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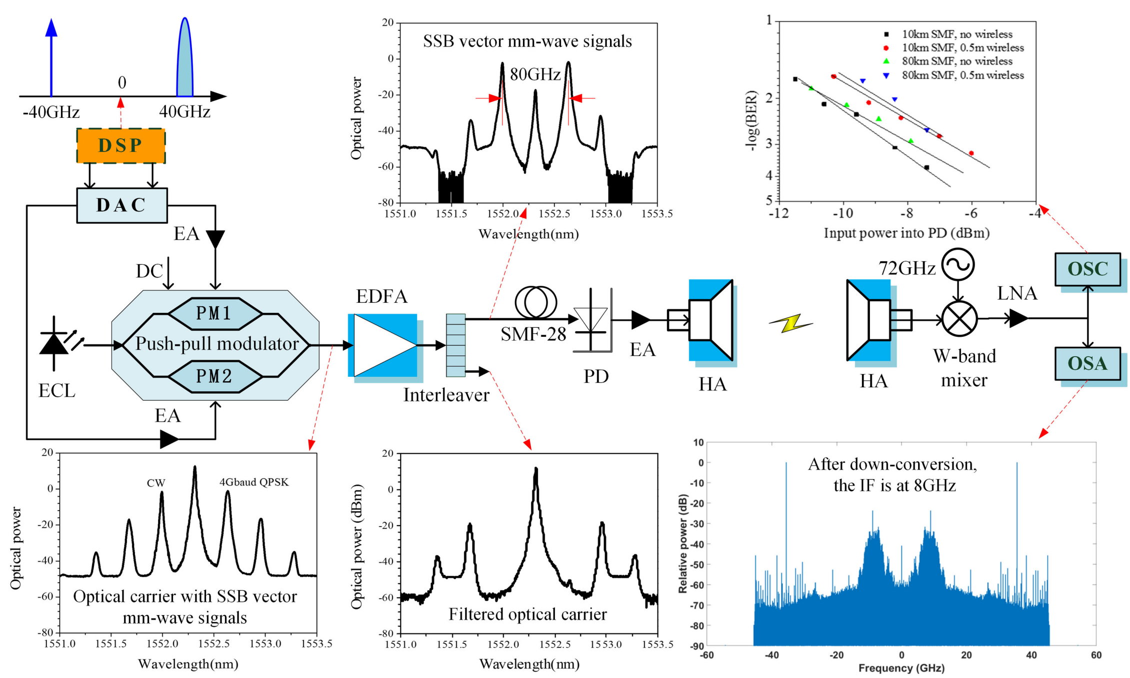

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F. Zhao ,[1] J. L. Li,[1] J. M. Gong,[1] J. R. Bai ,[1] S. Y. Liang,[1] Z. Q. Hui ,[1] D. D. Han,[1] B. Liu,[1,2] and X. J. Xin[1,2]

[1]School of Electronic Engineering, Xi'an University of Posts and Telecommunications, Xi'an 710121, China
[2]School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China

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Abstract: A novel push-pull modulator based scheme to generate W-band millimeter-wave (mm-wave) vector signal was proposed and experimentally demonstrated. Related to an I/Q modulator, push-pull modulator has the advantages of simple architecture, small insertion loss and low cost. Through combining one 40 GHz upper sideband (USB) using a quadrature-phase-shift-keying (QPSK) modulation with a -40 GHz unmodulated lower sideband (LSB), a QPSK modulated 4 G-Baud 80 GHz single sideband vector mm-wave signal was successfully generated.

Index Terms: Fiber optics systems, microwave photonics signal processing.

1. Introduction

Due to the small loss, an optical fiber can provide ultra-long transmission distance and high transmission capacity. But it is cannot realize wide-area seamless coverage due to wire-line delivery. Wireless communication can cover anywhere in theory. But it has limited available spectrum resources. Furthermore, wireless communication has very limited transmission distance. Radio-over-fiber (RoF) which combining the merits of fiber and wireless communication has advantages of broadband wireless access properties [1]–[4]. In order to simplify optical millimeter-wave (mm-wave) generation, a few good schemes have been proposed and demonstrated [5]–[14]. These schemes have demonstrated different mm-wave generations methods and high speed modulation techniques which not only does it significantly reduces the demand for device bandwidth, but also it provides high purity and stability vector mm-wave [8], [10], [14]. To meet the large-capacity demand by the rising mobile data communication, the W-band (75–110 GHz) mm-wave with a high vector modulation spectral-efficiency and a large available bandwidth has been applied into RoF systems [15]–[23]. In Ref. [15] a scheme based on an I/Q modulator was proposed, the generation and the delivery experiment of a W-band vector mm-wave signal was reported. Only one laser source and one I/Q modulator were employed to produce the W-band vector mm-wave signals. This single sideband (SSB) modulated mm-wave signals can tolerate fiber dispersion [12]–[13], and as an efficient and economical modulation technique, has been employed in broad-band RoF system for decades [3].

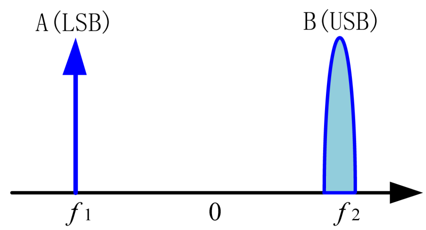

Fig. 1. The generated signal of two carriers in digital domain. (A: continuous wave, B: QAM).

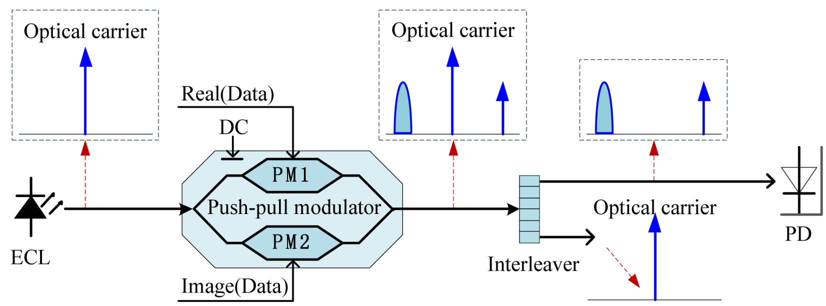

Fig. 2. Schematic of a push-pull modulator based scheme for generating photonic vector mm-wave signal.

In this work, we present a push-pull modulator based W-band mm-wave vector signal generation scheme. Related to the I/Q modulator, a push-pull modulator has a marginal insertion loss, simple DC (Direct-current) control system (only one DC bias), and only 1/3 cost of an I/Q modulator. An experiment was performed to generate a 4 G-Baud 80 GHz single sideband vector mm-wave signal with a quadrature-phase-shift-keying (QPSK) modulation by combining a 40 GHz QPSK modulated upper sideband (USB) with a −40 GHz unmodulated lower sideband (LSB).

2. Principle

Figure 1 shows the generation of the signal with two carriers in digital domain by using MATLAB programing. As shown in the Fig. 1, one carrier only carries CW (continuous wave) at f_1 (on low sideband, LSB), the other carries a QAM signal at f_2 (on upper sideband, USB).

The generated signal in digital domain can be expressed by:

$$\mathrm{Data} = \mathrm{A}e^{\mathrm{i}\omega_1 \mathrm{t}} + \mathrm{B}e^{-\mathrm{i}\omega_2 \mathrm{t}}, \tag{1}$$

where $\omega_1 = 2\pi f_1$, $\omega_2 = 2\pi f_2$, A is the DC value, B is a baseband QAM (quadrature-amplitude-modulation) signal, such as QPSK or 8QAM, 16QAM, 32QAM, etc.

Our optical vector mm-wave signal synthetizing scheme depends on one push-pull modulator featuring an optical SSB modulation, and the principle is presented in Fig. 2. For generating a base-band vector signal, a vector modulation and low-pass filtering were applied on a certain long pseudorandom binary sequence (PRBS) by using MATLAB programming at the transmitter side. Various vector modulations, such as QPSK, 32QAM, 16QAM and 8QAM, can be used onto the obtained baseband vector signal.

The optical mm-wave signal is generated based on a push-pull modulator, which has two integrated phase modulators. We assume the push-pull modulator works at linear area with DC biased at quadrature point [5], [13], the two PMs with a DC bias difference of $V_p/2$. When a continuous light wave $E_{CW} = E_0 \exp(j2\pi f_{cw} t)$ winch emitted by an external cavity laser (ECL) incident on the

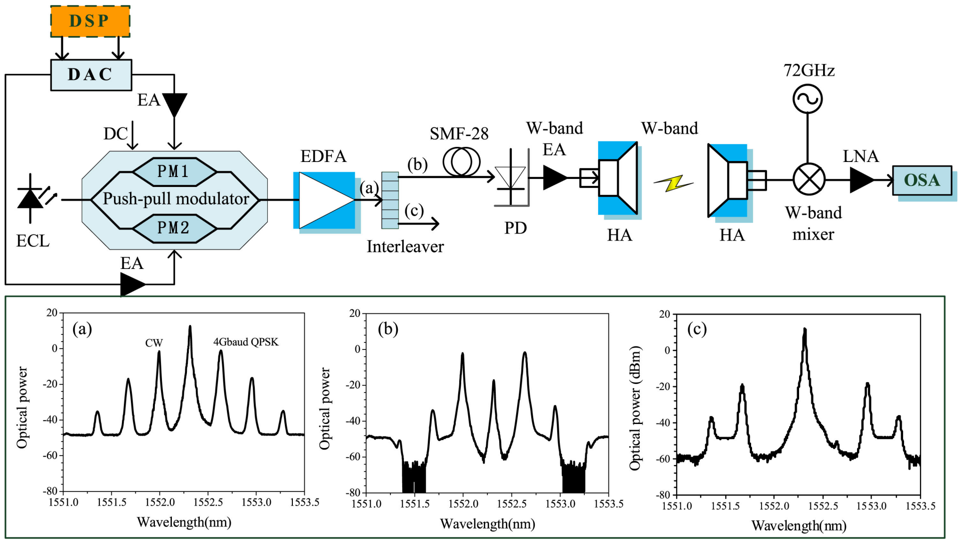

Fig. 3. Experiment setup and calculated spectra for: (a) the SSB vector mm-wave signals generated by push-pull modulator, (b) the SSB vector mm-wave signals after filtering by an interleaver, and (c) the signals filtered out by interleaver.

modulator, its optical output power is given by,

$$\begin{aligned} &E_{CW} \cdot [R\,(\mathrm{Real}\,(\mathrm{Data}) - i * \mathrm{Image}\,(\mathrm{Data})) + P_0] \\ &= E_0 \exp(i2\pi f_{cw} t) \cdot [R\,(A \cos(\omega_1 t) + B \cos(\omega_2 t) - i * A \sin(\omega_1 t) + i * B \sin(\omega_2 t)) + P_0] \\ &= RE_0 A e^{-i\omega_1 t + i2\pi f_{cw} t} + RE_0 B e^{i\omega_2 t + i2\pi f_{cw} t} + P_0 E_0 \exp(i2\pi f_{cw} t). \end{aligned} \tag{2}$$

Where R is the E/O (Electro-optic) response of push-pull modulator, a constant P_0 is the output power from the modulator without any driving signal. From (2), we can see that the generated two carriers at angle frequency ω_1 and ω_2, respectively. But the USB and LSB are exchanged. However, it will not affect our mm-wave signal generation. One optical filter was used to obtain these two carriers, and the data after PD (Photodiodes) can be expressed by,

$$2RPABe^{-i(\omega_1 - \omega_2)t}. \tag{3}$$

Where P is the comprehensive coefficient of PD. Hence, the electrical mm-wave was generated by optical beat mode with PD, and its center frequency is at $\omega_1 - \omega_2$.

3. Experimental Details

The experimental setup in Fig. 3 depends on our proposed generating and delivering scheme of an 80 GHz mm-wave vector signal with 4 G-Baud QPSK. At the transmitter side, according to equation (1), the DSP (Digital signal processing) is conducted with MATLAB programming for generating signals with PRBS length of 2^9. Then, its real part and imaginary part are output with a 92 GSa/s DAC (Digital to analog converter), which has a 3 dB electrical bandwidth of 16 GHz. After EA (Electronic amplifier, SHF818), the amplified two outputs with a 3 volts amplitude are adopted to drive a 37 GHz push-pull modulator. A 1552.524 nm continuous wave was emitted by an ECL with a 14.5 dBm optical output power and a less 100 kHz line-width is input into and modulated by a push-pull modulator featuring a 5 dBm optical output power. At the output of the modulator, we get a 4 G-Baud baseband vector signal, comprising one QPSK modulated USB vector signal at a 40 GHz carrier frequency and one unmodulated LSB signal located at −40 GHz.

An EDFA (Erbium-Doped-Fiber-Amplifier) for amplifying the generator optical mm-wave vector signal is introduced. An optical spectrum of output signals with a resolution of 0.02 nm shows an

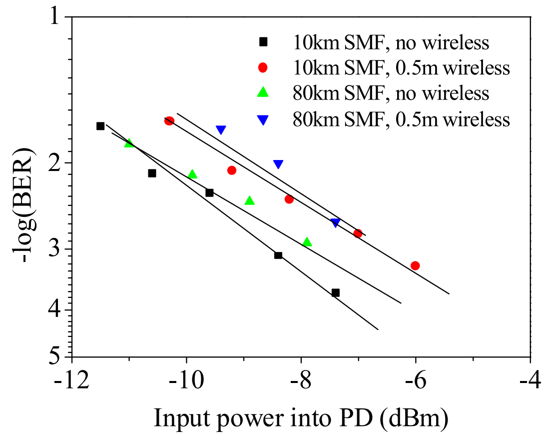

Fig. 4. BER vs. PD input power.

unmodulated optical LSB as well as a QPSK modulated optical USB with an 80 GHz separation which is inset (a) in Fig. 3.

Next, the 4 G-Baud baseband vector signal was transmitted to an optical interleaver with 50/100 GHz spacing, where the sideband signal was separated from its carriers. A spectrum of interleaver separated optical SSB signals is shown in Fig. 3(b). Due to the modulated data has only 4 Gbaud and the resolution of the optical spectrum analyzer is 0.02 nm (2.5 GHz), the sideband with the modulated signal looks no difference from that without the modulated signal, as shown in Fig. 3(b) .the suppression about 37 dB was observed in the central optical carrier, and the spectrum of interleaver filtered carrier signals is presented in Fig. 3(c).

Transmitting the obtained 80 GHz optical SSB signal is conducted by using a single mode fiber (SMF-28), and without compensation of fiber dispersion. After that, the optical mm-wave signal is input into a single ended W-band PD featuring a 75 GHz optical bandwith and up-converted to an electrical mm-wave signal of 80 GHz with a QPSK modulation, which is then amplified by a W-band EA. The saturation and gain output power of the EA are 3 dBm and 35 dB, respectively. Finally, a W-band horn antenna (HA) with a high directionality and a 25 dBi gain is employed to radiate the obtained mm-wave signal into air space.

At the wireless receiver end, another identical HA is placed 0.5 m away to receive the 80 GHz QPSK modulated mm-wave signal. Then, the received 80 GHz mm-wave signal is down-converted into an 8 GHz intermediate frequency (IF) signal with a balanced commercial mixer featuring a 72 GHz sinusoidal radio frequency (RF) source, and then the IF signal is input into a low noise amplifier (LNA) with a 15 dB gain. The RF source output power is 16 dBm. Finally, it is recorded using a 120 GSa/s and 45 GHz bandwidth real time digital storage oscilloscope (OSC). Offline digital signal processing (DSP) techniques such as down-conversion, constant-modulus-algorithm (CMA) equalization, carrier recovery and bit error rate (BER) calculation are adopted to recover the data captured by OSC from the 8 GHz IF signal [3].

4. Results

The experimental BERs of the 80 GHz mm-wave signals vs. PD input powers are shown in Fig. 4, and the following four typical scenarios were considered: (1) only transmitted 10 km single mode fiber, (2) both transmitted 10 km single mode fiber and 0.5 m wireless, (3) only transmitted 80 km single mode fiber, (4) both transmitted 80 km single mode fiber and 0.5 m wireless. Comparing with Ref. [15] proposed scheme which based on an I/Q modulator with our proposed one, to achieve a BER of 0.0038 after transmitted over 80 km SMF-28, the receiver sensitivity less than −8 dBm is required in our proposed scheme, while the proposed scheme in Ref. [15] at least needs 1 dBm.

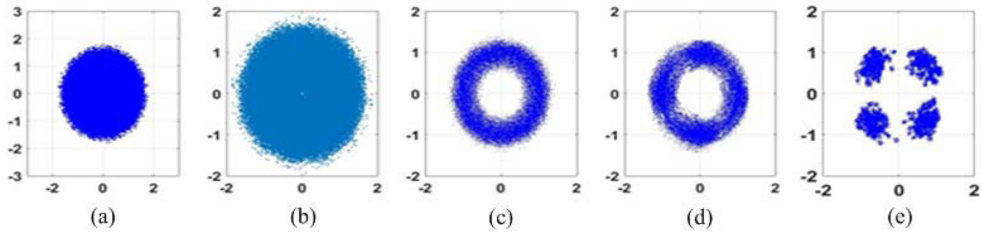

Fig. 5. Results of recovered QPSK for the mm-wave signal after 80-km SMF-28 and 0.5 m wireless transmission. (a) recorded data without any processing, (b-e) after down-conversion, equalization, frequency recovery, and phase recovery, respectively.

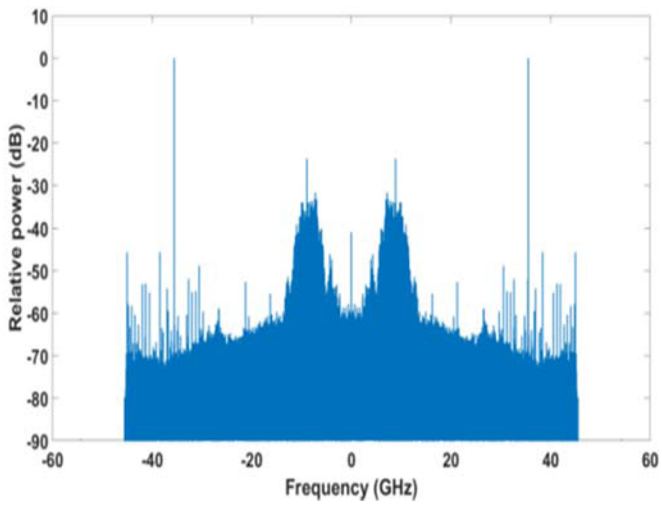

Fig. 6. The measured 8 GHz IF signal spectrum of the 80 GHz mm-wave signal after transmission in scenario (4).

The main reason to have better receiver sensitivity is that our system has more gain with better electrical amplifiers and low power loss of the push-pull modulator.

Figure 5 gives the recovered QPSK constellations of the 80 GHz mm-wave signal at different DSP steps after 80 km SMF plus 0.5 m wireless transmission. Fig. 5(a) is the recorded data without any processing, Fig. 5(b) is the recorded data after down-conversion, Fig. 5(c) is the data after down-conversion and constant modulus algorithm (CMA) equalization, Fig. 5(d) is the data after down-conversion, CMA equalization and frequency recovery, Fig. 5(e) is the data after phase recovery in Fig. 5(d).

After the transmission in scenario (4), an 8 GHz IF signal spectrum down-converted from the 80 GHz mm-wave signal is measured and presented in Fig. 6. PD input power of −4.3 dBm is selected, and seen from the recovered result, there is no bit error was recorded.

5. Conclusions

One novel scheme based on a push-pull modulator for generating W-band vector mm-wave signals was proposed and experimentally demonstrated. The push-pull modulator has only one DC-bias and 1/3 cost of an I/Q modulator. It is a simple architecture and low cost operation. We generated a 4 G-Baud QPSK mm-wave at 80 GHz and realized 80 km wireline and 0.5 m wireless delivery with small penalty. The obvious change between the receiver sensitivities after 10 km and 80 km transmission in SMF-28 fiber was observed. It is a SSB modulation, so the fiber chromatic dispersion of has a small impact on mm-wave vector signals.

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