A High Spectral Efficiency Radio Over Fiber Link Based on Coherent Detection and Digital Phase Noise Cancellation

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***Abstract*—An approach to transmitting two independent microwave vector signals on a single optical carrier with one polarization state based on coherent detection and digital phase noise cancellation is proposed and experimentally demonstrated. At the transmitter, two independent microwave vector signals are modulated on an optical carrier via a dual-drive Mach-Zehnder modulator (DD-MZM). The modulated optical signals are transmitted over a single-mode fiber (SMF) and sent to a coherent receiver. At the receiver, the optical signals are detected where a local oscillator (LO) optical wave generated by a second free-running laser source is also applied. To recover the two microwave vector signals, a novel digital signal processing (DSP) algorithm is developed and applied to eliminate the joint phase noise terms from the transmitter and the LO laser sources as well as the unstable offset frequency between the two laser sources. An experiment is performed. The transmission of two independent 16 quadrature amplitude modulation (16-QAM) microwave vector signals at 4 GHz with a symbol rate of 1 GSymb/s over a 9-km SMF is demonstrated. The transmission performance in terms of error vector magnitudes (EVMs) and bit error rates (BERs) is also evaluated.**

***Index Terms*—Coherent detection, digital signal processing (DSP), laser frequency offset, laser phase noise, phase noise cancellation, Radio over fiber (RoF).**

I. Introduction

RADIO over fiber (RoF), a technique to transmit microwave signals over an optical fiber link, has been well studied for the past few decades and can find applications such as antenna remoting, cable television (CATV), and broadband wireless access, due to its intrinsic advantages including low insertion loss, large bandwidth, and immunity to electromagnetic interference (EMI) [1]–[4]. A conventional RoF link based on intensity modulation and direct detection (IM-DD), in which a microwave signal is modulated on an optical carrier by changing the carrier intensity and then detected after fiber transmission at a photodetector (PD), has a simple structure and low cost. But such a link has a low spectral efficiency, since only the intensity-modulated optical signal can be detected. In addition, the receiver sensitivity is limited due to the use of direct detection. To ensure a good signal-to-noise ratio (SNR), a high optical power is needed, which is not wanted especially considering the nonlinearity of the fiber link. A coherent RoF link, on the other hand, can detect both intensity- and phase-modulated optical signals and has about 20 dB higher receiver sensitivity due to the use of coherent detection [5]. In a coherent RoF link, a local oscillator (LO) light source which is usually not phase-locked to the transmitter laser source is used to perform coherent detection. The joint phase noise and the offset frequency from the two laser sources will be directly translated to the detected microwave signal, making the transmission performance greatly degraded. To solve this problem, numerous schemes have been proposed. For example, an optical phase-locked loop (OPLL) can be used to lock the phase terms of the transmitter and LO laser sources [6]–[8], thus the joint phase noise at the receiver is fully canceled. Since the two light sources, however, are located at different locations, the loop length is very long, making effective phase locking hard to achieve. The use of a two-tone LO light source at a coherent receiver can also eliminate the joint phase noise and offset frequency from the two laser sources [9], [10]. But to generate a two-tone light source, a high-quality microwave source and a Mach-Zehnder modulator (MZM) are needed, making the systems complicated and costly. Recently, digital phase noise cancellation solutions have been proposed to eliminate the joint phase noise and the offset frequency at a digital signal processing (DSP) unit [11]–[16]. For example, an intensity-modulated optical signal, when detected coherently at a receiver, can have two equal-amplitude quadrature signals with the joint phase noise in both signals. By summing the squared versions of the in-phase and quadrature components,

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the joint phase noise is fully eliminated [11], [12]. However, this approach allows only a single microwave vector signal to be transmitted, making poor use of the optical spectrum resources. To increase the spectral efficiency, two microwave vector signals modulated on a single optical carrier based on both intensity modulation and phase modulation were proposed [13], [16]. To ensure effective detection, a pilot tone or a modulated optical signal must be orthogonally polarized with the optical signals. Since two orthogonal polarization directions are being used, the data rate cannot be further increased based on polarization multiplexing, making the spectral efficiency limited. To improve the spectral efficiency, we proposed an approach to transmitting four microwave vector signals on a single optical carrier based on optical independent sideband modulation (OISB) and optical orthogonal modulation [15]. Again, two additional electrical pilot tones at different frequencies are employed, which again reduces the spectral efficiency and the system flexibility and energy efficiency are also poor.

In this paper, we propose an approach to transmitting two independent microwave vector signals modulated on a single optical carrier with one polarization state based on coherent detection and digital phase noise cancellation. At the transmitter, the intensity of an optical carrier is modulated by two independent microwave vector signals at a dual-drive Mach-Zehnder modulator (DD-MZM) biased at the quadrature transmission point. A modulated optical signal is generated, then is transmitted to the receiver over a single-mode fiber (SMF) and detected at a coherent receiver where an LO light generated by another free-running laser source is applied. To effectively recover the two microwave vector signals, a DSP algorithm is developed to eliminate the phase fluctuation including joint phase noise and unstable offset frequency introduced by the transmitter laser source and the LO laser source. The proposed scheme is evaluated experimentally. In the experiment, two independent 16 quadrature amplitude modulation (16-QAM) microwave vector signals at 4 GHz with a symbol rate of 1 GSymb/s are transmitted over a 9-km SMF and recovered at a coherent receiver. The transmission performance of the RoF link is evaluated by measuring the error vector magnitudes (EVMs) and bit error rates (BERs). The results show that the EVMs for the two recovered 16-QAM signals are 9.27% and 9.75%, which are good enough to achieve error-free transmission with forward error correction (FEC).

II. Principle

Fig. 1 shows the schematic diagram of the proposed RoF transmission link based on coherent detection and digital phase noise cancellation. At the transmitter, a laser diode (LD) is used as the transmitter laser source to generate an optical wave, which is sent, via a polarization controller (PC), to a DD-MZM. The DD-MZM has a Mach-Zehnder interferometer (MZI) structure with a phase modulator (PM) in each of the two arms. The DD-MZM is biased at the quadrature transmission point. Two independent microwave vector signals are applied to the DD-MZM via the two radio-frequency (RF) ports. A modulated optical signal is generated and is transmitted over an SMF to a receiver, where coherent detection and DSP are performed to recover the

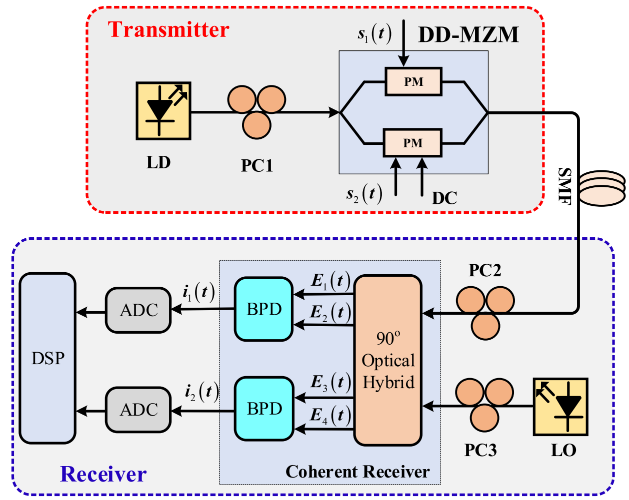

Fig. 1. Schematic diagram of the proposed RoF transmission link based on coherent detection and digital phase noise cancellation. LD: laser diode; PC: polarization controller; PM: phase modulator; DC: direct current; DD-MZM: dual-drive Mach-Zehnder modulator; SMF: single-mode fiber; LO: local oscillator; BPD: balanced photodetector; ADC: analog-to-digital converter; DSP: digital signal processing.

two microwave vector signals. To perform coherent detection, a second optical wave generated by a free-running laser source, as a LO light, is also sent to the coherent receiver. At the output of the coherent receiver, two electrical signals are generated which are sampled by an oscilloscope (OSC) and processed by a DSP unit.

Assume that the two microwave vector signals are given by

$$s_1(t) = m_1(t)\cos[\omega_R t + \theta_1(t)] \tag{1}$$

$$s_2(t) = m_2(t)\cos[\omega_R t + \theta_2(t)] \tag{2}$$

where $m_1(t)$ and $m_2(t)$ are the amplitudes of the two microwave signals, $\theta_1(t)$and $\theta_2(t)$are the phases of the two microwave signals, and $\omega_R$is the center angular frequency of the two microwave vector signals. When the DD-MZM is biased at the quadrature transmission point, under small-signal modulation, the optical field at the output of the DD-MZM can be approximately expressed as [17]

$$\begin{aligned} E_s(t) = &\frac{\sqrt{2P_sL}}{2}\exp j[\omega_c t + \varphi_c(t)] \\ &\times\left[\exp j\left(\frac{\pi}{V_\pi}s_1(t)\right) + \exp j\left(\frac{\pi}{V_\pi}s_2(t) + \frac{\pi}{2}\right)\right] \\ \approx &\frac{\sqrt{2P_sL}}{2}\exp j[\omega_c t + \varphi_c(t)] \\ &\left\{\frac{\pi}{V_\pi}[s_1(t) + js_2(t)] + 1 + j\right\} \end{aligned} \tag{3}$$

where P_s is the optical power of the optical wave at the output of the LD, $\omega_c$is the angular frequency of the optical wave, L is the link loss between the LD and DD-MZM, $\varphi_c(t)$ is the phase noise induced by the LD, and $V_\pi$is the half-wave voltage of the DD-MZM. From (3), it can be seen that the two microwave vector signals are linearly mapped to the optical domain with a phase shift of 90º introduced due to the bias of the DD-MZM at the quadrature transmission point.

After transmission over the SMF, the modulated optical signal is coherently detected at the coherent receiver. The coherent receiver consists of a 90º optical hybrid and two balanced photodetectors (BPDs). A free-running optical wave generated by the LO light source, is given by

$$E_{LO}(t) = \sqrt{P_{LO}} \exp j\left[\omega_{LO}t + \varphi_{LO}(t)\right] \tag{4}$$

where P_{LO} is the optical power of the optical wave at the output of the LO laser source, ω_{LO} is the angular frequency of the optical wave, and $\varphi_{LO}(t)$ is the phase noise induced by the laser source. After the 90º optical hybrid, four optical signals are obtained, which are given by

$$E_1(t) = E_s(t) + E_{LO}(t) \tag{5}$$

$$E_2(t) = E_s(t) - E_{LO}(t) \tag{6}$$

$$E_3(t) = E_s(t) + jE_{LO}(t) \tag{7}$$

$$E_4(t) = E_s(t) - jE_{LO}(t) \tag{8}$$

Then, the four optical signals are detected at the two BPDs and the photocurrents are given by

$$\begin{aligned} i_1(t) &= \frac{1}{2}R\left[E_1(t)E_1^*(t) - E_2(t)E_2^*(t)\right] \\ &= \frac{R\sqrt{2P_sLP_{LO}}}{2}\begin{Bmatrix} \cos\left[\Delta\omega t + \varphi(t)\right] \\ -\sin\left[\Delta\omega t + \varphi(t)\right] \end{Bmatrix} \\ &\quad + \frac{R\sqrt{2P_sLP_{LO}}}{2}\frac{\pi}{V_\pi}\begin{Bmatrix} s_1(t)\cos\left[\Delta\omega t + \varphi(t)\right] \\ -s_2(t)\sin\left[\Delta\omega t + \varphi(t)\right] \end{Bmatrix} \end{aligned} \tag{9}$$

$$\begin{aligned} i_2(t) &= \frac{R}{2}\left[E_3(t)E_3^*(t) - E_4(t)E_4^*(t)\right] \\ &= \frac{R\sqrt{2P_sLP_{LO}}}{2}\begin{Bmatrix} \sin\left[\Delta\omega t + \varphi(t)\right] \\ +\cos\left[\Delta\omega t + \varphi(t)\right] \end{Bmatrix} \\ &\quad + \frac{R\sqrt{2P_sLP_{LO}}}{2}\frac{\pi}{V_\pi}\begin{Bmatrix} s_1(t)\sin\left[\Delta\omega t + \varphi(t)\right] \\ +s_2(t)\cos\left[\Delta\omega t + \varphi(t)\right] \end{Bmatrix} \end{aligned} \tag{10}$$

where *R* is the responsivity of the BPDs, $\Delta\omega = \omega_c - \omega_{LO}$ is the angular frequency difference between the optical waves from the transmitter laser source and the LO laser source, and $\varphi(t)$ is the joint phase noise introduced by the two laser sources. As can be seen from (9) and (10), the first term in each of the two currents is the phase fluctuations, including the joint phase noise and the unstable offset frequency between the transmitter laser source and LO laser source while the second term is a microwave vector signal, which is affected by the phase fluctuations. If the frequency difference between the two laser sources is lower than the center frequency of the microwave vector signal, the two terms can be easily separated by a digital filter.

Then, the two photocurrents, $i_1(t)$ and $i_2(t)$, are sent to the DSP unit where an algorithm is performed to eliminate the joint phase noise and unstable offset frequency introduced by the two laser sources and recover the two microwave vector signals. Two flow charts to show the algorithm are shown in Figs. (2) and (3). The first terms ($i_4(t)$ and $i_6(t)$) of the two photocurrents ($i_1(t)$ and $i_2(t)$) are obtained via a digital low-pass filter (LPF), while the second terms ($i_3(t)$ and $i_5(t)$) are obtained by using a digital bandpass filter (BPF). The detailed signal processing can be expressed by the following expressions.

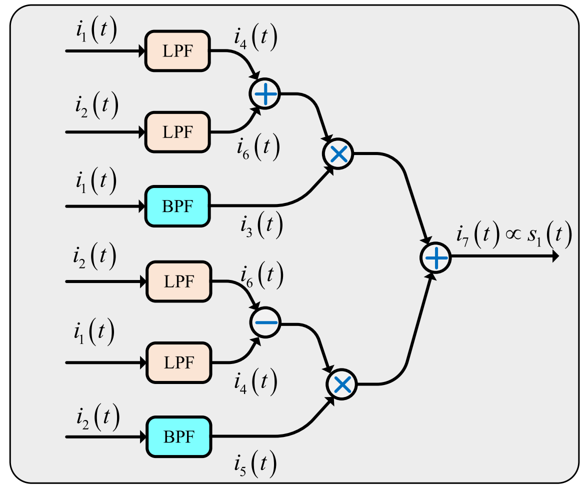

Fig. 2. Flow chart to show the algorithm by which the cancelation of the joint phase noise and unstable offset frequency and the recovery of the microwave vector signal $s_1(t)$ are performed. LPF: low-pass filter; BPF: bandpass filter.

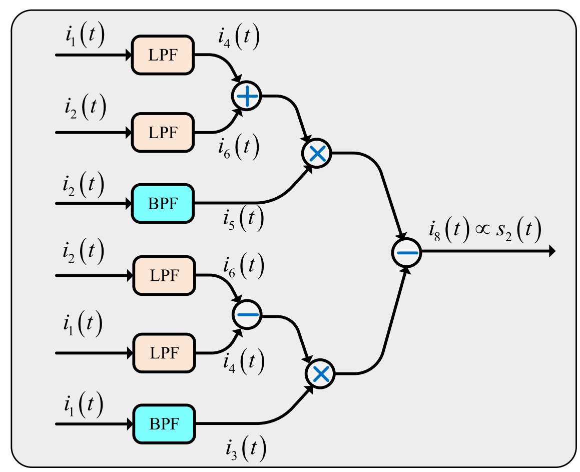

Fig. 3. Flow chart to show the algorithm by which the cancelation of the joint phase noise and unstable offset frequency and the recovery of the microwave vector signal $s_2(t)$ are performed. LPF: low-pass filter; BPF: bandpass filter.

$$\begin{aligned} i_3(t) &= BPF\left(i_1(t)\right) \\ &= \frac{R\sqrt{2P_sLP_{LO}}}{2}\frac{\pi}{V_\pi}\begin{Bmatrix} s_1(t)\cos\left[\Delta\omega t + \varphi(t)\right] \\ -s_2(t)\sin\left[\Delta\omega t + \varphi(t)\right] \end{Bmatrix} \end{aligned} \tag{11}$$

$$\begin{aligned} i_4(t) &= LPF\left(i_1(t)\right) \\ &= \frac{R\sqrt{2P_sLP_{LO}}}{2}\begin{Bmatrix} \cos\left[\Delta\omega t + \varphi(t)\right] \\ -\sin\left[\Delta\omega t + \varphi(t)\right] \end{Bmatrix} \end{aligned} \tag{12}$$

$$\begin{aligned} i_5(t) &= BPF\left(i_2(t)\right) \\ &= \frac{R\sqrt{2P_s L P_{LO}}}{2}\frac{\pi}{V_\pi}\left\{\begin{array}{l} s_1(t)\sin\left[\Delta\omega t+\varphi(t)\right] \\ +s_2(t)\cos\left[\Delta\omega t+\varphi(t)\right] \end{array}\right\} \end{aligned} \tag{13}$$

$$\begin{aligned} i_6(t) &= LPF\left(i_2(t)\right) \\ &= \frac{R\sqrt{2P_s L P_{LO}}}{2}\left\{\begin{array}{l} \sin\left[\Delta\omega t+\varphi(t)\right] \\ +\cos\left[\Delta\omega t+\varphi(t)\right] \end{array}\right\} \end{aligned} \tag{14}$$

$$\begin{aligned} i_7(t) &= \left(i_4(t)+i_6(t)\right)*i_3(t)+\left(i_6(t)-i_4(t)\right)*i_5(t) \\ &= P_s L P_{LO} R^2 \frac{\pi}{V_\pi}\left\{\begin{array}{l} s_1(t)\cos^2\left[\Delta\omega t+\varphi(t)\right] \\ -\frac{s_2(t)\sin\left[2\Delta\omega t+2\varphi(t)\right]}{2} \\ +s_1(t)\sin^2\left[\Delta\omega t+\varphi(t)\right] \\ +\frac{s_2(t)\sin\left[2\Delta\omega t+2\varphi(t)\right]}{2} \end{array}\right\} \\ &= P_s L P_{LO} R^2 \frac{\pi}{V_\pi} s_1(t) \end{aligned} \tag{15}$$

$$\begin{aligned} i_8(t) &= \left(i_4(t)+i_6(t)\right)*i_5(t)-\left(i_6(t)-i_4(t)\right)*i_3(t) \\ &= P_s L P_{LO} R^2 \frac{\pi}{V_\pi}\left\{\begin{array}{l} \frac{s_1(t)\sin\left[2\Delta\omega t+2\varphi(t)\right]}{2} \\ +s_2(t)\cos^2\left[\Delta\omega t+\varphi(t)\right] \\ -\frac{s_1(t)\sin\left[2\Delta\omega t+2\varphi(t)\right]}{2} \\ +s_2(t)\sin^2\left[\Delta\omega t+\varphi(t)\right] \end{array}\right\} \\ &= P_s L P_{LO} R^2 \frac{\pi}{V_\pi} s_2(t) \end{aligned} \tag{16}$$

It can be seen from (15) and (16), the two microwave vector signals ($s_1(t)$ and $s_2(t)$) are recovered and free from the joint phase noise and unstable offset frequency.

III. Experimental Setup And Results

To verify the proposed scheme, an experiment based on the setup shown in Fig. 1 is performed. A continuous-wave (CW) optical wave at 1550 nm generated by the transmitter laser source (Yokogawa, AQ2201) with a linewidth of 100 kHz and an output optical power of 8 dBm is sent to the DD-MZM (Fujitsu, FTM7821ER) via PC1. Note that PC1 is used to minimize the polarization-dependent loss (PDL). The DD-MZM has a half-wave voltage of 4 V, a 3-dB bandwidth of 10 GHz, and an insertion loss of 6 dB. Two independent 16 quadrature amplitude modulation (16-QAM) microwave vector signals generated by an arbitrary waveform generator (AWG, Keysight M8195A) with a sampling rate of 65 GSa/s and a bandwidth of 25 GHz are sent to the DD-MZM via the two RF input ports. The center frequency, baud rate, and output voltage of the two signals are set to be 4 GHz, 1 GSym/s, and 1 V, respectively. The DD-MZM is biased at the quadrature transmission point. A modulated optical signal is generated at the output of the DD-MZM, transmitted over a 9 km SMF, and sent to the coherent receiver (Discovery Semiconductors DP-QPSK 40/100 Gb/s Coherent Receiver Lab Buddy) through the signal port via PC2. Another CW optical wave at 1550.01 nm generated by the LO laser source (Agilent N7714A) with a linewidth of 100 kHz and an output optical power of 10 dBm is sent to the coherent receiver through the LO port via PC3. The two PCs (PC2 and PC3) are used to co-polarize the modulated optical signal and the LO optical signal. The wavelength difference between the transmitter laser source and LO laser source is 0.01 nm, corresponding to an offset frequency of 1.25 GHz. After coherent detection, the detected electrical signals are sampled by the digital storage oscilloscope (Agilent DSO-X 93204A) with a sampling rate of 80 GSa/s and a bandwidth of 32 GHz. The sampled signal is sent to the DSP unit where the two microwave vector signals are processed to eliminate the joint phase noise and the unstable offset frequency and to recover the two signals.

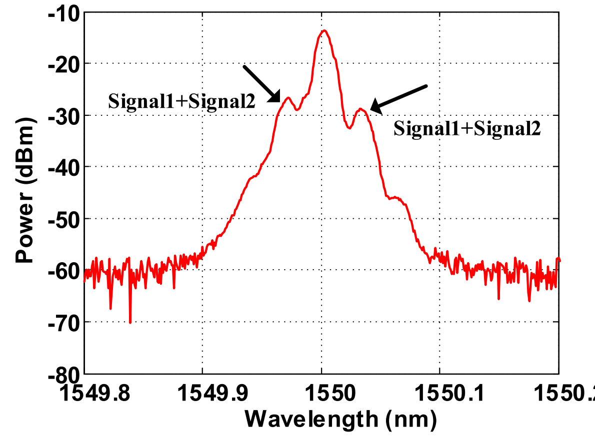

Fig. 4. The measured spectrum of the optical signal at the output of the DD-MZM.

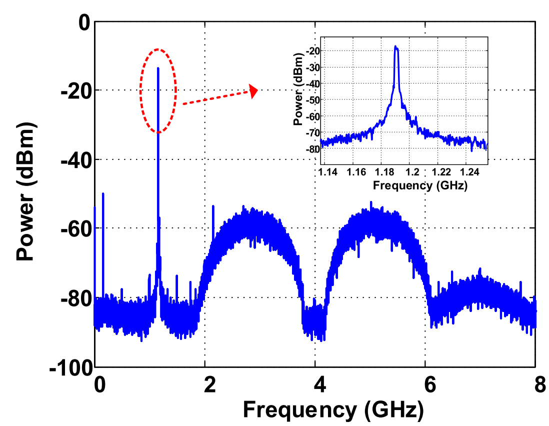

Fig. 5. The measured spectrum of the electrical signal at the output of the coherent receiver ($i_1(t)$).

Fig. 4 shows the measured spectrum of the optical signal at the output of the DD-MZM. It can be seen that the two modulated optical signals are overlapped in the spectral domain due to the same center frequency and baud rate of the two microwave vector signals, which could double the spectral efficiency. Fig. 5 shows the measured spectrum of the electrical signal at one of the two outputs of the coherent receiver ($i_1(t)$). It can be seen a microwave signal around 1.2 GHz is generated due to the frequency difference between the transmitter laser source and the LO laser source. A zoom-in view of the spectrum at 1.2 GHz is shown in the inset of Fig. 5. The 1.2 GHz signal contains the joint phase noise and the unstable offset frequency. Two mixing

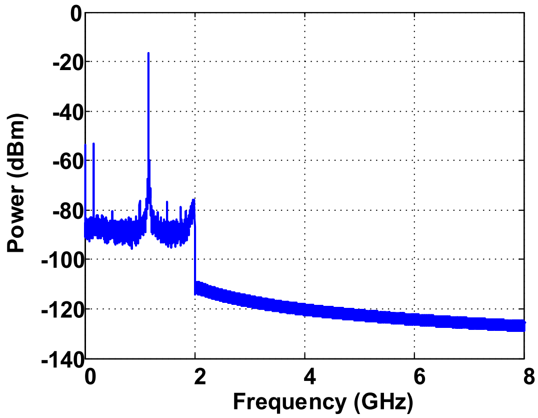

Fig. 6. The measured spectrum of the electrical signal after an LPF ($i_4(t)$).

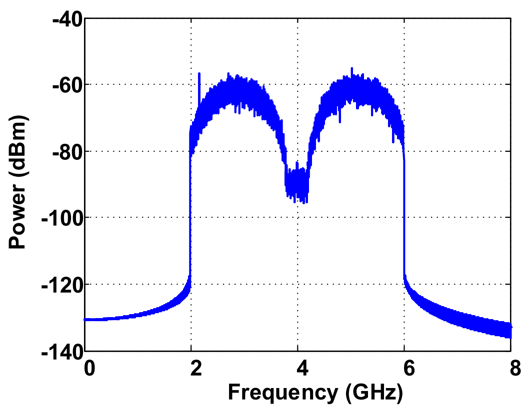

Fig. 7. The measured spectrum of the electrical signal after a BPF ($i_3(t)$).

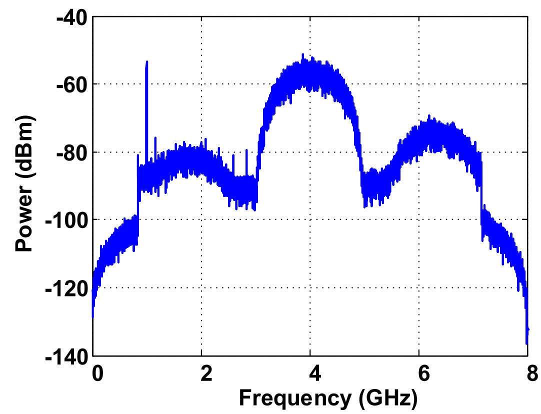

Fig. 8. The measured spectrum of the recovered electrical signal free from phase noise and unstable offset frequency ($i_7(t)$).

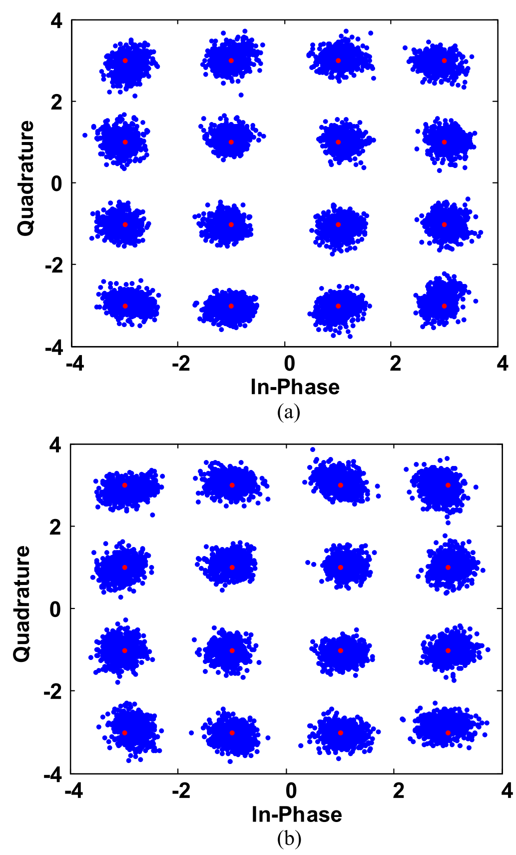

Fig. 9. Measured constellations of the two recovered 16-QAM microwave vector signals at the output of the DSP unit (fiber length: 9 km, the received optical power: -10 dBm). (a) $s_1(t)$ and (b) $s_2(t)$.

products generated between the 1.2 GHz microwave signal and the 4 GHz microwave vector signals at 2.8 and 5.2 GHz are observed, which agrees well with the theoretical analysis given by (9). The 1.2 GHz signal can be separated from the 2.8 and 5.2 GHz signals by an LPF, as shown in Fig. 6. The microwave vector signals can be separated from the 1.2 GHz microwave signal by using a BPF, as shown in Fig. 7. Through DSP, a recovery of one 16-QAM microwave vector signal ($i_7(t)$) free from the joint phase noise and the unstable offset frequency is achieved, as shown in Fig. 8. Fig. 9 shows the measured constellations of the two recovered 16-QAM microwave vector signals at the output of the DSP unit, where the optical power at the input of the coherent receiver is -10 dBm. The EVMs for the two microwave vector signals are calculated, which are 9.27% and 9.75%.

To further evaluate the performance of the system, the EVMs at different received optical power levels are measured, which are given in Fig. 10 and the corresponding BERs are shown in Fig. 11. When calculating the BERs, we assume that the noise after the DSP unit is a stationary random process with Gaussian statistics [18]–[20]. As can be seen, when the received optical power is -20 dBm, the EVMs for the two recovered 16-QAM microwave vector signals are 17.51% and 18.38% and the corresponding BERs are 4×10^{-3} and 5.6×10^{-3}, which are beyond the FEC limit. When the optical power is increased to -18 dBm, the BERs are measured to be 9.3×10^{-4} and 2×10^{-3}, which are well within the FEC limit. By employing a state-of-the-art FEC technique, a raw BER of up to 3×10^{-3} can be improved to an effective BER of 1×10^{-15} at the expense of a 6.7% overhead [21]. Error-free transmission can be achieved.

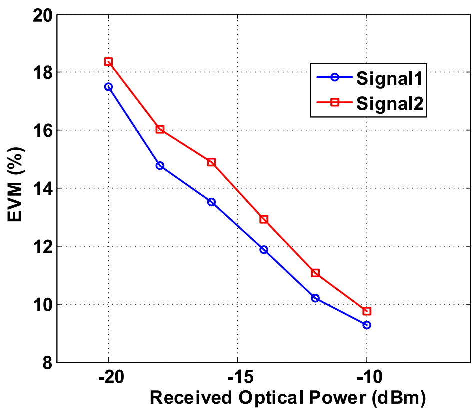

Fig. 10. Measured EVMs at different received optical power levels for the two recovered 16-QAM microwave vector signals transmitted over a 9-km SMF.

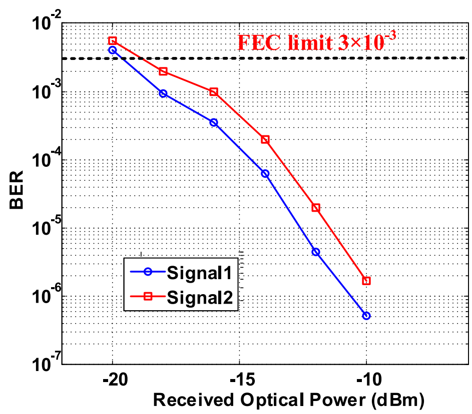

Fig. 11. BERs at different received optical power levels for the two recovered 16-QAM microwave vector signals transmitted over a 9-km SMF.

IV. Conclusion

We have proposed and experimentally demonstrated an approach to transmitting two independent microwave vector signals modulated on a single optical carrier with one polarization state based on coherent detection and digital phase noise cancellation. At the transmitter, a DD-MZM, which was biased at the quadrature transmission point, was employed to linearly map two 16-QAM signals to the optical domain, to generate two optical signals with a phase difference of 90°. After transmission over an SMF, the optical signals were detected at a coherent receiver, to which an LO light wave from a free-running laser source was applied. By using the developed algorithm, a recovery of the two microwave vector signals free from the joint phase noise and unstable offset frequency was achieved. An experiment was conducted. The transmission of two independent 16-QAM microwave vector signals at 4 GHz with a baud rate of 1 GSymb/s over a 9-km SMF was demonstrated. The EVMs for the two recovered 16-QAM signals were measured to be 9.27% and 9.75%, which are good enough to achieve error-free transmission with FEC.

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