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

YING Xiang-yue (应祥岳)**, **XU Tie-feng** (徐铁峰), **LIU Tai-jun** (刘太君), **NIE Qiu-hua** (聂秋华), **WEN Hua-feng** (文化锋), **and LI Jun** (李军)

College of Information Science and Engineering, Ningbo University, Ningbo 315211, China

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In this paper, a novel radio-over-fiber (ROF) scheme to simultaneously generate and transmit wideband code division multiple access (WCDMA) 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, the highly transparent fiber-wireless networks, which are ideal for multi-standard wireless system operation, can be realized.

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Radio-over-fiber (ROF) technique has raised great interest in the last decade to provide optical transmission of radio signals to multiple simplified base stations (BSs) for multiple operators, also exploiting existing optical infrastructures for the wireless mobile signal distribution[1-3]. ROF system is very cost-effective because of simple BS and localization of signal processing in central station (CS). ROF technique can support multiple wireless standards, as well as millimeter wave (MMW) transmission[4]. And the co-channel interference can be greatly reduced due to low radiated power in pico and micro cells structures. In order to reduce the infrastructure cost, the convergence of multi-service access networks over ROF system has been investigated recently[5]. Most of the works focus on the simultaneous multi-band modulation and transmission[6]. In Ref.[7], optical tunable filtering and polarization de-multiplexing have been used to realize reconfigurable remote access modes for transmission of 60 GHz MMW and baseband signals. In Ref.[8], a novel passive optical network architecture supporting radio-over-fiber signals and orthogonal frequency-division multiple signals has been proposed. A wavelength division multiplexing passive optical network (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.[9,10].

Recently, multi-band modulation with a single optical modulator technique is inquired to reduce the overall system cost. In Ref.[11], a single electro-absorption modulator is employed to realize a multi-band ROF system transmitting WCDMA and baseband signals simultaneously. However, the system requires 60 GHz generators and 60 GHz optical modulator, which means high cost of the infrastructure. In Ref.[12], a single MZM is employed for both digital modulation and continuous wave (CW) signal modulation. A 60 GHz signal and a 20 GHz signal with the same data stream are generated simultaneously. In Ref.[13], a single MZM is used to generate independent wired and wireless signals, but only on-off keying (OOK) modulation format is supported in this configuration. In Ref.[14], broadband millimeter wave generation and 2.5 Gbit/s baseband transmission are simultaneously realized. The millimeter wave modulation impacts to the baseband signal for different modulation formats are deeply investigated. But this system requires two MZMs.

Moreover, most of the previous works focus on the simultaneous modulation and transmission of digital baseband signal and MMW/MW signal. However, in certain cases, analog signal transport offers unique benefits. In this paper, a novel ROF scheme to simultaneously generate and transmit WCDMA and MMW signals by using a single dual-electrode MZM is proposed. The proposed ROF scheme is shown in Fig.1. In the central office (CO), a 2.5 Gbit/s baseband signal is mixed with the 30 GHz carrier, which is at half of the local oscillation (LO) frequency. The mixed signal and the WCDMA signal are applied simultaneously to drive the dual-electrode Mach-Zehnder modulator (MZM) biased

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** E-mail: yingxiangyue@nbu.edu.cn

in linear regime. The 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 WCDMA signal is imposed on the optical carrier. The optical spectra after modulation are depicted in Fig.1 as the inset (ii). At the base station (BS), a fiber grating is utilized to separate these two signals, as shown in the inset (iii) and inset (iv) of Fig.1, and each signal is transmitted to the corresponding photodetector.

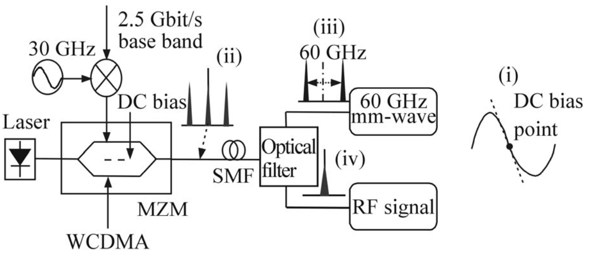

Fig.1 Schematic diagram for simultaneous generation of independent WCDMA and millimeter-wave signals using a dual-electrode MZM

The electrical field at the output of the MZM can be given by

$$E(t)=\frac{A}{2}\exp(\mathrm{j}\omega_{\mathrm{c}}t)\{\exp[\mathrm{j}\gamma\pi+\mathrm{j}\alpha\pi\sin(\omega_{\mathrm{WCDMA}}t+\phi_{\mathrm{WCDMA}}(t)]+\exp[\mathrm{j}\beta\pi\sin(\omega_{\mathrm{MM}}t+\phi_{\mathrm{MM}}(t))]\}, \quad (1)$$

where A and ω_{c} are the amplitude and angular frequency of the input optical carrier, respectively. $\gamma=\frac{1}{2}$ is a constant phase shift that is induced by the DC biased voltage. $\alpha=V_{\mathrm{WCDMA}}(t)/V_{\pi}$ is the modulation index of WCDMA signal. $V_{\mathrm{WCDMA}}(t)$, $\phi_{\mathrm{WCDMA}}(t)$ and ω_{WCDMA} are the amplitude, phase and angular frequency of the WCDMA signal, respectively. $\beta=V_{\mathrm{MM}}(t)/V_{\pi}$ is the modulation index of MMW signal. $V_{\mathrm{MM}}(t)$, $\phi_{\mathrm{MM}}(t)$ and ω_{MM} are the amplitude, phase and angular frequency of the MMW signal, respectively. And V_{π} is the half-wave voltage of the MZM.

Using the Jacobi-Anger identity with high-order Bessel function ignored, the electrical field at the input of the MMW photodetector PD1 can be simplified as

$$E_1(t)=\frac{A}{2}\exp(\mathrm{j}\omega_{\mathrm{c}}t)\{J_1(\beta\pi)\exp[\mathrm{j}(\omega_{\mathrm{MM}}t+\phi_{\mathrm{MM}}(t))]+J_{-1}(\beta\pi)\exp[\text{-}\mathrm{j}(\omega_{\mathrm{MM}}t+\phi_{\mathrm{MM}}(t))]\}, \quad (2)$$

where J_{n} is the n-order Bessel function of the first kind.

The photocurrent at the MMW photodetector PD1 can be written as

$$i_{\mathrm{PD1}}=k_1\left|E_1(t)\right|^2=\frac{k_1A^2}{2}J_1(\beta\pi)^2\times\{1-\cos[2\omega_{\mathrm{MM}}t+2\phi_{\mathrm{MM}}(t)]\}, \quad (3)$$

where k_1 is the responsivity of the MMW photodetector.

The electrical field at the input of the WCDMA photodetector PD2 can be simplified as

$$E_2(t)=\frac{A}{2}\exp(\mathrm{j}\omega_{\mathrm{c}}t)\exp(\mathrm{j}\frac{\pi}{2})\{J_0(\alpha\pi)+J_1(\alpha\pi)\exp[\mathrm{j}(\omega_{\mathrm{WCDMA}}t+\phi_{\mathrm{WCDMA}}(t))]+J_{-1}(\alpha\pi)\exp[-\mathrm{j}(\omega_{\mathrm{WCDMA}}t+\phi_{\mathrm{WCDMA}}(t))]\}+\frac{A}{2}\exp(\mathrm{j}\omega_{\mathrm{c}}t)J_0(\beta\pi). \quad (4)$$

The photocurrent at the WCDMA photodetector PD2 can be written as

$$i_{\mathrm{PD2}}=i_{\mathrm{DC}}+k_2A^2J_0(\alpha\pi)J_1(\alpha\pi)\sin[\omega_{\mathrm{WCDMA}}t+\phi_{\mathrm{WCDMA}}(t)]-\frac{k_2A^2}{2}J_1(\alpha\pi)^2\cos[2\omega_{\mathrm{WCDMA}}t+2\phi_{\mathrm{WCDMA}}(t)], \quad (5)$$

where

$$i_{\mathrm{DC}}=\frac{k_2A^2}{4}[J_0(\beta\pi)^2+J_0(\alpha\pi)^2+2J_1(\alpha\pi)^2], \quad (6)$$

where k_2 is the responsivity of the WCDMA photodetector.

Finally, the desired MMW and WCDMA signals can be derived as:

$$i_{\mathrm{MM}}=\frac{k_1A^2}{4}J_1(\beta\pi)^2\cos[2\omega_{\mathrm{MM}}t+2\phi_{\mathrm{MM}}(t)], \quad (7)$$

$$i_{\mathrm{WCDMA}}=k_2A^2J_0(\alpha\pi)J_1(\alpha\pi)\sin[\omega_{\mathrm{WCDMA}}t+\phi_{\mathrm{WCDMA}}(t)]. \quad (8)$$

The experimental setup for simultaneous generation and transmission of independent WCDMA and millimeter-wave signals based on a dual-electrode MZM is shown in Fig.2. The continuous wave (CW) laser with wavelength of 1550 nm generated by a distributed feedback laser from Conquer Optical Technology is delivered to a 30 GHz dual-electrode MZM from Fujitsu Optical Components Limited, via a polarization controller (PC). One electrode of the dual-electrode MZM is driven by a 30 GHz microwave signal with power of 17 dBm generated by analog signal generator 8257D from Agilent Technologies. Moreover, a 3GPP-FDD WCDMA signal from Agilent VSG N5182A is fed into the other electrode of the dual-electrode MZM. The modulated lightwave is amplified by an erbium-doped fiber amplifier (EDFA) before it is transmitted over single mode fiber (SMF). An optical band pass filter is employed to reject out-band amplified spontaneous emission (ASE) noise. At the BS, a fiber Bragg grating (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 photodetector from U2T photonics with responsivity of 0.6 A/W, while the WCDMA signal is received by a 10 GHz bandwidth photodetector and an electrical amplifier. The received signals are evaluated with a spectrum analyzer E4448A and a wide-bandwidth oscilloscope 86100C from Agilent Technologies.

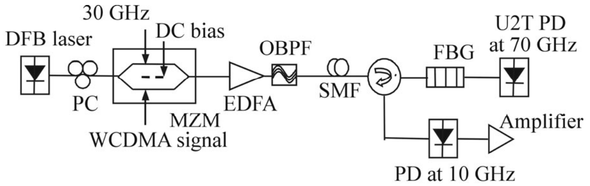

Fig.2 Experimental setup for simultaneous generation of independent WCDMA and millimeter-wave signals using a dual-electrode MZM

Fig.3 shows the spectrum of the received WCDMA signal. It can be seen that there is no obvious out-of-band regrowth induced by the ROF system. The adjacent channel power ratio (ACPR) of the output spectrum of the WCDMA signal is -48 dBc. The temporal waveform of the generated MMW signal is shown in Fig.4. The time scale is 8.3 ps/div and the power scale is 120 μW/div. The spectrum of the generated mm-wave signal is shown in Fig.5. The experimental results show that a pure 60 GHz mm-wave signal is generated regardless of the existence of the WCDMA signal. It is exactly consistent with the theoretical analysis above.

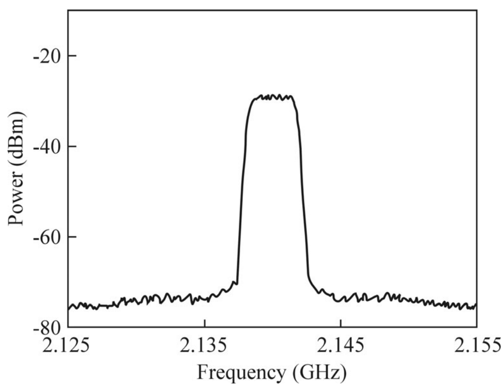

Fig.3 Spectrum of the WCDMA signal after detection

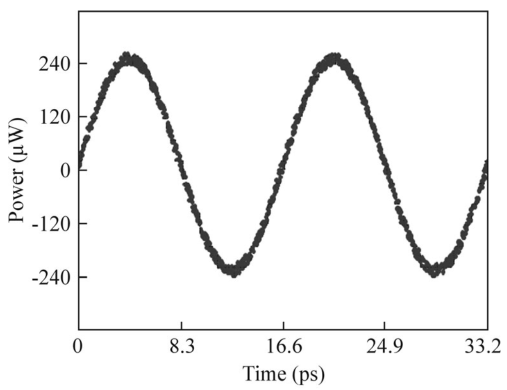

Fig.4 Temporal waveform of the generated mm-wave signal (The time scale is 8.3 ps/div and the power scale is 120 μW/div.)

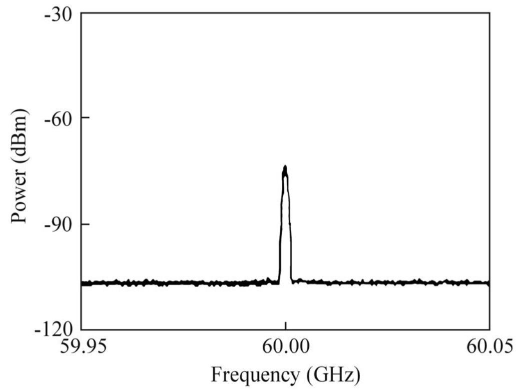

Fig.5 Spectrum of the generated mm-wave signal

In this paper, a novel ROF system to simultaneously generate and transmit WCDMA and MMW signals by using a single dual-electrode MZM is demonstrated. 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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