A Microwave Photonic Link With Quadrupled Capacity Based on Coherent Detection and Digital Phase Noise Cancellation

Peng Li, *Student Member, IEEE*, Zheng Dai, Lianshan Yan, *Senior Member, IEEE*, and Jianping Yao, *Fellow, IEEE, Fellow, Optica*

***Abstract*—A microwave photonic link (MPL) with quadrupled capacity based on coherent detection and digital phase noise cancellation is proposed and experimentally demonstrated. At the transmitter, a continuous-wave (CW) light wave is intensity modulated by four independent microwave vector signals with two having an identical center microwave frequency at a dual-parallel Mach-Zehnder modulator (DPMZM) consisting of two dual-drive MZMs (DEMZMs) with the sub-DEMEMs biased at the quadrature transmission point. Four intensity-modulated optical signals are generated and transmitted over a single-mode fiber (SMF) to a coherent receiver. To perform coherent detection, a second CW laser source as a local oscillator (LO) is also applied to the coherent receiver. To recover the microwave vector signals, a novel digital phase noise cancellation algorithm is developed and applied to eliminate the joint phase noise from the transmitter laser source and the LO laser source as well as the unstable offset frequency between the two laser sources. A theoretical analysis is performed to show the recovery of the microwave vector signals which is verified by an experiment. For four independent 16 quadrature amplitude modulation (16-QAM) microwave vector signals with a symbol rate of 0.5 GSymbol/s, error-free transmission over a 9-km SMF is achieved when the received optical power at the coherent receiver is higher than −18 dBm with forward error correction (FEC).**

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

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I. Introduction

COMPARED with a copper coaxial analog link, a microwave photonic link (MPL) or radio over fiber (RoF) link has several advantages, including low insertion loss, large bandwidth, and immunity to electromagnetic interference (EMI), which has been considered one of the promising solutions for broadband wireless access networks [1]–[5]. To support higher data rate mobile communications, the transmission of multiple microwave signals over a single optical carrier to improve the spectral efficiency of RoF links is highly needed.

In a conventional RoF link, wavelength-division multiplexing (WDM), a technique to multiplex multiple optical wavelengths and transmit them over a single optical fiber, is employed for multiple microwave signal transmission over a fiber [6], [7]. To improve the spectral efficiency, it is expected that a single wavelength or optical carrier can carry multiple microwave signals. One effective solution is to use coherent detection [8]–[14]. For example, two microwave vector signals modulated on a single optical carrier based on IQ modulation and coherent detection was proposed [8]. In the system, an unmodulated optical carrier from the transmitter laser source is transmitted and used as the local oscillator (LO) laser source. Since the LO light is generated by the transmitter laser source, the phase noise can be canceled at the coherent receiver. However, to perform coherent detection, the LO light should have much higher power, which required the LO light to be amplified. In addition, an additional wavelength that does not carry information will make the spectrum efficiency reduced. To avoid transmitting an LO light from the transmitter, one may use an independent laser source at the coherent receiver. The major challenge using an independent LO laser source is the joint phase noise between the transmitter laser source and the LO laser source, which is translated directly to the detected microwave signal, making the signal has poor signal-to-noise ratio (SNR). In addition, the unstable offset frequency between the two laser sources also makes the recovery of the microwave signal difficult. Thanks to the advancement of state-of-the-art digital signal processors that can operate at a high speed, by implementing real-time signal processing to eliminate the joint phase noise and the unstable offset frequency, the microwave signal can be accurately recovered. For example, the transmission of two microwave vector signals on a single optical carrier that is detected based on a coherent receiver with an independent LO laser source was proposed [9], [10]. The approach was then expanded to transmit four independent microwave vector signals [11]. Although the microwave signals were modulated on a single optical wavelength, two polarization states were employed, making polarization multiplexing to further extend the spectral efficiency impossible [9], [10]. Recently, we have proposed an approach to transmitting two microwave vector signals on a single optical carrier with one polarization state based on coherent detection with an independent LO laser source [13]. By using digital phase noise cancellation, the two microwave vector signals are recovered free from the joint phase noise and unstable offset frequency. To double the spectral efficiency, polarization multiplexing was employed to transmit four independent microwave vector signals on a single optical carrier [14]–[15]. By using a digital phase noise cancellation algorithm and a polarization demultiplexing algorithm, the four microwave vector signals free from the joint phase noise and unstable offset frequency were recovered.

To further increase the spectral efficiency without using a second polarization state, in this paper we propose and experimentally demonstrated a novel approach that is able to transmit four independent microwave vector signals on a single optical carrier with one polarization state, in which a new digital signal processing (DSP) algorithm is developed. Since only a single polarization state is employed, the capacity can be further increased to transmit eight independent microwave vector signals on a single optical carrier if polarization division multiplexing (PDM) is employed, which is, to the best of our knowledge, the first time that eight microwave vector signals are transmitted on a single optical carrier over an MPL. The proposed MPL consists of a transmitter and a coherent receiver (including a DSP module). At the transmitter, a CW light from a transmitter laser source is sent to a dual-parallel Mach-Zehnder modulator (DPMZM) driven by four independent microwave vector signals. The DPMZM consists of two dual-drive MZMs (DDMZMs) biased at the quadrature transmission point. Four intensity-modulated optical signals are generated at the output of the DPMZM and sent to a coherent receiver via a single-mode fiber (SMF). To perform coherent detection, an independent LO laser source is employed to generate a CW light which is applied to the coherent receiver. To recover the four microwave vector signals, a digital phase noise cancellation algorithm is developed to eliminate the phase fluctuations 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, four independent 16 quadrature amplitude modulation (16-QAM) microwave vector signals with a symbol rate of 0.5 GSymb/s are transmitted over a 9-km SMF and recovered at a coherent receiver. The transmission performance of the proposed MPL link is evaluated by measuring the error vector magnitudes (EVMs) and bit error rates (BERs). The results show that when the received optical power at coherent receiver is higher than −18 dBm, error-free transmission is achieved with forward error correction (FEC).

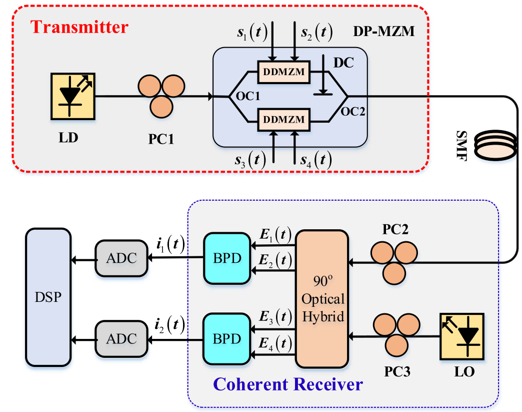

Fig. 1. Schematic diagram of the proposed RoF link for four independent vector signal transmission. LD: laser diode; PC: polarization controller; DDMZM: dual-drive Mach-Zehnder modulator; OC: optical coupler; DC: direct current; DPMZM: dual-parallel Mach-Zehnder modulator; SMF: single-mode fiber; LO: local oscillator; BPD: balanced photodetector; ADC: analog-to-digital converter; DSP: digital signal processing.

II. Principle

Fig. 1 shows the schematic diagram of the proposed MPL link for four microwave vector signal transmission based on coherent detection and digital phase noise cancellation. A laser diode (LD), as a transmitter laser source, is used to generate a CW light which is sent to a DPMZM via a polarization controller (PC1). PC1 is used to minimize the polarization-dependent loss (PDL). The DPMZM consists of two sub-DDMZMs (sub-DDMZM1 and sub-DDMZM2). Four microwave vector signals are applied to the DPMZM. Both the sub-DDMZMs are biased at the quadrature transmission point. At the output of the DPMZM, four intensity-modulated optical signals are generated, which are transmitted over an SMF, and sent to a coherent receiver. To perform coherent detection, a second laser source is used to generate an LO light which is applied to the receiver. At the output of the coherent receiver, two currents are generated, which are sampled and processed at a signal processor. Thanks to the use of our developed DSP algorithm, the four microwave vector signals that are free from the joint phase noise and unstable offset frequency are recovered.

Assuming that the four microwave vector signals with two different center frequencies are given by

$$s_1(t) = m_1(t)\cos[\omega_1 t + \theta_1(t)] \tag{1}$$

$$s_2(t) = m_2(t)\cos[\omega_1 t + \theta_2(t)] \tag{2}$$

$$s_3(t) = m_3(t)\cos[\omega_2 t + \theta_3(t)] \tag{3}$$

$$s_4(t) = m_4(t)\cos[\omega_2 t + \theta_4(t)] \tag{4}$$

where $m_i(t)$ and $\theta_i(t)$ are the amplitude and phase of the *i*-th microwave vector signal, ω_1 is the center angular frequency of $s_1(t)$ and $s_2(t)$, ω_2 is the center angular frequency of $s_3(t)$and $s_4(t)$, and *B* is the bandwidth of the four microwave vector signals. Here, we assume $\omega_2 > \omega_1$, thus the angular frequency difference is $\delta\omega = \omega_2 - \omega_1$.

In the system, the two sub-MZMs are biased at the quadrature transmission point and the main MZM is biased at the null point.

The optical field at the output of the DPMZM is given by [16]

$$E(t) = \frac{\sqrt{P_s L}}{2} \exp j\left[\omega_c t + \varphi_c(t)\right] \times \begin{bmatrix} \exp j\left(\frac{\pi}{V_\pi} s_1(t)\right) + \exp j\left(\frac{\pi}{V_\pi} s_2(t) + \frac{\pi}{2}\right) \\ + \exp j\left(\frac{\pi}{V_\pi} s_3(t)\right) + \exp j\left(\frac{\pi}{V_\pi} s_4(t) + \frac{\pi}{2}\right) \end{bmatrix} \approx \frac{\sqrt{P_s L}}{2} \exp j\left(\omega_c t + \varphi_c(t)\right) \times \left\{2 + 2j + \frac{\pi}{V_\pi}\left[s_1(t) + j s_2(t) + s_3(t) + j s_4(t)\right]\right\} \quad (5)$$

where P_s is the optical power of the optical wave at the output of the transmitter laser source, L is the link loss between the transmitter laser and the DPMZM, ω_c and $\varphi_c(t)$are angular frequency and phase noise term of the optical wave from the transmitter laser source, and $V_\pi$is the half-wave voltage of the DPMZM.

It can be seen from (5), four intensity-modulated optical signals are generated. The two microwave vector signals, $s_1(t)$and $s_2(t)$, are linearly mapped to the optical domain with a phase shift of 90° due to the bias of sub-DDMZM1 at the quadrature transmission point. Similarly, $s_3(t)$and $s_4(t)$ are also mapped to the optical domain with a phase shift 90° due to the bias of sub-DDMZM2 at the quadrature transmission point. The generated optical signals are transmitted over an SMF and then detected at a coherent receiver consisting of a 90° optical hybrid and two balanced photodetectors (BPDs), as shown in Fig. 1. To perform coherent detection, a light wave generated by the LO laser source is also applied to the coherent receiver. The optical field at the output of the LO laser source can be written as

$$E_{LO}(t) = \sqrt{P_{LO}} \exp j\left[\omega_{LO} t + \varphi_{LO}(t)\right] \quad (6)$$

where P_{LO} , ω_{LO}, and $\varphi_{LO}(t)$ are the optical power, angular frequency, and phase noise term of the light wave at the output of the LO laser. After the 90° optical hybrid, four optical signals are generated, with two applied to each of the two BPDs. At the output of the BPDs, two photocurrents can be obtained, which are given by

$$i_1(t) = \frac{1}{2} R\left(E_1(t) E_1^*(t) - E_2(t) E_2^*(t)\right) = \frac{R\sqrt{2P_s L P_{LO}}}{2} \begin{pmatrix} \cos\left[\Delta\omega t + \varphi(t)\right] \\ - \sin\left[\Delta\omega t + \varphi(t)\right] \end{pmatrix} + \frac{\pi R\sqrt{2P_s L P_{LO}}}{4V_\pi} \begin{pmatrix} s_1(t) \cos\left[\Delta\omega t + \varphi(t)\right] \\ - s_2(t) \sin\left[\Delta\omega t + \varphi(t)\right] \end{pmatrix} + \frac{\pi R\sqrt{2P_s L P_{LO}}}{4V_\pi} \begin{pmatrix} s_3(t) \cos\left[\Delta\omega t + \varphi(t)\right] \\ - s_4(t) \sin\left[\Delta\omega t + \varphi(t)\right] \end{pmatrix} \quad (7)$$

$$i_2(t) = \frac{1}{2} R\left(E_3(t) E_3^*(t) - E_4(t) E_4^*(t)\right) = \frac{R\sqrt{2P_s L P_{LO}}}{2} \begin{pmatrix} \sin\left[\Delta\omega t + \varphi(t)\right] \\ + \cos\left[\Delta\omega t + \varphi(t)\right] \end{pmatrix} + \frac{\pi R\sqrt{2P_s L P_{LO}}}{4V_\pi} \begin{pmatrix} s_1(t) \sin\left[\Delta\omega t + \varphi(t)\right] \\ + s_2(t) \cos\left[\Delta\omega t + \varphi(t)\right] \end{pmatrix} + \frac{\pi R\sqrt{2P_s L P_{LO}}}{4V_\pi} \begin{pmatrix} s_3(t) \sin\left[\Delta\omega t + \varphi(t)\right] \\ + s_4(t) \cos\left[\Delta\omega t + \varphi(t)\right] \end{pmatrix} \quad (8)$$

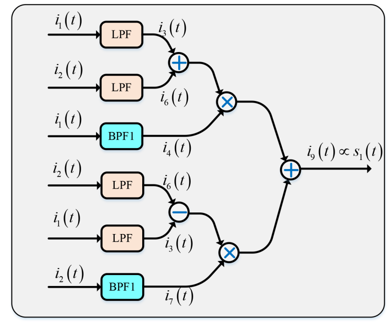

Fig. 2. Flow chart to recover the microwave vector signal $s_1(t)$ free from the joint phase noise and unstable offset frequency. LPF: low-pass filter; BPF: bandpass filter.

where R is the responsivity of the two BPDs, $\Delta\omega = \omega_c - \omega_{LO}$ is the angular frequency difference between the light waves from the transmitter laser source and the LO laser source, and $\varphi(t)$ are the joint phase noise introduced by the transmitter laser source and the LO laser source. As can be seen from (7) and (8), the first term in each of the two currents consists of two sinusoidal functions of the phase fluctuations including the joint phase noise and the unstable offset between the transmitter laser source and the LO laser source, the second term is the crosstalk between the microwave vector signals $s_1(t)$and $s_2(t)$, which is affected by the phase fluctuations, and the last term is the crosstalk between the microwave vector signals $s_3(t)$and $s_4(t)$, which is also affected by the phase fluctuations. As can be seen, the four microwave vector signals cannot be recovered from the two photocurrents if no further signal processing is implemented.

If the two photocurrents are sampled and digitized, then we can apply digital signal processing solutions to recover the four microwave vector signals. Specifically, when the frequency difference between the two laser sources $\Delta\omega$ is lower than $\omega_1 - 2\pi B - \Delta\omega$, the first term can be obtained by using a digital lowpass filter (LPF). When $\omega_1 + 2\pi B + \Delta\omega$ is less than $\omega_2 - 2\pi B - \Delta\omega$, the second and third terms do not overlap and can be separated by using two bandpass filters (BPFs) with different center frequencies. The process is shown in the flow charts given by Figs. 2 –5 and it is mathematically expressed by the four equations,

$$i_9(t) = \left(i_3(t) + i_6(t)\right) \times i_4(t) + \left(i_6(t) - i_3(t)\right) \times i_7(t) = \left(\frac{\pi P_s L P_{LO} R^2}{2V_\pi}\right) s_1(t) \quad (9)$$

$$i_{10}(t) = \left(i_3(t) + i_6(t)\right) \times i_7(t) - \left(i_6(t) - i_3(t)\right) \times i_4(t) = \left(\frac{\pi P_s L P_{LO} R^2}{2V_\pi}\right) s_2(t) \quad (10)$$

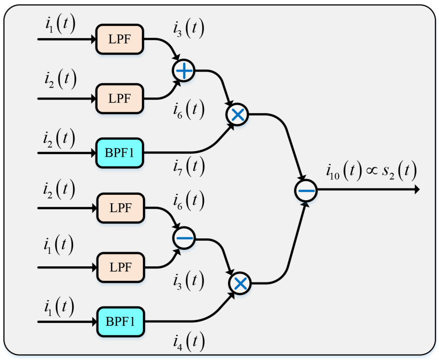

Fig. 3. Flow chart to recover the microwave vector signal $s_2(t)$ free from the joint phase noise and unstable offset frequency. LPF: low-pass filter; BPF: bandpass filter.

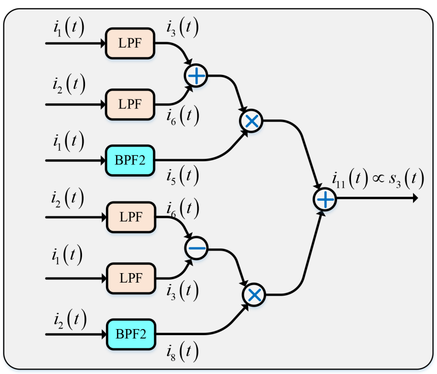

Fig. 4. Flow chart to recover the microwave vector signal $s_3(t)$ free from the joint phase noise and unstable offset frequency. LPF: low-pass filter; BPF: bandpass filter.

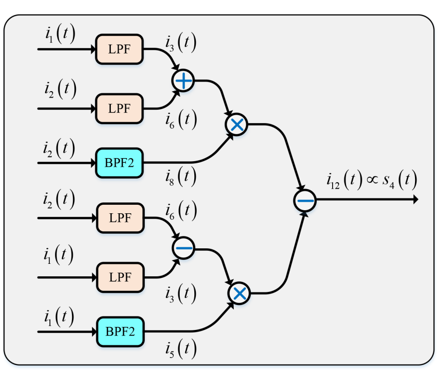

Fig. 5. Flow chart to recover the microwave vector signal $s_4(t)$ free from the joint phase noise and unstable offset frequency. LPF: low-pass filter; BPF: bandpass filter.

$$i_{11}(t) = (i_3(t) + i_6(t)) \times i_5(t) + (i_6(t) - i_3(t)) \times i_8(t) = \left(\frac{\pi P_s L P_{LO} R^2}{4V_\pi}\right) s_3(t) \quad (11)$$

$$i_{12}(t) = (i_3(t) + i_6(t)) \times i_8(t) - (i_6(t) - i_3(t)) \times i_5(t) = \left(\frac{\pi P_s L P_{LO} R^2}{4V_\pi}\right) s_4(t) \quad (12)$$

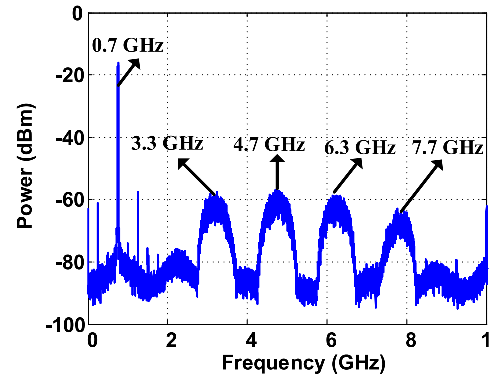

Fig. 6. The measured spectrum of the electrical signal at the first output port of the coherent receiver ($i_1(t)$).

It can be seen from (9) to (12), after the phase noise cancellation algorithm, the four microwave vector signals are recovered and free from the joint phase noise and unstable offset frequency introduced by the transmitter laser source and the LO laser source.

III. Experimental Setup and Results

An experiment based on the setup as shown in Fig. 1 is conducted. At the transmitter, a CW light at 1550 nm from a transmitter laser (Yokogawa, AQ2201) with a power of 8 dBm and a linewidth of 100 kHz is sent to a DPMZM (JDS-U) via PC1. Note that PC1 is used to minimize the PDL at the DPMZM. The bandwidth and half-wave voltage of the DPMZM are 10 GHz and 6.3 V, respectively. Two independent 16-QAM microwave vector signals ($s_1(t)$and $s_2(t)$) with a center frequency of 4 GHz and a baud rate of 0.5 GSym/s are generated by an arbitrary waveform generator (AWG, Keysight M8195A). The AWG has a sampling rate of 65 GSa/s and a bandwidth of 25 GHz. The two generated microwave vector signals are applied to sub-DDMZM1. Two other 16-QAM microwave vector signals ($s_3(t)$ and$s_4(t)$) with a center frequency of 7 GHz and a baud rate of 0.5 GSym/s, also generated by the AWG, are applied to sub-DDMZM2. The two sub-DDMZMs are both biased at the quadrature transmission point. At the output of the DPMZM, the modulated optical signals are transmitted over a 9-km SMF and sent to a coherent receiver (Keysight N4391A) via PC2. To perform coherent detection, a second CW light at 1550.006 nm from a LO laser source with a power of 10 dBm and a linewidth of 100 kHz is also applied to the coherent receiver via PC3. Note that the two PCs (PC2 and PC3) are used to co-polarize the modulated optical signal and the LO optical signal. After coherent detection, two electrical signals are generated which are sampled by a digital storage oscilloscope (Agilent DSO-Z 504A). The oscilloscope has a bandwidth of 50 GHz and a sampling rate of 160 GSa/s. The sampled signals are sent to a DSP unit where the four microwave vector signals free from the joint phase noise and unstable frequency offset introduced by the transmitter laser source and LO laser source are recovered.

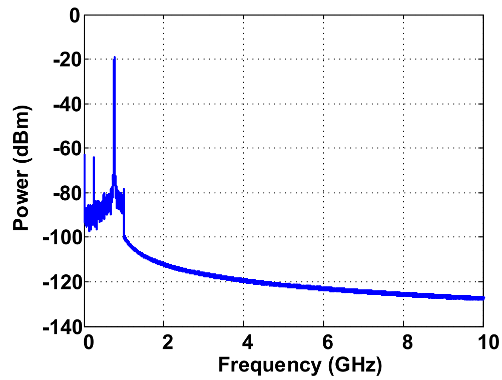

Fig. 7. The spectrum of the electrical signal at the output of an LPF ($i_3(t)$).

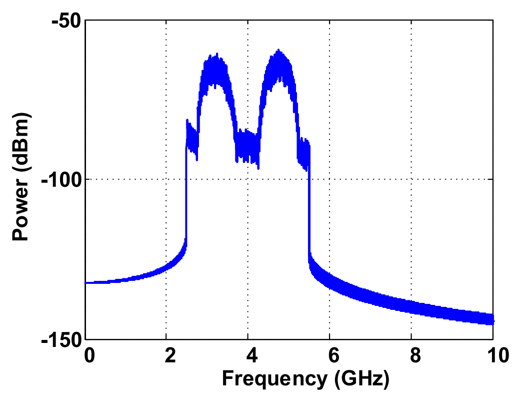

Fig. 8. The spectrum of the electrical signal at the output of a BPF1 ($i_4(t)$).

Fig. 6 shows the spectrum at one of the two outputs of the coherent receiver ($i_1(t)$). It can be seen, a microwave signal around 0.7 GHz is generated due to the wavelength difference between the transmitter laser source and the LO laser source. Two microwave signals at 3.3 GHz and 4.7 GHz with a bandwidth of 0.5 GHz are generated due to the mixing products between the 0.7 GHz microwave signal and the 4 GHz microwave vector signals. The other two microwave signals at 6.3 GHz and 7.7 GHz with a bandwidth of 0.5 GHz are also observed due to the mixing products between the 0.7 GHz microwave signal and the 7 GHz microwave vector signals. The electrical powers of the four microwave signals are different due to the different frequency response of the DPMZM at 4 GHz and 7 GHz. The 0.7 GHz microwave signal can be obtained by using an LPF with a bandwidth of 1 GHz, as shown in Fig. 7. The two microwave signals at 3.3 GHz and 4.7 GHz can be obtained by using a BPF with a center frequency of 4 GHz and a bandwidth of 3 GHz, as shown in Fig. 8, while the other two microwave signals at 6.3 GHz and 7.7 GHz are separated by using a BPF with a center frequency of 7 GHz and a bandwidth of 3 GHz, as shown in Fig. 9. Through digital phase noise cancellation, microwave vector signals $s_1(t)$ and $s_3(t)$ are recovered and free from the joint phase noise and the unstable offset frequency, as shown in Figs. 10 and 11. Fig. 12 shows the measured constellations of the four recovered microwave vector signals at the output of the DSP unit, where the optical power at the input of the coherent

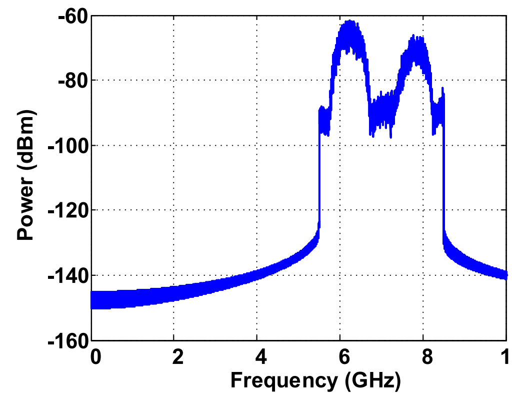

Fig. 9. The spectrum of the electrical signal at the output of a BPF2 ($i_5(t)$).

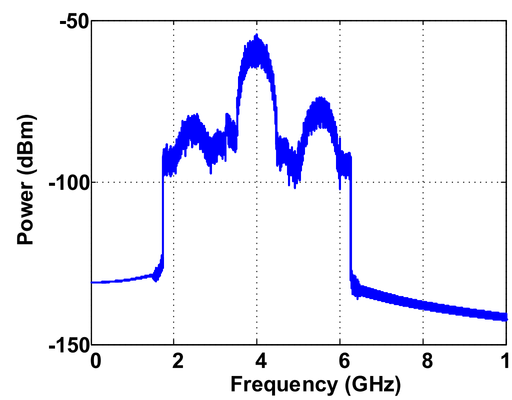

Fig. 10. The spectrum of the recovered microwave vector signal $s_1(t)$ at the output of the digital phase noise cancellation ($i_9(t)$).

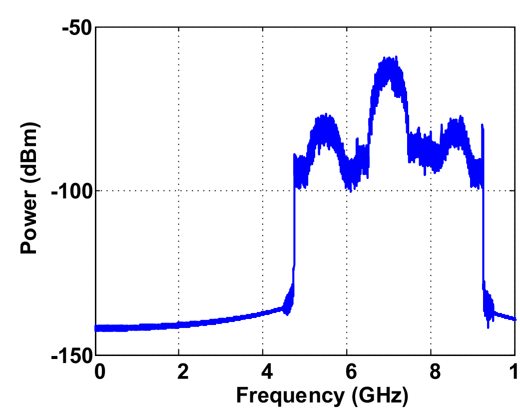

Fig. 11. The spectrum of the recovered microwave vector signal $s_3(t)$ at the output of the digital phase noise cancellation ($i_{11}(t)$).

receiver is -10 dBm. It can be seen that the constellations are very clear which indicates the four microwave vector signals are successfully recovered.

Figs. 13 and 14 show the measured EVMs and corresponding estimated BERs as a function of the received optical power for the four recovered microwave vector signals over a 9-km SMF, which is changed from -20 dBm to -10 dBm with a step of 2 dBm. Here, BERs are estimated based on the assumption

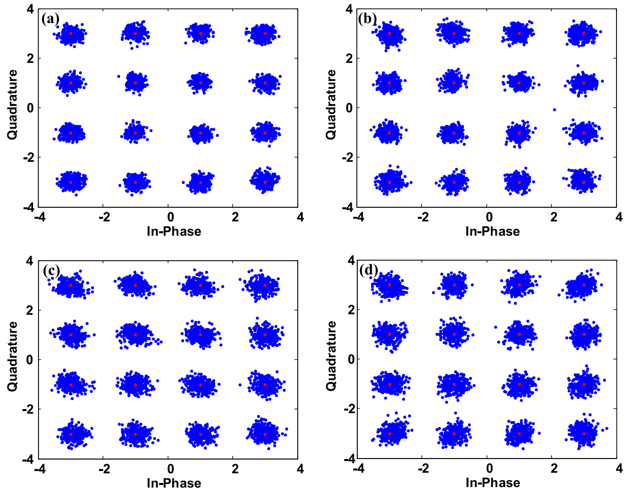

Fig. 12. Measured constellations of the four recovered 16-QAM microwave vector signals at the output of the DSP unit (fiber length: 9 km, the received optical power: -10 dBm). (a) $s_1(t)$, (b) $s_2(t)$, (c) $s_3(t)$, and (d) $s_4(t)$.

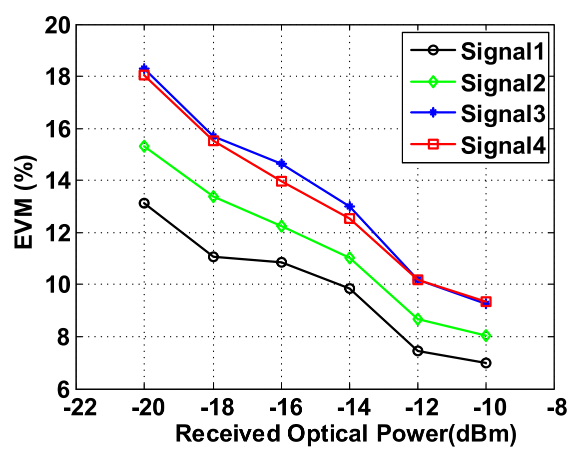

Fig. 13. Measured EVMs at different received optical power levels for the four recovered 16-QAM microwave vector signals transmitted over a 9-km SMF.

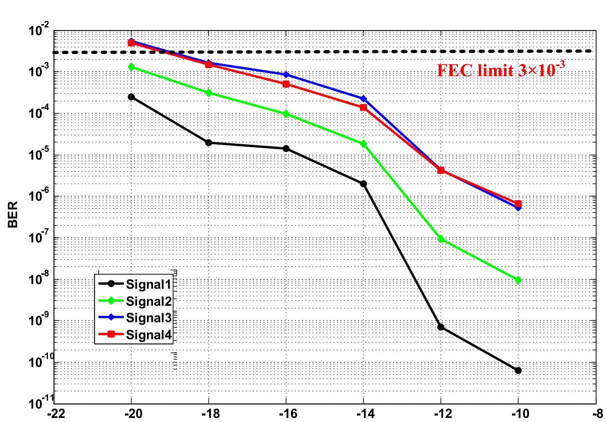

Fig. 14. Estimated BERs at different received optical power levels for the four recovered 16-QAM microwave vector signals transmitted over a 9-km SMF.

that the noise after the DSP unit is a stationary random process with Gaussian statistics [17]–[19]. It can be seen that, when the received optical power is -10 dBm, the EVMs for the four recovered 16-QAM microwave vector signals are 7.7%, 8.0%, 9.3%, and 9.4% and the estimated BERs are 6.3×10^{-11}, 9.6×10^{-9}, 5.3×10^{-7}, and 6.6×10^{-7}, which are far below the FEC limit. The quality of the recovered microwave vector Signal3 and Signlal4 are slightly lower than that of Signal1 and Signal2 due to the different frequency response of the DPMZM at 4 GHz and 7 GHz. When the optical power is -18 dBm, the estimated BERs are 1.9×10^{-5}, 3.1×10^{-4}, 1.6×10^{-3}, and 1.5×10^{-3}, which are all lower than 3×10^{-3}, thus the four microwave vector signals can be error-free transmitted when the state-of-the-art FEC technique is employed at the expense of a 6.7% overhead [20].

IV. Conclusion

We have proposed and experimentally demonstrated an MPL with quadrupled capacity based on coherent detection and digital phase noise cancellation. Four microwave vector signals with two sharing the same center microwave frequency were modulated on an optical carrier at a DPMZM and transmitted over an SMF. The signals were detected at a coherent receiver, to which an LO light from a free-running laser source was also applied. A new digital phase noise cancellation algorithm was developed, which was employed to recover the four microwave vector signals, to eliminate the joint phase noise and unstable offset frequency. The operation of the MPL was experimentally evaluated in which four independent 16-QAM microwave vector signals with a symbol rate of 0.5 GSymb/s were transmitted. When the received optical power was -10 dBm, the EVMs for the four recovered 16-QAM microwave vector signals were 7.7%, 8.0%, 9.3%, and 9.4% and the estimated BERs were 6.3×10^{-11}, 9.6×10^{-9}, 5.3×10^{-7}, and 6.6×10^{-7}, which are far below the FEC limit. When the optical power was -18 dBm, the estimated BERs were 1.9×10^{-5}, 3.1×10^{-4}, 1.6×10^{-3}, and 1.5×10^{-3}, which are all lower than 3×10^{-3}, thus error-free transmission of the four microwave vector signals can be achieved when the state-of-the-art FEC technique is employed. If PDM is employed, the capacity of the MPL can be further increased to transmit eight microwave vector signals.

References

[1] A. Seeds and K. Williams, "Microwave photonics," *J. Lightw. Technol.*, vol. 24, no. 12, pp. 4628–4641, Dec. 2006.

[2] C. Cox, E. Ackerman, G. Betts, and J. Prince, "Limits on the performance of RF-over-fiber links and their impact on device design," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 2, pp. 906–920, Feb. 2006.

[3] J. Capmany and D. Novak, "Microwave photonics combines two worlds," *Nature Photon.*, vol. 1, no. 6, pp. 319–330, Jun. 2007.

[4] J. Yao, "Microwave photonics," *J. Lightw. Technol.*, vol. 27, no. 3, pp. 314–335, Feb. 2009.

[5] J. Beas, G. Castanon, I. Aldaya, A. Zavala, and G. Campuzano, "Millimeter-wave frequency radio over fiber systems: A survey," *IEEE Commun. Surv. Tut.*, vol. 15, no. 4, pp. 1593–1619, Mar. 2013.

[6] R. Q. Shaddad, A. B. Mohammad, and M. A. Al-hetar, "Spectral efficient hybrid wireless optical broadband access network (WOBAN) based on transmission of wireless MIMO OFDM signals over WDM PON," *Opt. Commun.*, vol. 285, no. 20, pp. 4059–4067, Jun. 2012.

[7] G.-K. Chang *et al.*, "Key technologies of WDM-PON for future converged optical broadband access networks," *J. Opt. Commun. Netw.*, vol. 1, no. 4, pp. C35–C49, Sep. 2009.

[8] Y. Chen, T. Shao, A. Wen, and J. Yao, "Microwave vector signal transmission over an optical fiber based on IQ modulation and coherent detection," *Opt. Lett.*, vol. 39, no. 6, pp. 1509–1512, Mar. 2014.

[9] X. Chen and J. Yao, "A high spectral efficiency coherent microwave photonic link employing both amplitude and phase modulation with digital phase noise cancellation," *J. Lightw. Technol.*, vol. 33, no. 14, pp. 3091–3097, Jul. 2015.

[10] H. Zhang, A. Wen, W. Zhang, W. Zhang, W. Zhai, and Z. Tu, "A novel spectral-efficient coherent radio-over-fiber link with linear digital-phase demodulation," *IEEE Photon. J.*, vol. 12, no. 1, Feb. 2020, Art. no. 5500208.

[11] X. Chen and J. Yao, "Data rate quadrupled coherent microwave photonic link," *IEEE Photon. Technol. Lett.*, vol. 29, no. 13, pp. 1071–1074, Jul. 2017.

[12] X. Chen and J. Yao, "4×4 multiple-input multiple-output coherent microwave photonic link with optical independent sideband and optical orthogonal modulation," *Chin. Opt. Lett.*, vol. 15, no. 1, Jan. 2017, Art. no. 01008.

[13] P. Li, R. Xu, Z. Dai, Z. Lu, L. Yan, and J. Yao, "A high spectral efficiency radio over fiber link based on coherent detection and digital phase noise cancellation," *J. Lightw. Technol.*, vol. 39, no. 20, pp. 6443–6449, Aug. 2021.

[14] P. Li, Z. Dai, L. Yan, and J. Yao, "A microwave photonic link to transmit four microwave vector signals on a single optical carrier based on coherent detection and digital signal processing," *Opt. Exp.,* vol. 30, no. 5, pp. 6690–6699, Feb. 2022.

[15] P. Li, Z. Dai, L. Yan, and J. Yao, "Radio over fiber links with increased spectral efficiency based on coherent detection and digital processing," in *Proc. Int. Topical Meeting Microw. Photon.*, 2021, pp. 1–4.

[16] L. Zhang, Q. Zhang, T. Zuo, E. Zhou, G. Liu, and X. Xu, "C-band single wavelength 100-Gb/s IM-DD transmission over 80-km SMF without CD compensation using SSB-DMT," in *Proc. Opt. Fiber Commun.*, Los Angeles, CA, USA, 2015, pp. 1–3.

[17] D. H. Wolaver, "Measure error rates quickly and accurately," *Electron. Des.*, vol. 43, no. 11, pp. 89–98, May 1995.

[18] A. Brillant, *Digital and Analog Fiber Optic Communication For CATV and FTTx Applications*. Bellingham, WA, USA: SPIE, 2008, pp. 653–660.

[19] V. J. Urick, J. X. Qiu, and F. Bucholtz, "Wide-band QAM-over-fiber using phase modulation and interferometric demodulation," *IEEE Photon. Technol. Lett.*, vol. 16, no. 10, pp. 2374–2376, Oct. 2004.

[20] R. Schmogrow *et al.*, "512QAM Nyquist sinc-pulse transmission at 54 Gbit/s in an optical bandwidth of 3 GHz," *Opt. Exp.*, vol. 20, no. 6, pp. 6439–6447, Mar. 2012.

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