IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 12, Number 5, October 2020

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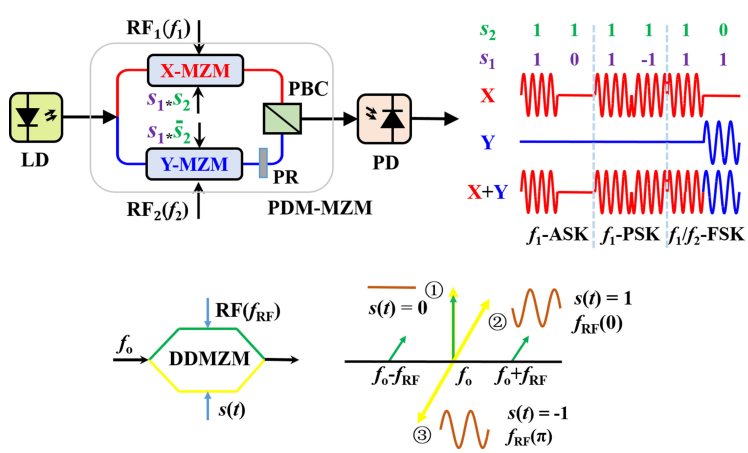

DOI: 10.1109/JPHOT.2020.3022659

IEEE photonics SOCIETY
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Photonic Approach for Generation and Fast Switching of Binary Digitally Modulated RF Signals

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DOI:10.1109/JPHOT.2020.3022659

Manuscript received August 19, 2020; revised September 2, 2020; accepted September 4, 2020. Date of publication September 8, 2020; date of current version October 2, 2020. This work was supported by the National Natural Science Foundation of China under Grants 61860206006 and 61922069, in part by the National Key Research and Development Program of China under Grant 2019YFB2203204, in part by the Open Project Program of Wuhan National Laboratory for Optoelectronics under Grant 2018WNLOKF016, and in part by the "111" Plan (B18045). Corresponding author: Lianshan Yan. (e-mail: lsyan@home.swjtu.edu.cn).

Abstract: A photonic method to generate hybrid binary digitally modulated radio frequency (RF) signals (i.e. ASK, PSK, and FSK) by using a polarization-division-multiplexed Mach-Zehnder modulator (PDM-MZM) is proposed. The PDM-MZM is driven by two RF signals with different carrier frequencies and two multiplied digital signals. By properly controlling the offsets and the amplitudes of the digital signals, ASK, PSK, and FSK signals can be generated and switched fastly. RF signals at 4/6 GHz and 10/15 GHz with switchable modulation formats are experimentally generated. Moreover, the performances of the generated signals are evaluated in a wireless transmission system and corresponding bit error rate (BER) curves of the signals are presented.

Index Terms: Radio frequency photonics, microwave signal generation, modulation.

1. Introduction

Amplitude shift keying (ASK), phase shift keying (PSK) and frequency shift keying (FSK) are basic communication modulation formats, which have been widely used in wireless communication, remote sensing, radar, electronic warfare, etc. [1]–[4]. Traditionally, microwave modulated signals are generated by using electrical methods. However, the operating frequency range and bandwidth of the generated signal are limited by the electrical circuits. Because of the limited electrical spectrum resources, high-frequency bands are exploited and developed. Consequently, the signals generated by photonic methods are favored due to its large bandwidth, low loss, no electromagnetic interference, etc. [5], [6].

Up to now, various photonic methods have been proposed to generate microwave modulated signals. Direct space-to-time (DST) optical pulse shaping and spectrum shaping with frequency-to-time mapping (FTTM) are two recognized methods to generate arbitrary microwave signals. FSK and PSK signals have been generated based on DST optical pulse shaping in Refs. [7],

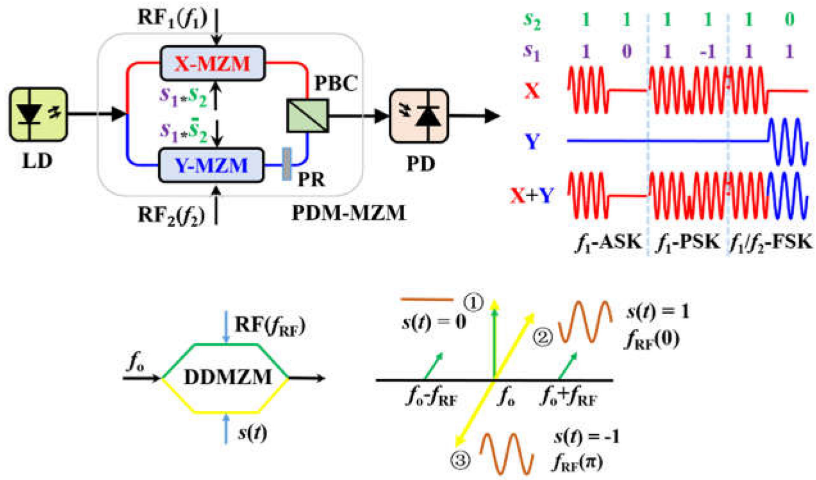

Fig. 1. Schematic diagram of the proposed scheme for ASK/PSK/FSK signals generation; LD, laser diode; PDM-MZM, polarization-division-multiplexed Mach-Zehnder modulator; PR, polarization rotator; PBC, polarization beam combiner; PD, photodetector; DDMZM, dual-drive MZM.

[8]. FSK, PSK and ASK signals are generated based on spectrum shaping with FTTM in Ref. [9]. However, the use of a spatial light modulator (SLM) has the drawbacks of bulkiness and large loss. Two schemes using polarization modulator (PolM) and polarization diversified comb filter based on FTTM have been proposed to generate FSK, PSK, and ASK signals [10], [11]. Compared with optical pulse/spectrum shaping methods, optical heterodyne approaches are more competitive because of its simpler structure, lower loss, and better stability. ASK signals have been generated by using an integrated Mach-Zehnder modulator (MZM) [12], [13]. PSK signals have been generated using a dual-polarization dual-parallel MZM [14], [15], a dual-parallel MZM [16], [17], or a dual-drive MZM [18], [19]. FSK signals have been generated by using a polarization multiplexing dual-drive MZM [20], a single MZM [21], or a PolM [22], [23]. However, in some practical applications, such as dynamic high-speed communication networks, a scheme to simultaneously generate ASK/PSK/FSK signals with fast switching speed is required. Previously, we have proposed a scheme that can generate ASK, PSK, and FSK signals simultaneously based on a phase-coding optical comb [24]. However, the modulation format is selected by tuning an optical filter which limits the switching speed due to manually controlling the optical filter.

In this paper, a scheme using a polarization-division-multiplexed Mach-Zehnder modulator (PDM-MZM) to generate ASK, PSK, and FSK signals simultaneously is proposed and experimentally demonstrated. In the scheme, two radio frequency (RF) signals with different frequencies are applied to the upper arms of the two branches of the PDM-MZM. Two digital signals are multiplied and then applied to the lower arms of the two branches of the PDM-MZM. One digital signal is used to control the phase of the generated signals, and the other behaves as a frequency switch signal to control the carrier frequency of the generated signals. Consequently, ASK/PSK/FSK signals can be achieved. The modulation formats could be switched fastly by directly controlling the two digital signals.

2. Principle

Fig. 1 shows the schematic diagram of the proposed scheme. A light wave from a laser diode (LD) is injected into a PDM-MZM. The PDM-MZM mainly consists of two dual-drive MZMs (DD-MZMs: X-MZM and Y-MZM), one polarization rotator (PR), and one polarization beam combiner (PBC). For a DD-MZM, an RF signal and a digital signal s(t) are applied to the two arms. When s(t) = 0, the DD-MZM is equivalent to a phase modulator. And there is no signal achieved after detection. When s(t) = 1 and −1, two RF signals with phase difference π can be obtained after detection. Therefore, when the carrier frequencies of the RF signals applied to the X and Y -MZMs are different and the patterns of digital signals applied to the X and Y -MZMs are varied with different combinations, ASK, PSK, and FSK signals can be generated. Here, two digital signals applied to the X and Y -MZMs are set as $s_1(t) * s_2(t)$ and $s_1(t) * \overline{s_2}(t)$. "$*$" is the mathematical operation symbol of product. $\overline{s_2}(t)$ is the unary complement of the $s_2(t)$. Two RF signals at carrier frequencies of f_1 and f_2 are applied to X and Y -MZMs, respectively. The optical field at the output of the PDM-MZM can be expressed as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \frac{1}{2} E_o \exp(j\omega_o t) \begin{bmatrix} \exp(j\beta_1 \cos\omega_1 t) + \exp(j\gamma_1 s_1(t) * s_2(t) + j\varphi_1 + j\psi_1) \\ \exp(j\beta_2 \cos\omega_2 t) + \exp(j\gamma_2 s_1(t) * \bar{s}_2(t) + j\varphi_2 + j\psi_2) \end{bmatrix} \quad (1)$$

where E_o and ω_o are the amplitude and angular frequency of the optical wave from LD, $\beta_{1,2} = \pi V_{RF1,2}/V_{\pi 1,2}$ and $\gamma_{1,2} = \pi V_{S1,2}/V_{\pi 1,2}$ are the modulation indexes of the two arms of the X/Y-MZM, respectively. $V_{RF1,2}$ and $V_{S1,2}$ are the amplitudes of the $RF_{1,2}$ signals and the two multiplied digital signals, respectively. $\omega_{1,2} = 2\pi f_{1,2}$. $\varphi_{1,2} = \pi V_{DC1,2}/V_{\pi 1,2}$ are phase shifts caused by the bias voltages. $\psi_{1,2}$ are the intrinsic phase shifts of the two arms of the X/Y-MZM. After detection at a photodetector (PD), the electrical signal can be expressed as

$$I \propto \cos[\beta_1 \cos\omega_1 t - \gamma_1 s_1(t) * s_2(t) - \varphi_1 - \psi_1] + \cos[\beta_2 \cos\omega_2 t - \gamma_2 s_1(t) * \bar{s}_2(t) - \varphi_2 - \psi_2] \quad (2)$$

Appling the Bessel expansion of Eq. (2), the first-order components are considered, while the higher orders are ignored under the small-signal modulation. The signal can be expressed as

$$I \propto J_1(\beta_1)\cos(\omega_1 t)\sin[\gamma_1 s_1(t) * s_2(t) + \varphi_1 + \psi_1] + J_1(\beta_2)\cos(\omega_2 t)\sin[\gamma_2 s_1(t) * \bar{s}_2(t) + \varphi_2 + \psi_2] \quad (3)$$

For $\varphi_{1,2}+\psi_{1,2} = 0$, $\gamma_{1,2} = \pi/2$, the signal can be expressed as

$$I_{ASK} \propto \begin{cases} J_1(\beta_1)\cos\omega_1 t, & s_1(t) = 1, \quad s_2(t) = 1 \\ 0 & s_1(t) = 0, \quad s_2(t) = 1 \end{cases} \quad (4a)$$

$$I_{PSK} \propto \begin{cases} J_1(\beta_1)\cos\omega_1 t, & s_1(t) = 1, \quad s_2(t) = 1 \\ -J_1(\beta_1)\cos\omega_1 t, & s_1(t) = -1, \quad s_2(t) = 1 \end{cases} \quad (4b)$$

$$I_{FSK} \propto \begin{cases} J_1(\beta_1)\cos\omega_1 t, & s_1(t) = 1, \quad s_2(t) = 1 \\ J_1(\beta_2)\cos\omega_2 t, & s_1(t) = 1, \quad s_2(t) = 0 \end{cases} \quad (4c)$$

It can be seen from Eq. (4) that, three kinds of binary digitally modulated signals, ASK (f_1), PSK (f_1) and FSK (f_1/f_2), can be obtained by controlling the combinations of the digital signals $s_1(t)$ and $s_2(t)$. The digital signal $s_2(t)$ is a binary signal which behaves as a frequency switch signal. When $s_2(t)$ is bit-'1', the frequency of the generated signal is f_1. When $s_2(t)$ is bit-'0', the signal is generated at frequency of f_2. The digital signal $s_1(t)$ is a three level signal which can be regarded as a phase switch signal. When $s_1(t)$ takes the positive sign of '1', the generated signal with phase 0 is achieved. The generated signal with phase π is achieved when $s_1(t)$ is the negative sign of '−1'. Moreover, there is no signal generated when $s_1(t)$ is '0'. Thus, for $s_2(t)$ is bit-'1', as $s_1(t)$ is the pattern of '0' and '1', an ASK signal with carrier frequencies of f_1 can be generated; as $s_1(t)$ is the pattern of '1' and '−1', a PSK signal with carrier frequencies of f_1 can be generated. For $s_1(t)$ is all '1' (or '−1'), when $s_2(t)$ is the pattern of '0' and '1', an FSK signal at carrier frequencies of f_1 and f_2 can be obtained. Besides, another ASK and PSK signals with carrier frequencies of f_2 can also be achieved when $s_2(t)$ is bit-'0'. Therefore, when $s_2(t)$ is all '1', and $s_1(t)$ is changed from the pattern of '1/0' to '1/−1', the modulation format of the generated signal is switched from ASK to PSK. Then, when changing $s_2(t)$ from the pattern of all '1' to '1/0', $s_1(t)$ from '1/−1' to all '1' or all

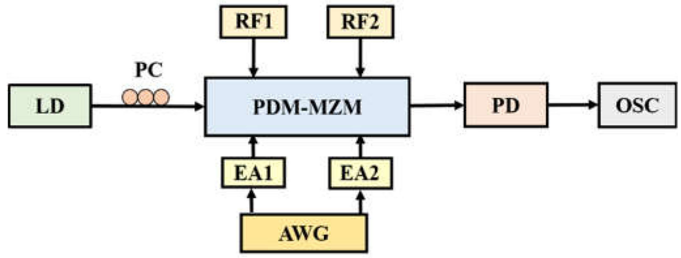

Fig. 2. The experimental framework of the proposed scheme; PC, polarization controller; EA, electrical amplifier; AWG, arbitrary waveform generator; and OSC, Oscilloscope.

'−1', the generated modulation format is switched from PSK to FSK. Similarly, three modulation formats can be switched to each other rapidly by directly controlling the patterns of $s_2(t)$ and $s_1(t)$.

3. Experimental Results

To verify the proposed scheme, an experiment is carried out with the framework shown in Fig. 2. A light wave from a laser (PS-TNL, TeraXion) at the center wavelength of 1549.1 nm is sent into a PDM-MZM (FTM7980EDA). The half-wave voltage of the PDM-MZM is less than 3.5 V at 21.5 Gbps. Two RF signals with frequencies of 4 and 6 GHz and the same power of 8 dBm generated by two signal generators (Anritsu, MG3694C/B) are applied to the upper arms of X and Y -MZMs of the PDM-MZM. Two multiplied digital signals $s_1(t) * s_2(t)$ and $s_1(t) * \overline{s_2}(t)$ at modulation rates of 1 Gbps are generated by an arbitrary waveform generator (AWG, Keysight M9502A). Then the digital signals are amplified by two electrical amplifiers (EAs) and applied to the lower arms of X and Y -MZMs of the PDM-MZM. The output signal from the PDM-MZM is detected by a PD (Agilent, 11982A) with 3 dB bandwidth of 15 GHz. Finally, the generated binary digitally modulated signals are captured by a Digital Storage Oscilloscope (OSC, Keysight, DSOZ634A) with the sampling rate of 80 GSa/s.

When the modulation indexes $\gamma_{1,2}$ are set to be $\pi/2$ by properly adjusting the amplitudes of the digital signals, the bias voltages of the modulator are controlled to make $\varphi_{1,2}+\psi_{1,2} = 0$, the generated signal is shown in Fig. 3(a). Zooming in the area A of Fig. 3(a), a PSK signal at 6 GHz is shown in Fig. 3(b). Obvious phase jumps can be found. The extracted phase shift information based on coherent demodulation is tagged as the red line shown in Fig. 3(b). The PSK signal at 6 GHz is generated when $s_1(t)$ is set to be a stream of bipolar signal, and $s_2(t)$ is all '1', which agrees well with the Eq. (4b). Zooming in the area B of Fig. 3(a), an ASK signal at 6 GHz is shown in Fig. 3(c), which is generated when $s_1(t)$ is set to be a stream of binary signal, and $s_2(t)$ is all '1', which matches well with the Eq. (4a). Fig. 3(d) is the enlarged view of the area C of Fig. 3(a), an FSK signal at 4/6 GHz is generated when $s_1(t)$ is all '1', and $s_2(t)$ is set to be a stream of binary signal, which agrees well with Eq. (4c). The calculated instantaneous frequency using Hilbert transform is tagged as the red line shown in Fig. 3(d). Thus, ASK, PSK, and FSK signals are simultaneously generated. From area A to B to C, PSK switches to ASK, then ASK switches to FSK. Three modulation formats can be switched fastly corresponding to the changing of digital signals. The experimental results are coincident with the theoretical analysis.

Next, the carrier frequencies of RF signals are tuned to be 10 and 15 GHz with the power of 8 and 12 dBm while the other parameters are unchanged. The generated signal is shown in Fig. 4(a). The enlarged view of area A of Fig. 4(a) is shown in Fig. 4(b), a PSK signal at 15 GHz is achieved with the phase changing corresponding to the pattern of signal $s_1(t)$. The extracted phase shift information is shown as the red line of Fig. 4(b). Fig. 4(c) is the enlarged view of area B of Fig. 4(a). An ASK signal at 15-GHz is achieved with the amplitude changing corresponding to the pattern of signal $s_1(t)$. Zooming in the area C of Fig. 4(a), an FSK signal at 10/15 GHz is achieved shown in Fig. 4(d). The carrier frequency variation according to the pattern of the signal $s_2(t)$ is observed.

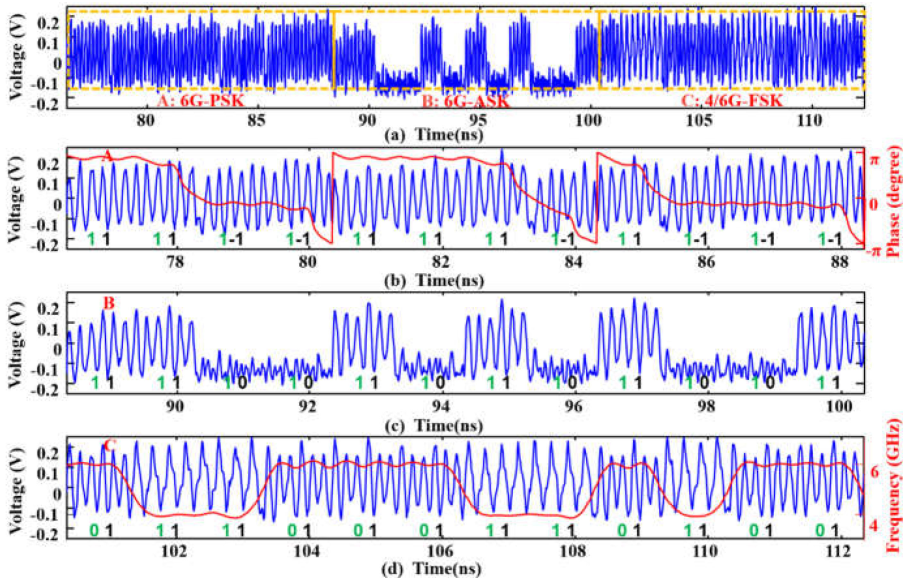

Fig. 3. (a) The generated hybrid ASK, PSK and FSK signal, (b) 6 GHz PSK signal (blue line) and the extracted phase information (red line), (c) 6 GHz ASK signal, and (d) 4/6 GHz FSK signal (blue line) and its instantaneous frequency (red line).

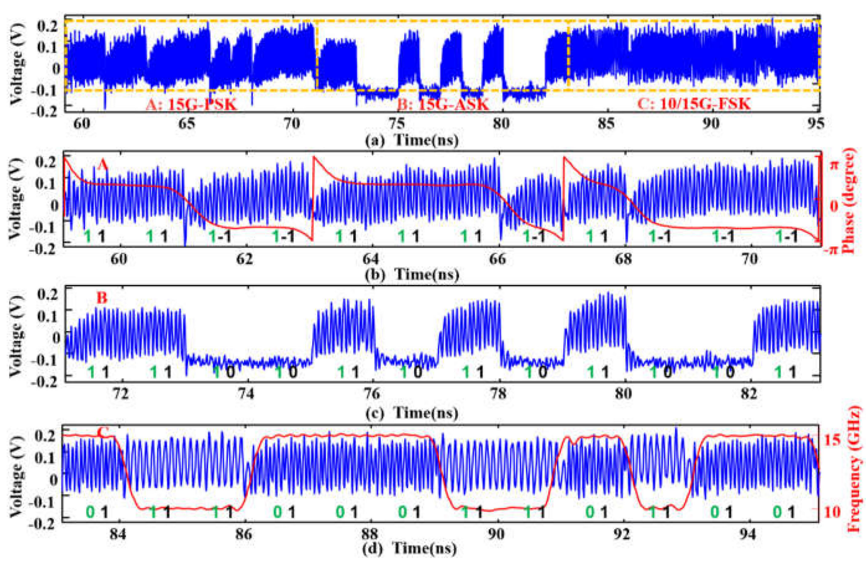

Fig. 4. (a) The generated hybrid ASK, PSK and FSK signal, (b) 15 GHz PSK signal (blue line) and the extracted phase information (red line), (c) 15 GHz ASK signal, and (d) 10/15 GHz FSK signal (blue line) and its instantaneous frequency (red line).

The calculated instantaneous frequency is shown as the red line of Fig. 4(d). The tunability of the carrier frequency of the proposed scheme is verified. The bandwidth of the generated signal is subject to the minimum of the bandwidths of the modulator, EAs, and the PD.

Subsequently, the modulation rates of digital signals are tuned from 1 to 2 Gbps while other parameters are unchanged. The generated signal is shown in Fig. 5(a). Fig. 5(b) and (c) are the enlarged views of area A1 and B1, PSK and ASK signals at 15 GHz with a modulation rate of

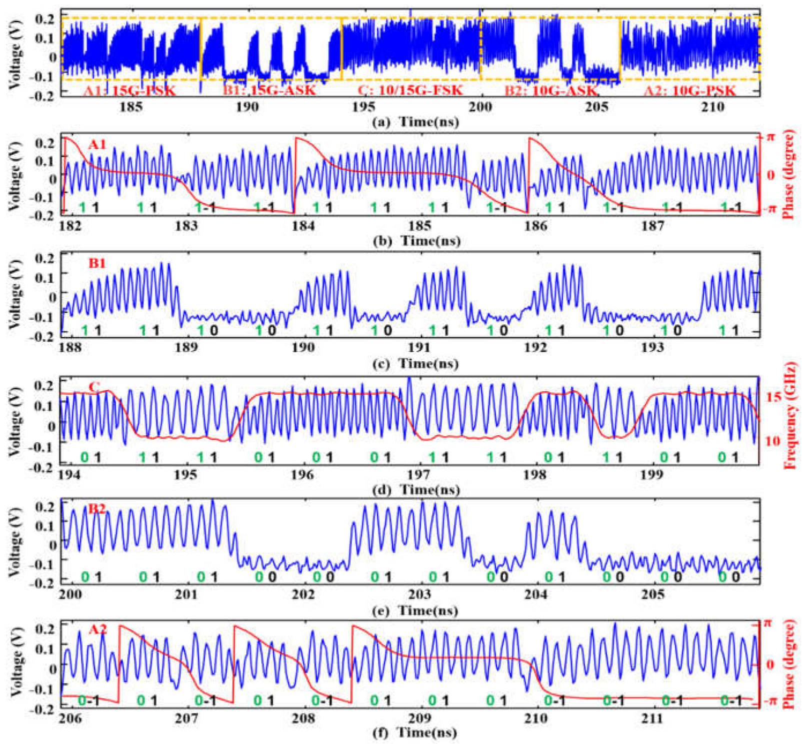

Fig. 5. (a) The generated hybrid ASK, PSK and FSK signal, (b) 15 GHz PSK signal (blue line) and the extracted phase information (red line), (c) 15 GHz ASK signal, (d) 10/15 GHz FSK signal (blue line) and its instantaneous frequency (red line), (e) 10 GHz ASK signal, and (f) 10 GHz PSK signal (blue line) and the extracted phase information (red line).

2 Gbps are generated. An FSK signal at 10/15 GHz with a modulation rate of 2 Gbps is shown in Fig. 5(d) corresponding to the enlarged view of area C of Fig. 5(a). The tunability of the modulation rate of the generated signal is realized. The PSK and ASK signals at 15 GHz are generated above as $s_2(t)$ is all '1'. In addition, the other ASK signal at 10 GHz is generated as shown in Fig. 5(e) corresponding to the enlarged view of area B2 of Fig. 5(a) while $s_1(t)$ is set to be a stream of binary signal, and $s_2(t)$ is all '0'. And the other PSK signal at 10 GHz is generated as shown in Fig. 5(f) corresponding to the enlarged view of area A2 of Fig. 5(a) while $s_1(t)$ is set to be a stream of bipolar signal, and $s_2(t)$ is all '0'. Two pairs of PSK and ASK signals with different carrier frequencies, and an FSK signal are presented in Fig. 5. It further demonstrates that the binary signal $s_2(t)$ is used as a frequency switch signal, the digital signal $s_1(t)$ is regarded as a phase switch signal. The modulation formats of the generated signal are completely determined by the digital signals.

Eventually, in order to investigate the performances of the generated modulated signals, a wireless transmission system is built as shown in Fig. 6. After detected by the PD, the obtained electrical signals are amplified by a low noise amplifier (LNA, MWLA-001100G30) and then emitted by a horn antenna (XB-HA90-10S) with the bandwidth of 8.2–12.4 GHz. The wireless signals are received by the other same type antenna and then amplified by the other LNA (SHF-100-AP). Finally, the signals are captured by a real-time OSC (LeCroy, 813Zi) with the sampling rate of 40 GSa/s and the bandwidth of 13 GHz.

The carrier frequencies of the two RF signals are set to be 9 and 12 GHz with the power of 11.8 and 12 dBm, and the modulation rates of the two digital signals are both 1 Gbps. By controlling the two digital signals, 9/12 GHz FSK, 12 GHz ASK, and 12 GHz PSK modulated signals are generated and transmitted. Then the received signals are demodulated by using a coherent demodulation method with the offline digital signal processing (DSP). Fig. 7 gives the measured bit error rate

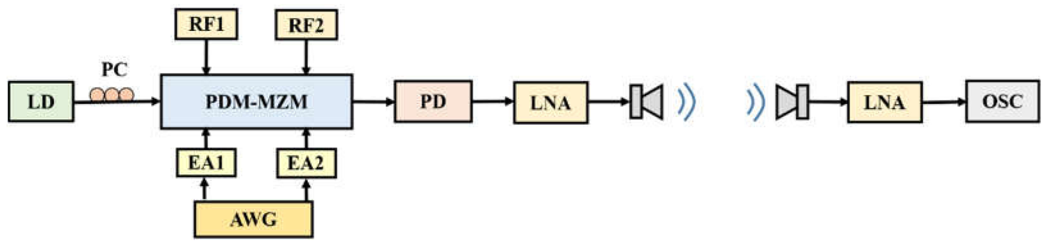

Fig. 6. Experimental setup of the wireless transmission system. LNA, low noise amplifier.

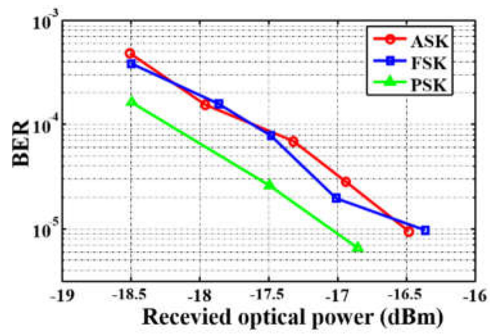

Fig. 7. BER versus the received optical power of the generated signals for wireless transmission.

(BER) curves of the three modulated signals for 1.5 m wireless transmission. The red line with the circle markers, the blue line with the square markers, and the green line with the triangle markers denote the curves of ASK, FSK, and PSK signals, respectively. It can be seen that the BER for ASK modulated signal is measured to be 2.83×10^{-5} with the input optical power to PD of -16.94 dBm, the BER for FSK modulated signal is 1.96×10^{-5} with the input optical power of -17.01 dBm, and the BER for PSK modulated signal is 2.62×10^{-5} with the input optical power of -17.49 dBm.

4. Conclusion

In conclusion, a scheme for simultaneously generating binary digitally modulated RF signals is proposed and experimentally demonstrated. In the experiments, ASK, PSK, and FSK signals at 4/6 GHz with a modulation rate of 1 Gbps, at 10/15 GHz with modulation rates of 1 and 2 Gbps are generated. The modulation formats of the generated signals are determined by the applied digital signals and can be switched fastly by controlling the digital signals. The performances of the generated signals have been also investigated by establishing a wireless transmission system. The BER curves have been measured. The feasibility of the proposed scheme is further verified. This scheme has a simple structure, low loss, flexible tunability which may be used in dynamic high-speed communication systems and networks.

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