cos\left[\omega_{3\text{G}}t+\theta_{3\text{G}}(t)\right]+$$
$$\frac{R_2A^2}{2}J_1^2\left(m_{3\text{G}}\pi\right)\cos\left[2\omega_{3\text{G}}t+2\theta_{3\text{G}}(t)\right], \tag{4}$$

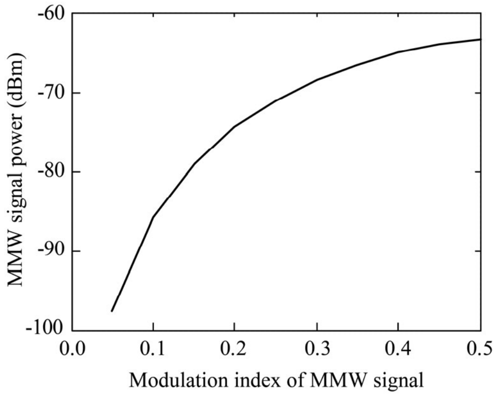
where $i_{\text{DC}}=\frac{R_2A^2}{4}\left[J_0^2\left(m_{\text{MM}}\pi\right)+J_0^2\left(m_{3\text{G}}\pi\right)+2J_1^2\left(m_{3\text{G}}\pi\right)\right]$ is the DC component, and R_1 and R_2 are the responsivities of the two PDs, respectively. Finally, the desired MMW and 3G signals can be derived as

$$i_{\text{MM}}=R_1\left|E_{\text{MM}}(t)\right|^2=$$
$$\frac{R_1A^2}{2}J_1^2\left[m_{\text{MM}}(t)\pi\right]\cos\left[2\omega_{\text{MM}}t+2\theta_{\text{MM}}(t)\right], \tag{5}$$
$$i_{3\text{G}}=-R_2A^2J_0\left(m_{\text{MM}}\pi\right)J_1\left(m_{3\text{G}}\pi\right)\cos\left[\omega_{3\text{G}}t+\theta_{3\text{G}}(t)\right]. \tag{6}$$

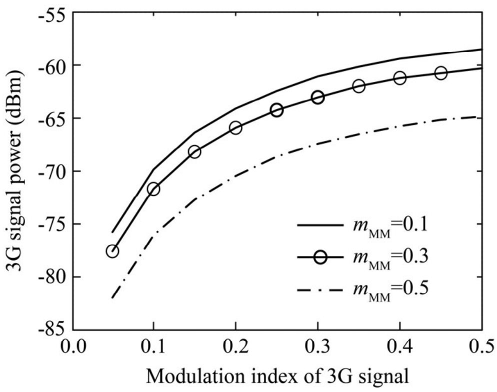
It can be seen from Eqs.(5) and (6) that the output MMW signal can not be affected by the 3G signal, while the output 3G signal is impacted by the modulation index of MMW signal. That's because one component of the optical carrier is determined by MMW signal as mentioned previously, and this component can't be separated by filter from the 3G signal. However, if the MMW signal is a constant envelope signal, such as phase shift keying modulation, the modulation index of MMW signal m_{MM} is a constant, and then the MMW signal only affects the link gain of 3G signal. As a result, there is no apparent nonlinearity for both signals in this approach.

The calculated powers of the output MMW and 3G signals are shown in Fig.3. The input optical powers of two PDs are both assumed to be 0 dBm, and PD responsivities are both 0.6 mA/mW. It can be seen from

Fig.3(b) that the received power of 3G signal decreases with the increase of modulation index of MMW signal.



(a) MMW signal



(b) 3G signal

Fig.3 The powers of generated MMW and 3G signals versus their corresponding modulation index

The experimental setup for simultaneous generation and transmission of independent 3G and MMW signals based on dual-electrode MZM is shown in Fig.4. A distributed-feedback (DFB) laser from Beijing Conquer Optical Technology Co., Ltd. is used to generate light wave at 1 550 nm. The light wave is delivered to a 30 GHz bandwidth dual-electrode MZM from Fujitsu Optical Components Limited via a polarization controller (PC). One electrode of the MZM is driven by a 30 GHz microwave signal with power of 17 dBm generated by Agilent analog signal generator 8257D. Moreover, a single-carrier WCDMA signal and a two-carrier CDMA2000 signal from Agilent VSG N5182A are power combined and then fed into the other electrode of the MZM. The modulated light wave is amplified by an erbium-doped fiber amplifier (EDFA) before transmission over single-mode fiber (SMF). An optical band pass filter is employed to reject out-of-band amplified spontaneous emission (ASE) noise. At the BS, an FBG with a 3 dB bandwidth of 0.1 nm and a reflection ratio of 90% is used to separate the MMW signal and WCDMA signal. The MMW signal is detected by a 70 GHz bandwidth PD from U2T photonics with responsivity of 0.6 A/W, while the 3G signal is received by a 10 GHz bandwidth PD and an electrical amplifier. The received signals are evaluated with a spectrum analyzer E4448A and a wide-bandwidth oscilloscope 86100C from Agilent Technologies.

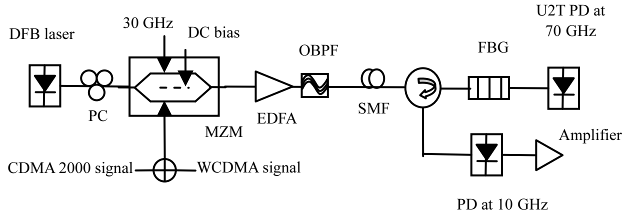


Fig.4 Schematic diagram of experimental setup for simultaneous generation of 3G and MMW signals using a dual-electrode MZM

Fig.5 shows the spectra of the received 3G signal. It can be seen that there is no obvious out-of-band spectra regrowth induced by the ROF system. The increase of the noise floor may be introduced by the power amplifier after the PD or the noise of the optical fiber link. The temporal waveform of the generated MMW signal is shown in Fig.6, where the time scale is 6.6 ps/div and the power scale is 250 μW/div. The spectrum of the generated MMW signal is shown in Fig.7. The experimental results show that a pure 60 GHz MMW signal is generated regardless of the existence of 3G signal. It is exactly corresponding to the theoretical analysis.

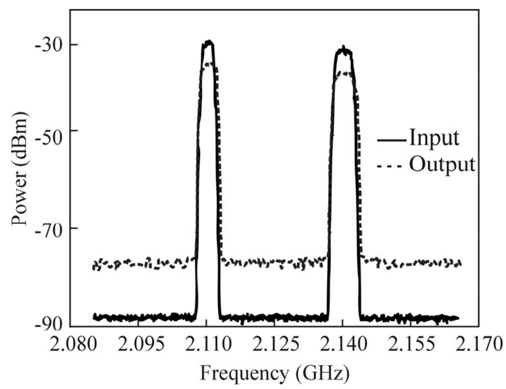


Fig.5 Spectra of the 3G signal after detection

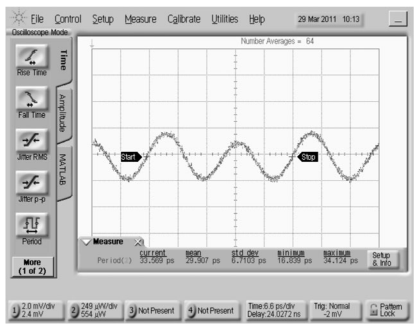


Fig.6 Temporal waveform of the generated MMW signal

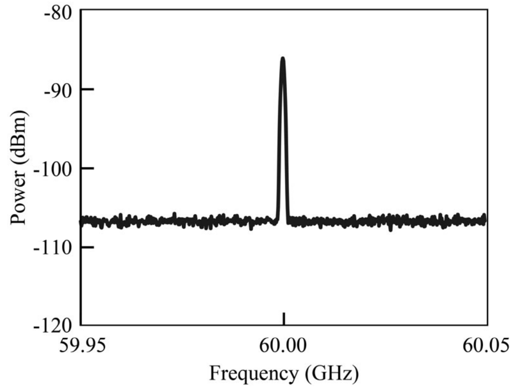


Fig.7 Spectrum of the generated MMW signal

In this paper, a novel ROF system is demonstrated to simultaneously generate and transmit 3G and MMW signals by using a single dual-electrode MZM. There is no apparent nonlinearity induced by the ROF system. This scheme has unique advantages in terms of system simplicity, reliability and flexibility. The experimental results show that it is a suitable solution for the future ROF-based optical-wireless access networks.

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