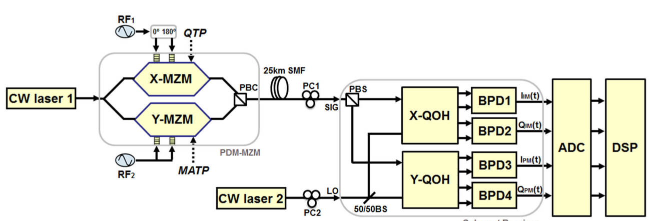
IEEE Photonics Journal
An IEEE Photonics Society Publication

A Novel Spectral-Efficient Coherent Radio-Over-Fiber Link With Linear Digital-Phase Demodulation

Volume 12, Number 1, February 2020

Huixing Zhang
Aijun Wen, *Senior Member, IEEE*
Wu Zhang
Weipeng Zhang
Weile Zhai
Zhaoyang Tu



DOI: 10.1109/JPHOT.2019.2946385

IEEE photonics SOCIETY
IEEE

A Novel Spectral-Efficient Coherent Radio-Over-Fiber Link With Linear Digital-Phase Demodulation

Huixing Zhang[1,2] **Aijun Wen**[1,2] ***Senior Member, IEEE,***
Wu Zhang,[1,2] **Weipeng Zhang,**[1,2] **Weile Zhai,**[1,2] **and Zhaoyang Tu**[1,2]

[1]State Key Laboratory of Integrated Service Networks, Xidian University, Xi'an 710071, China
[2]Collaborative Innovation Center of Information Sensing and Understanding, Xidian University, Xi'an 710071, China

DOI:10.1109/JPHOT.2019.2946385

Manuscript received September 6, 2019; revised September 30, 2019; accepted October 5, 2019. Date of publication October 9, 2019; date of current version January 8, 2020. Corresponding author: Aijun Wen (e-mail: ajwen@xidian.edu.cn).

Abstract: In this paper, a novel spectral-efficient coherent radio-over-fiber (RoF) link with linear digital phase demodulation is proposed and experimentally demonstrated. At the transmitter, to make an efficient use of the optical power and spectra, an intensity-modulated optical signal serving as the optical reference signal and a phase-modulated optical signal are polarization-multiplexed on a single optical carrier. At the receiver, the two optical signals are coherently detected with an optical local oscillator (OLO) and demodulated free of laser phase fluctuation through digital signal processing. Owing to simple and linear digital phase demodulation, an RF input signal is linearly demodulated from the optical phase without approximations and preconditions, which preserves the linearity of the phase-modulated RoF optical link from the transmitter end to the receiver end. The proposed scheme is experimentally verified by 25-km single-mode-fiber (SMF) transmission of two 16-QAM microwave vector signals at 2 GHz and 2.4 GHz, both with a symbol rate of 50 Msymbol/s. The transmission performance in term of error vector magnitude (EVM) is evaluated. Additionally, 25-km SMF transmission of the phase-modulated input signal with a spurious-free dynamic range (SFDR) of 112.8 dB·Hz$^{2/3}$ is obtained.

Index Terms: Radio-over-fiber, coherent detection, laser-phase-fluctuation-insensitive, digital signal processing, microwave vector signal.

1. Introduction

As an efficient manner to transmit radio-frequency (RF) signal with low loss, radio-over-fiber (RoF) technology has been extensively studied for many years [1]. The most concerned aspect of RoF links is the linearity which guarantees that RF signals dropped from the fiber routes are non-distorted. In general, RoF links are grouped into two categories, namely the direct-detected and the coherent-detected RoF link, depending on the detection approach used. The direct-detected RoF link is low cost and simple, but it is only effective if the RF signal is modulated on the intensity of the optical carrier. Such links are not strictly linear due to the sinusoidal intensity modulation process based on external modulation at the transmitter. The coherent-detected RoF link is comparatively costly and complex, but with higher receiver sensitivity and flexibility to detect either intensity-modulated or phase-modulated optical signals [2]. Additionally, with phase modulation at the transmitter and the digital signal processing (DSP)-aided in-phase/quadrature-phase (I/Q) demodulation at the receiver, the coherent-detected RoF link has been reckoned as the only solution to achieve the rigorously linear transportation of radio-frequency (RF) signals over the fiber route so far [3].

However, coherent-detected RoF links are highly sensitive to the laser phase fluctuation, including the laser phase noises and the frequency offset between the transmitter laser and the optical local oscillator (OLO) laser. Numerous methods have been developed to mitigate the effects of the laser phase fluctuation. The simplest manner is the self-homodyne-detected RoF link wherein the laser phase fluctuation is avoided by employing the same laser source for both the transmitter and the OLO. However, it requires that the optical paths of the interferometer are well matched. In the self-homodyne system proposed by Clark *et al.* [3], an electrical feedback control loop was used to realize the path-length alignment. However, such a scheme is limited for short-reach links and difficult to be accommodated in wireless access networks. In our previous work [4], we have proposed a self-homodyne scheme with an extended transmission distance and increased spectral efficiency by delivering an intensity-modulated OLO signal and a phase modulated optical signal via two orthogonal polarization states in a single fiber. However, in both of the two schemes mentioned above [3], [4], the erbium doped fiber amplifiers (EDFAs) are used to improve the receiver sensitivity because sending the OLO signal from the transmitter over long distance yields a low LO power at the receiver. Thus, additional amplified spontaneous emission (ASE) noises are introduced by the optical amplifier in such schemes.

Coherent-detected RoF links containing an OLO at the receiver are more desirable because high receiver sensitivity can be obtained without using optical amplifiers. In such schemes, the intuitive method to eliminate the laser phase fluctuation is to lock the phase of the two lasers by an optical phase locked loop (OPLL) [5]. However, the bandwidth of an OPLL is limited below 1 MHz even for state-of-the-art products, which makes the system unstable [6]. In addition, the challenges from both the technical and economic aspects also hinder the deployment of OPLLs in practical cases. Recently, many approaches relying on signal post processing in the digital domain are proposed to avoid the use of the OPLL [7]–[14]. Owing to the powerful DSP algorithms combined with proper link design, such schemes successfully minimize the impact of the laser phase fluctuation. However, for the phase-modulated coherent RoF link, the DSP algorithms should be carefully designed because the linearity of the transmission might be deteriorated. For example, in X. Chen's work [8]–[11], although the phase-modulated optical signal can be demodulated free from laser phase fluctuation, the demodulation process is not linear unless either the small signal approximation or a certain precondition, i.e., the spectrum of the laser phase noise was not overlapped with that of the signal, was satisfied. To maintain the linearity of the phase-modulated RoF link at the demodulation stage, several approaches are presented. In [12], a digital phase-locked loop (DPLL) is built to serve as the counterpart of an OPLL in digital domain. In such a scheme, the phase demodulation is linear but the DSP algorithm is complex. In [13], by employing a Sagnac loop to deliver an empty optical carrier as the remote optical reference signal along with the phase-modulated optical signal to the receiver, the RF signal can be linearly demodulated from the optical phase by a simple DSP algorithm. However, an unmodulated optical reference signal results a waste of the optical power and spectra. Besides, the Sagnac loop is susceptible to environmental interference which may affect the system performance.

In this paper, we propose a novel spectral-efficient coherent RoF link based on intradyne detection with linear digital phase demodulation. As the central station is supposed to endure more complexity than the remote radio unit, our scheme is assumed to be applied to uplink RoF systems. It can also be applied to a point-to-point high-speed wireless transmission system. In the proposed scheme, at the transmitter, an intensity-modulated optical reference signal and a phase-modulated optical signal are generated on a single optical carrier by a polarization division multiplexing Mach-Zehnder modulator (PDM-MZM) to achieve a highly efficient use of the optical power and spectra. Since an integrated modulator is used, the transmitter is less sensitive to the environmental disturbance. At the receiver, the two optical signals are coherently detected with an OLO and then demodulated with laser-phase-fluctuation cancelled through digital signal processing. Particularly, for the phase-

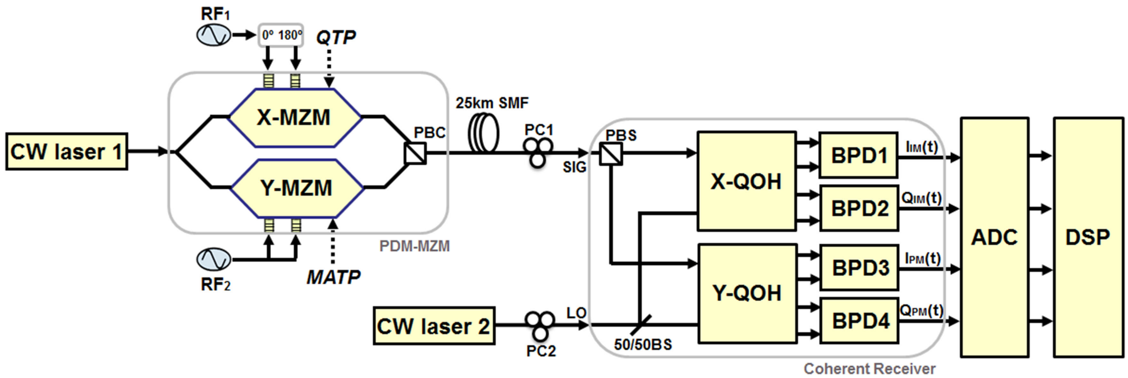


Fig. 1. Schematic diagram of the proposed RoF link. CW, continuous wave; RF, radio frequency; PDM-MZM, polarization division multiplexing Mach–Zehnder modulator; QTP, quadrature transmission point; MATP, maximum transmission point; PBC, polarization beam combiner; SMF, single mode fiber; PC, polarization controller; PBS, polarization beam splitter; LO, local oscillator; SIG, signal; BPD, balanced photodetector; ADC, analog-to-digital converter; DSP, digital signal processing; BS, beam splitter; QOH, quadrature optical hybrid; IM, intensity modulation; PM, phase modulation.

modulated optical signal, the RF signal is linearly demodulated from the optical phase without approximations and conditional assumptions. This linear phase demodulation is very simple and easy to manipulate. Our proposed scheme is experimentally demonstrated by transporting a 50 Msymbol/s intensity-modulated 16-QAM microwave vector signal at 2.4 GHz and a 50 Msymbol/s phase-modulated 16-QAM microwave vector signal at 2 GHz over a 25-km single mode fiber (SMF). The transmission performance is evaluated in term of error vector magnitude (EVM). Additionally, for the 25-km SMF transmission of the phase-modulated input signal, a spurious-free dynamic range (SFDR) of 112.8 dB·Hz$^{2/3}$ and a link gain of −8.5 dB are achieved.

2. Principles

The schematic diagram of our proposed scheme is illustrated in Fig. 1. The transmitter incorporates a continuous wave (CW) laser and a PDM-MZM. By the PDM-MZM which contains a Y-splitter, two dual-electrode MZMs and a polarization beam combiner (PBC), the light wave from CW laser 1 is split into two channels referred to as IM channel and PM channel in the rest of our paper for the subsequent intensity and phase modulation on two orthogonal polarization states respectively.

The intensity modulation in IM channel is accomplished by the push-pull usage of the X-MZM. Two RF signals generated from the same RF signal source but with π phase difference after a 180° electrical hybrid coupler are injected into the RF input ports of the X-MZM. The direct current (DC) bias of X-MZM is tuned at the quadrature transmission point (QTP). Supposing that the RF signal modulated on the amplitude of the light wave is denoted as $V_{RF,IM}(t)$ and the light wave from the CW laser 1 is expressed as $E_s(t) = \sqrt{P_s}e^{j[\omega_s t+\varphi_{ns}(t)]}$, where P_s, ω_s and $\varphi_{ns}(t)$ are the optical power, the angular frequency and the laser phase noise, respectively, then the output of the X-MZM can be written as

$$E_{IM}(t) = \frac{\sqrt{2}}{2}\sqrt{P_s}\cos\left(\pi\frac{V_{RF,IM}(t)}{V_\pi} + \frac{\pi}{4}\right)e^{j[\omega_s t+\varphi_{ns}(t)]}\overrightarrow{e_x} \tag{1}$$

In PM channel, another RF signal source is divided by an electrical divider before being launched into the RF input ports of the Y-MZM to accomplish the phase modulation. The DC bias of Y-MZM is tuned at the maximum transmission point (MATP). Assuming the RF signal imposed on the optical phase is denoted as $V_{RF,PM}(t)$, the output of the Y-MZM can be expressed as

$$E_{PM}(t) = \frac{\sqrt{2}}{2}\sqrt{P_s}e^{j\left(\omega_s t+\pi\frac{V_{RF,PM}(t)}{V_\pi}+\varphi_{ns}(t)\right)}\overrightarrow{e_y} \tag{2}$$

The two modulated optical signals are then combined by a PBC and transmitted over a 25-km SMF. At the receiver, the combined signals with two orthogonal polarization states are sent to the signal (SIG) input port of a coherent receiver. A light wave emitted from the CW laser 2 is fed into the LO input port of the coherent receiver. By tuning the polarization controller (PC1), the combined signals are split by a polarization beam splitter (PBS) inside the coherent receiver. Through tuning PC2, the polarization state of the LO signal is aligned at 45° relative to one principle axis of the PBS to facilitate the interference in the X-QOH and Y-QOH. Given that the responsivity of the balanced photodetectors (BPDs) in the coherent receiver is R, and the light wave from the CW laser 2 is expressed as $E_{lo}(t) = \sqrt{P_{lo}}e^{j[\omega_{lo}t+\varphi_{nlo}(t)]}$, where P_{lo}, ω_{lo} and $\varphi_{nlo}(t)$ are the optical power, the angular frequency and the laser phase noise respectively, the four outputs of the coherent receiver can be given by

$$I_{IM}(t) = \frac{\sqrt{2}}{4}R\sqrt{P_s P_{lo}}\cos\left(\pi\frac{V_{RF,IM}(t)}{V_\pi} + \frac{\pi}{4}\right)\cos\left[(\omega_s - \omega_{lo})t + \varphi_{ns}(t) - \varphi_{nlo}(t)\right] \tag{3}$$

$$Q_{IM}(t) = \frac{\sqrt{2}}{4}R\sqrt{P_s P_{lo}}\cos\left(\pi\frac{V_{RF,IM}(t)}{V_\pi} + \frac{\pi}{4}\right)\sin\left[(\omega_s - \omega_{lo})t + \varphi_{ns}(t) - \varphi_{nlo}(t)\right] \tag{4}$$

$$I_{PM}(t) = \frac{\sqrt{2}}{4}R\sqrt{P_s P_{lo}}\cos\left[(\omega_s - \omega_{lo})t + \varphi_{ns}(t) - \varphi_{nlo}(t) + \pi\frac{V_{RF,PM}(t)}{V_\pi}\right] \tag{5}$$

$$Q_{PM}(t) = \frac{\sqrt{2}}{4}R\sqrt{P_s P_{lo}}\sin\left[(\omega_s - \omega_{lo})t + \varphi_{ns}(t) - \varphi_{nlo}(t) + \pi\frac{V_{RF,PM}(t)}{V_\pi}\right] \tag{6}$$

The four electrical currents are sampled by the analog-to-digital converter (ADC) and then sent to the DSP unit for numerical processing. Assuming the input signal $V_{RF,IM}(t)$ is small, the first two outputs of the coherent receiver are applied to demodulate the intensity-modulated input signal by

$$K_{IM}(t) = I_{IM}(t) + jQ_{IM}(t) \tag{7}$$

$$\begin{aligned}
\left|K_{IM}(t)\right|^2 &= I_{IM}(t)^2 + Q_{IM}(t)^2 \\
&= \left[\frac{\sqrt{2}}{4}R\sqrt{P_s P_{lo}}\cos\left(\pi\frac{V_{RF,IM}(t)}{V_\pi} + \frac{\pi}{4}\right)\right]^2 \\
&= \frac{1}{16}R^2 P_s P_{lo}\left[1 - \sin\left(\frac{2\pi V_{RF,IM}(t)}{V_\pi}\right)\right] \\
&\approx \frac{1}{16}R^2 P_s P_{lo}\left(1 - \frac{2\pi V_{RF,IM}(t)}{V_\pi}\right)
\end{aligned} \tag{8}$$

And the laser phase fluctuation between the two lasers is estimated by extracting the phase of the complex quantity $K_{IM}(t)$ by

$$\arg\left[K_{IM}(t)\right] = (\omega_s - \omega_{lo})t + \varphi_{ns}(t) - \varphi_{nlo}(t) \tag{9}$$

Meanwhile, the phase-modulated input signal is therefore demodulated with the laser phase fluctuation cancelled by

$$K_{PM}(t) = I_{PM}(t) + jQ_{PM}(t) \tag{10}$$

$$\pi\frac{V_{RF,PM}(t)}{V_\pi} = \arg\left[K_{PM}(t)\right] - \arg\left[K_{IM}(t)\right] \tag{11}$$

From the Eq. (11), it is clear to see that the RF signal is linearly demodulated from the optical phase without approximations and preconditions. This linear phase demodulation is very simple and easy to conduct.

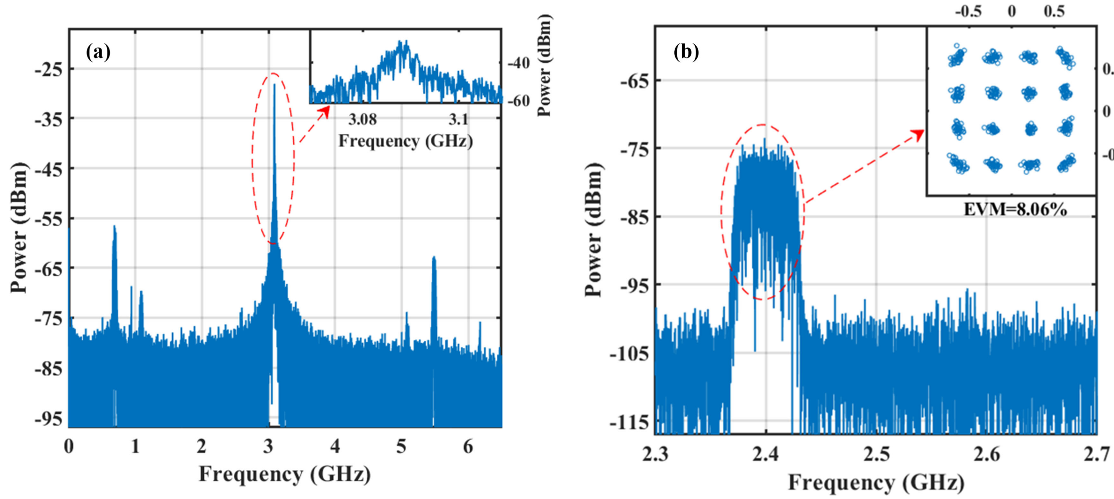


Fig. 2. Spectra of the output signal from I_{IM} port (a) and the demodulated signal after DSP (b) at IM channel.

3. Experiments and Results

A proof-of-concept experiment based on Fig. 1 is demonstrated. A light wave from a CW laser source (Neophotonics TTX1995) operating at a wavelength of 1551.710 nm, with a linewidth of about 20 kHz and an output optical power of 8.5 dBm is sent to the PDM-MZM (Fujitsu FTM7980EDA). The PDM-MZM contains two dual-electrode MZMs each with a half-voltage of 3.5 V and an extinction ratio of 20 dB. In IM channel, a 16-QAM microwave vector signal (generated by Rohde & Schwarz SMBV100A) at 2.4 GHz with a symbol rate of 50 Msymbol/s is split by an 180° electrical hybrid and then sent to the two RF input ports of the X-MZM for the intensity modulation. The DC bias of the X-MZM is tuned at QTP. In PM channel, another 16-QAM microwave vector signal (generated by Rohde & Schwarz SMW200A) at 2 GHz with the same symbol rate of 50 Msymbol/s is divided by an electrical divider and then injected into the two RF input ports of the Y-MZM for phase modulation. The DC bias of the Y-MZM is tuned at the MATP. The two modulated optical signals with orthogonal polarization states are subsequently combined by a PBC and transmitted over a 25-km SMF. At the receiver, the polarization multiplexed signals are launched to the SIG input port of an integrated coherent receiver (Neophotonics 100G IPBS MPD ICR) via PC1. The optical power at the SIG input port of the integrated coherent receiver (ICR) is −11.15 dBm. By tuning PC1, the two modulated signals are finely demultiplexed by the PBS inside the coherent receiver. It should be noted that, the PC1 can be replaced by a dynamic polarization controller [15] to avoid manual adjusting in a practical system. Another CW laser source (Emcore 1782) centered at the wavelength of 1551.685 nm with a linewidth of about 1 MHz and an output power of 2.84 dBm is served as the OLO source. Through tuning PC2, the polarization direction of the OLO signal is aligned to 45° relative to the principle axis of the PBS. After the detection, the four output electrical currents are digitized by an oscilloscope (Keysight DSOV334A) with a sampling rate of 20 Gsa/s. The numerical processing is processed offline based on the Eqs. (7–11) in a computer.

Fig. 2(a) shows the spectrum of the output signal from I_{IM} port at IM channel. As can be seen from Fig. 2(a), after coherent detection, an intermediate frequency (IF) around 3.1 GHz is generated corresponding to the wavelength difference of 0.025 nm between the transmitter laser and OLO laser. The noisy IF carrier blurred by the phase noises of the two un-locked lasers is also shown as the inset in Fig. 2(a). The 16-QAM microwave vector signal at 2.4 GHz is down- and up-converted to two prominent sidebands at 0.7 GHz and 5.5 GHz apart from the IF. Two weak sidebands at 1.1 GHz and 5.1 GHz corresponding to the mixing products between 16-QAM microwave vector signal at 2 GHz and the IF are also observed, which is due to the imperfect extinction ratio of

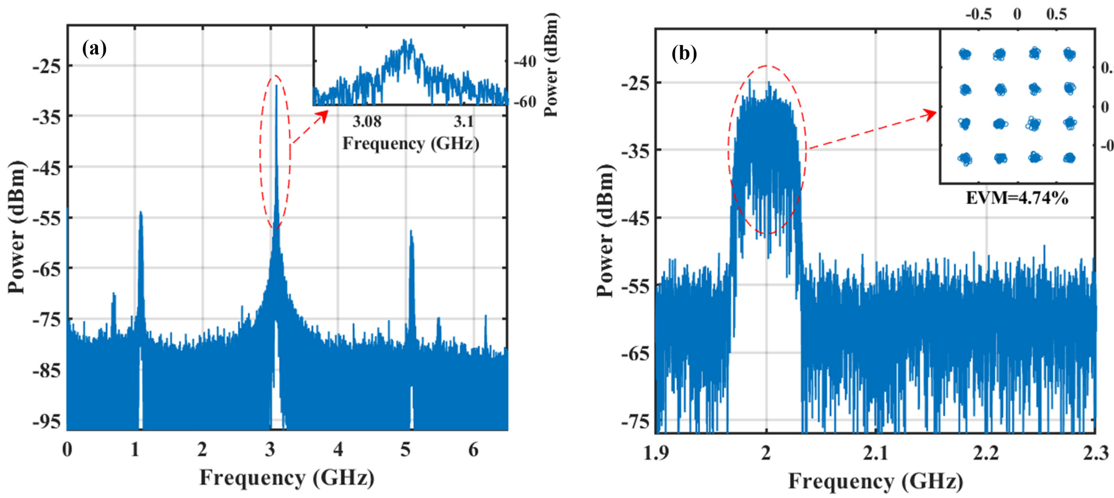


Fig. 3. Spectra of the output signal from I_{PM} port (a) and the demodulated signal after DSP (b) at PM channel.

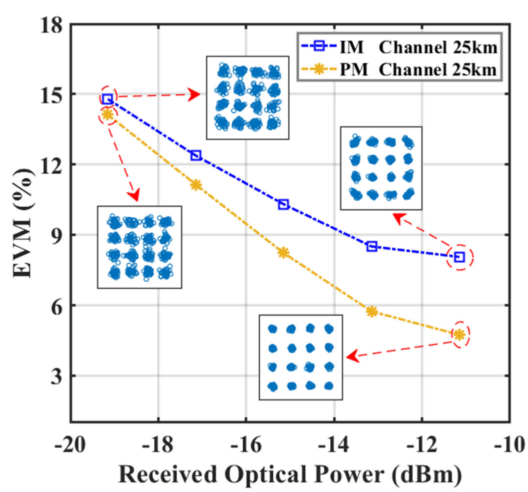


Fig. 4. Measured EVMs versus the received optical power for 25-km SMF transmission of 16-QAM microwave vector signals in PM and IM channel.

the PBS inside the coherent receiver. Fig. 2(b) shows the spectrum of the recovered signal after DSP at IM channel. The constellation diagram of the demodulated signal with an EVM of 8.06% is illustrated as the inset in Fig. 2(b).

Fig. 3(a) shows the spectrum of the output signal from I_{PM} port at PM channel. As seen in Fig. 3(a), the desired mixing products generated by 16-QAM microwave vector signal at 2 GHz and the IF are at 1.1 GHz and 5.1 GHz. The two weak sidebands at 0.7 GHz and 5.5 GHz are the leaking ones from IM channel due to the poor extinction ratio of the PBS. Similarly, laser phase noises account for the wide profile of the IF carrier which is illustrated as the inset in Fig. 3(a). The spectrum of the recovered signal at PM channel is shown in Fig. 3(b) and the constellation diagram with an EVM of 4.74% is shown in the inset.

The transmission performance of the proposed scheme in terms of EVM is evaluated. The experimental results are presented in Fig. 4. In Fig. 4, the EVMs versus the received optical power are measured for both channels. The LO input power of the ICR in this measurement is −0.8 dBm.

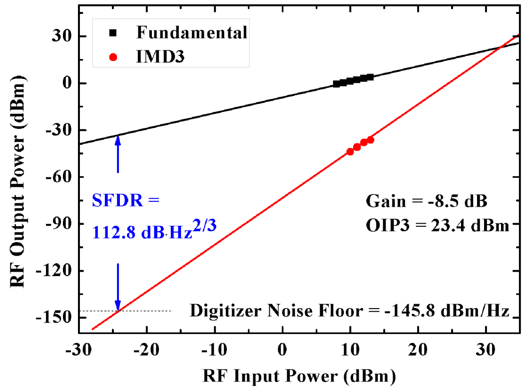


Fig. 5. Measured output powers of the fundamental term and the IMD3 in the recovered spectrum as a function of the RF input power after 25-km SMF transmission of an RF two-tone test signal in PM channel.

As can be seen, when the received optical power is at −19.15 dBm, the constellation diagrams at IM channel and PM channel both are separable.

In order to testify the effectiveness of the linear phase demodulation algorithm, the SFDR performance of the PM channel is investigated. In our test, a two-tone signal formed by two RF signals at 2 GHz and 2.1 GHz is served as the RF input source of the PM channel while the RF signal source of the IM channel is turned off. The optical powers launched into the SIG and LO input ports of the ICR are controlled to be −9 dBm and 5.8 dBm respectively. By increasing the RF input power of the two-tone signal from 8 dBm to 13 dBm, the output powers of the fundamental microwave signal and the third-order intermodulation distortion (IMD3) are measured from the spectrum of the recovered signal. The digitizer noise floor of the oscilloscope is −145.8 dBm/Hz during the experiment. As shown in Fig. 5, after 25-km SMF transmission, a SFDR of 112.8 dB·Hz$^{2/3}$, a link gain (the ratio of RF output power to RF input power) of −8.5 dB and an output third-order intercept point (OIP3) of 23.4 dBm are obtained for PM channel in our proposed scheme.

4. Conclusions

We have proposed a spectral-efficient coherent RoF link with linear digital phase demodulation. The proposed scheme can achieve an efficient use of the optical power and spectra by using a PDM-MZM to generate an intensity-modulated optical reference signal and a phase-modulated optical signal from the transmitter. At the receiver, aided by a DSP unit, both two signals can be successfully demodulated free from the laser phase fluctuation between the transmitter laser and the OLO laser. The digital phase demodulation in our scheme is linear and simple. A proof-of-concept experiment has been demonstrated. The transmission performance in term of the EVM is measured for 25-km SMF transmission of an intensity-modulated and a phase-modulated 16-QAM microwave vector signal, both at a symbol rate of 50 Msymbol/s. Additionally, a SFDR of 112.8 dB·Hz$^{2/3}$, a link gain of −8.5 dB and an OIP3 of 23.4 dBm are obtained for 25-km transmission of a two-tone test signal in PM channel and the results show that the good linearity of the PM channel is preserved by the linear phase demodulation.

Acknowledgment

The authors would like to thank Dr. R. Li at the Institute of Electrics, Chinese Academy of Sciences, for the fruitful discussion. This work was supported in part by The National Key Research and Development Program of China under Grant 2017YFB1104800 and in part by The Key Research and Development Program from Government of Shaanxi Province (2017GY-093).

References

[1] J. Capmany and D. Novak, "Microwave photonics combines two worlds," *Nature Photon.*, vol. 53, no. 6, pp. 319–331, Jun. 2007.
[2] A. Stöhr *et al.*, "Highly spectral-efficient and high capacity millimeter-wave wireless data transmission using a coherent radio-over-fiber system (CRoF)," in *Proc. 21st Eur. Conf. Netw. Opt. Commun.*, 2016, pp. 201–206, doi: 10.1109/NOC.2016.7507013.
[3] T. R. Clark, S. R. O'Connor, and M. L. Dennis, "A phase-modulation I/Q-demodulation microwave-to-digital photonic link," *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 11, pp. 3039–3058, Oct. 2010.
[4] H. Zhang, A. Wen, W. Zhang, W. P. Zhang, and Z. Tu, "A spectral efficient self-homodyne-detected microwave photonic link with an extended fiber-reach," *IEEE Photon. Technol. Lett.*, vol. 30, no. 19, pp. 1719–1722, Oct. 2018.
[5] Y. Li and P. Herczfeld, "Coherent PM optical link employing ACP-PPLL," *J. Lightw. Technol.*, vol. 27, no. 9, pp. 1086–1094, May 2009.
[6] K. Kikuchi, "Fundamentals of coherent optical fiber communications," *J. Lightw. Technol.*, vol. 34, no. 1, pp. 157–179, Jan. 2016.
[7] X. Chen, T. Shan, and J. Yao, "Digital phase noise cancellation for a coherent-detection microwave photonic link," *IEEE Photon. Technol. Lett.*, vol. 26, no. 8, pp. 805–808, Apr. 2014.
[8] X. Chen and J. Yao, "A coherent microwave photonic link with digital phase noise cancellation," in *Proc. Int. Topical Meeting Microw. Photon. Conf.*, 2014, pp. 438–441.
[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] X. Chen and J. Yao, "Wavelength reuse in a symmetrical radio over WDM-PON based on polarization multiplexing and coherent detection," *J. Lightw. Technol.*, vol. 34, no. 4, pp. 150–1157, Feb. 2016.
[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] D. Zibar, X. Yu, C. Peucheret, P. Jeppesen, and I. Monroy, "Digital coherent receiver for phase-modulated radio-over-fiber optical links," *IEEE Photon. Technol. Lett.*, vol. 21, no. 3, pp. 155–157, Feb. 2009.
[13] R. Li, X. Han, X. Chen, X. F. Chen, and J. Yao, "A phase-modulated microwave photonic link with an extended transmission distance," *IEEE Photon. Technol. Lett.*, vol. 27, no. 24, pp. 2563–2566, Dec. 2015.
[14] T. Kuri, T. Sakamoto, and T. Kawanishi, "Laser-phase-fluctuation-insensitive optical coherent transmission of 16-quadrature-amplitude-modulation radio-over-fiber signal," *J. Lightw. Technol.*, vol. 34, no. 2, pp. 683–690, Jan. 2016
[15] X. S. Yao, L.-S. Yan, B. Zhang, A. E. Willner, and J. Jiang, "All-optical scheme for automatic polarization division demultiplexing," *Opt. Exp.*, vol. 15, no. 12, pp. 7407–7414, Jun. 2007.