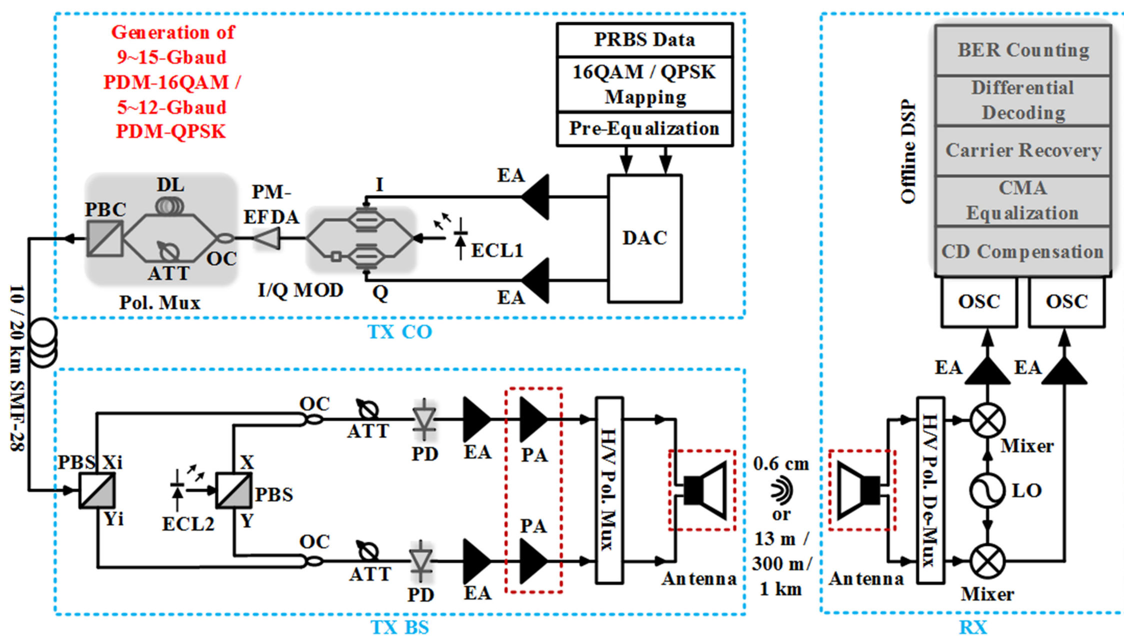
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

Delivering Dual Polarization-Division-Multiplexing Millimeter-Wave Signals at W-Band by One Pair of Antennas

Volume 11, Number 5, October 2019

Yifan Chen
Jiangnan Xiao, *Member, IEEE*
Ze Dong, *Member, IEEE*



DOI: 10.1109/JPHOT.2019.2936431

Delivering Dual Polarization-Division-Multiplexing Millimeter-Wave Signals at W-Band by One Pair of Antennas

Yifan Chen,[2] **Jiangnan Xiao**,[1] ***Member, IEEE***, **and Ze Dong**,[2] ***Member, IEEE***

[1]J. Xiao is with the Shanghai Key Lab of Modern Optical Systems, Terahertz Technology Innovation Research Institute, and Engineering Research Center of Optical Instrument and System, Ministry of Education, University of Shanghai for Science and Technology, Shanghai 200093, China
[2]Y. Chen and Z. Dong are with the College of Information Science and Technology, Huaqiao University, Xiamen 361021, China

DOI:10.1109/JPHOT.2019.2936431

Manuscript received May 11, 2019; revised August 9, 2019; accepted August 15, 2019. Date of publication August 21, 2019; date of current version September 4, 2019. This work was supported in part by the National Natural Science Foundation of China under Grants 61675048, 61401166, 61527801, 61720106015, 61835002, and 61805043, in part by the Fujian Province Science Fund for Distinguished Young Scholars under Grant 2016J06015 (11166004), in part by the Fundamental Research Funds for the Central Universities (ZQN-YX305) and in part by the Quanzhou City Science and Technology Program of China under Grant 2018C116R. Corresponding author: Jiangnan Xiao (e-mail: jiangnanxiao@usst.edu.cn).

Abstract: We propose and experimentally demonstrate a novel seamless fiber-wireless-integration system (FWI) to deliver up to 120-Gb/s (9∼15-Gbaud) polarization-division-multiplexing 16-ary quadrature-amplitude-modulation (PDM-16QAM)/40-Gb/s (5∼12-Gbaud) quadrature-phase-shift-keying (PDM-QPSK) signal over 10-km/20-km single-mode fiber-28 (SMF-28) and 0.6-cm/13-m, 300-m and 1-km 2 × 2 multi-input multi-output (MIMO) wireless link at W-band, realized by antenna polarization multiplexing and photonic millimeter-wave (mm-wave) generation techniques. With reduction of system size-based hardware complexity and power consumption, it is more convenient for the system adopting antenna polarization multiplexing to be installed and maintained. For simplification of network architecture, apart from being deployed as multiplexer/de-multiplexer, two ortho-mode transducer devices are used to be a pair of panel antennas at both the transmitter and the receiver sides in the scheme of the short-haul wireless link employing PDM-16QAM signal. The bit error ratio (BER) is less than the new-generation forward-error-correction (eFEC) threshold of 2×10^{-2} with CMA algorithm for equalization.

Index Terms: FWI, PDM-16QAM, PDM-QPSK, antenna polarization multiplexing, mm-wave, ortho-mode transducer.

1. Introduction

As the requirements for transmission rate and capacity of communication network are significantly increasing nowadays, Fiber-wireless-integration (FWI) communication systems have been progressively and extensively investigated in the research community [1]–[17]. With the superiority of large bandwidth and high mobility respectively taken from fiber-optic communication and wireless communication, FWI systems are expected as an appropriate solution for prospective communication networks [9], [10]. FWI communication systems enabled by photonic mm-wave technique are improved profoundly to realize mm-wave wireless signals with up to 100-Gb/s and beyond transmission rate for mobile data [11]–[17]. In fiber-optic systems, polarization multiplexing can be adopted to double transmission capacity, which is widely deployed in the real optical networks with coherent detection. However, in previous experiments, one pair of antennas to deliver horizontal (H-) or vertical (V-) polarization signal need to be well adjusted in position to reduce the crosstalk from the V- or H-polarization signal delivered by the other pair of antennas [18]. To put it in another way, the utilized 2 $\times$ 2 antenna array increases both the complexity and requirements for installment and maintenance of systems. For simplification and efficiency, antenna polarization multiplexing can be employed to lower signal baud rate, diminish performance requirements for optical and wireless devices, and improve wireless transmission capacity. Resultantly, the FWI system with only one pair of antennas for the delivery of both H- and V- signals is first proposed to diminish the requirements for the antennas and avoid the crosstalk, which is experimentally demonstrated in short- and long-haul cases.

In this letter, we propose a novel FWI transmission system realized by polarization multiplexing of only one pair of antennas for 120-Gb/s PDM-16QAM signal delivery over 10-km SMF-28 and 0.6-cm W-band wireless link as well as 40-Gb/s PDM-QPSK signal deliveries over 20-km SMF-28 and 13-m/300-m/1-km W-band wireless link. In our experiment for short-haul wireless scheme, two ortho-mode transducers, one for multiplexing at the transmitter and the other for de-multiplexing at the receiver with the average isolation of 27 dB for both H- and V- polarization of the signal, are used as a pair of panel antennas to deliver dual PDM-QAM signals at W-band as well. For long-haul wireless delivery, two PDM-QPSK signals are delivered by a pair of E-band Cassegrain antennas respectively connected with the one of two ortho-mode transducers as the multiplexer and de-multiplexer. The bit error ratio (BER) less than 2×10^{-2}, the new-generation forward-error-correction (eFEC) threshold, can be guaranteed for the proposed system when the required CMA tap length for short-distance wireless delivery is larger than 81 or that for long-haul scheme proves to be 37. The input power for the long-haul wireless link scheme is diminished by 1.2 dB by contrast with the short-distance one. Thus, better tolerance to nonlinear effect is gained.

2. Principle of PDM-16QAM/PDM-QPSK Signal Delivery

The principle of the previous scheme and that of the proposed one are respectively shown as Fig. 1(a) and Fig. 1(b).

According to Fig. 1 and Fig. 2, the proposed system is divided into four parts which are optical baseband transmitter, optical up-convertor, 2 $\times$ 2 MIMO, and wireless receiver at W-band.

The optical baseband transmitter generally consists of an external cavity laser (ECL), an in-phase/quadrature (I/Q) modulator, a polarization-maintaining optical coupler and a polarization multiplexer. The optical input signal is evenly divided by an I/Q modulator driven by QAM/QPSK signals, comprised of a Mach-Zehnder modulator (MZM) in the in-phase path, and a 90-degree phase shifter along with the other parallel MZM in the quadrature path, both MZMs biased at the null point and driven at the full swing. $\pi/2$ phase difference is kept for the signals in the upper and lower paths of the I/Q modulator and the output signal is converted from electrical domain to optical domain by modulating the optical carrier generated by an ECL [15], [16]. After the polarization multiplexer including a polarization-maintaining optical coupler (PM-OC), a variable optical delay line (DL), a variable optical attenuator (VOA), and a polarization beam combiner (PBC), the generated optical baseband signal employing PDM from two uncorrelated signals is obtained. A polarization-maintaining Erbium-doped fiber amplifier (EDFA) is used to compensate for signal loss in fiber transmission.

For the optical up-convertor, a local oscillator (LO), two polarization beam splitters (PBSs), two optical couplers (OCs) and two photo detectors (PDs) are applied to directly up-convert the X- and Y-components of the optical signal to W-band and complete optical-to-electrical conversion (O/E). The X- and Y-components are respectively amplified by an electrical amplifier (EA) before being sent into 2 $\times$ 2 MIMO wireless link.

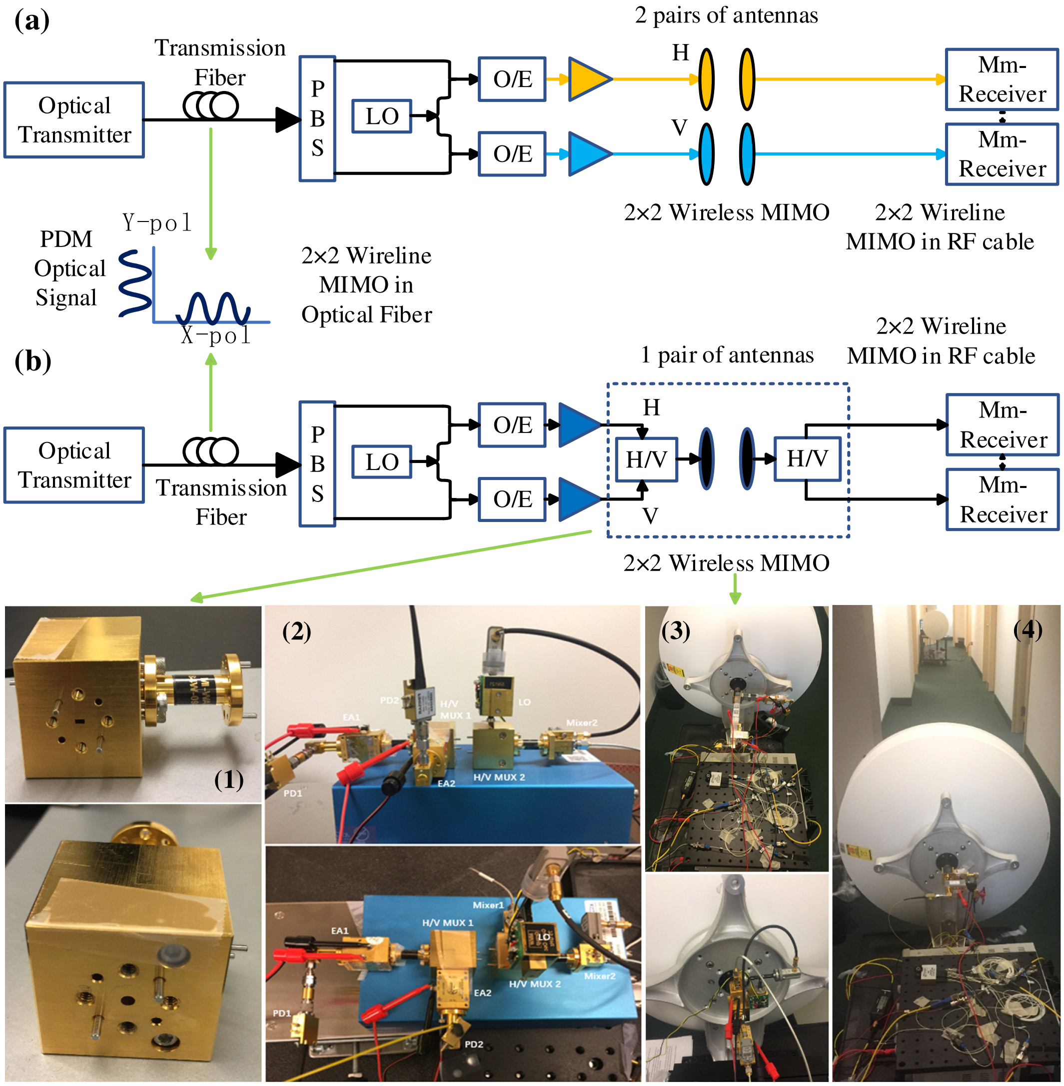


Fig. 1. (a) Principle of previous scheme. (b) Principle of proposed scheme. (1) Photos of ortho-mode transducer. (2) Photos of 0.6-cm wireless distance between ortho-mode transducer devices for the short-haul wireless scheme. (3) and (4) Photos of 13-m wireless distance between Cassegrain antennas connected with ortho-mode transducer device. PBS: polarization beam splitter, LO: local oscillator, O/E: optical-to-electrical convertor, H/V: polarization multiplexer/de-multiplexer.

The 2×2 MIMO wireless link contains a polarization multiplexer and an antenna at the transmitter as well as the other antenna and a polarization de-multiplexer at the receiver, in which the most significant improvement lies for the entire proposed system.

As shown in Fig. 1, compared with 2×2 antenna array in the previous FWI systems, the proposed construction adopts polarization multiplexing of only one pair of panel antennas with two ortho-mode transducer devices respectively horizontally and vertically polarized at the transmitter and the receiver for delivery of two polarization signals to make the network architecture simpler to be installed and maintained. Antenna polarization multiplexing doubles the transmission capacity of the proposed system and lowers the demands of signal baud rate and performance for optical and wireless devices.

Before being delivered by the two-polarization-direction antenna, two-polarization-direction signals are multiplexed by one polarization multiplexing device (H/V). In the receiver side, the other

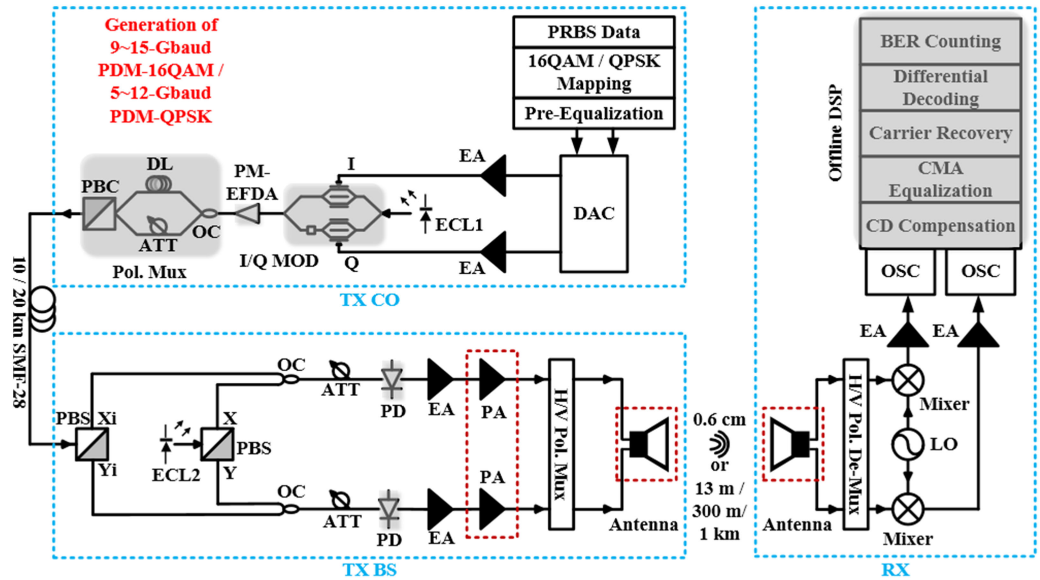


Fig. 2. Experimental setup for PDM-16QAM/PDM-QPSK modulated FWI transmission system at W-band. ECL: external cavity laser, DAC: digital-to-analog convertor, I/Q MOD: in-phase/quadrature (I/Q) modulator, PM-EDFA: polarization-maintaining Erbium-doped fiber amplifier, Pol. Mux: polarization multiplexer, PM-OC: polarization-maintaining optical coupler, DL: delay line, VOA: variable optical attenuator, PBC: polarization beam combiner, SMF: single-mode fiber, PBS: polarization beam splitter, OC: optical coupler, ATT: optical attenuator, PD: photonic detector, EA: electrical amplifier, PA: power amplifier, H/V Pol. Mux: H/V-polarization multiplexer, H/V Pol. De-Mux: H/V-polarization demultiplexer, LO: electrical local oscillator, OSC: real-time oscilloscope, TX CO: central office at the transmitter, TX BS: base station at the transmitter, RX: receiver.

identical antenna and polarization de-multiplexing device (H/V) are respectively used to receive and de-multiplex the two-polarization-direction signals before being detected by mm-wave receiver. For the short-haul wireless link scheme, one of two ortho-mode transducers is realistically employed as both the polarization multiplexer and the transmitter panel antenna while the other identical one is used as the receiver panel antenna and the de-multiplexer. As for the long-haul scheme, a pair of E-band Cassegrain antennas are introduced connected with the one of two ortho-mode transducers for higher gain.

At the wireless receiver, the first level of analog down-conversion for X- and Y-components is implemented in the mixer connected with an electrical LO to meet the bandwidth limitation of a subsequent digital oscilloscope (OSC) for analog-to-digital conversion (ADC). Further down-conversion operations are realized by the real-time OSC and the DSP block. DSP based constant modulus algorithm (CMA) is utilized for polarization de-multiplexing and crosstalk removal [9].

High-order modulation format is employed to enlarge system capacity because aggregate capacity can be enhanced by log (M) for M-ary communication systems in the light of Shannon expressions. In the proposed system, 16QAM for the short-haul wireless link scheme and QPSK for the long-distance scheme are adopted respectively for higher spectral efficiency (SE) and anti-jamming ability.

The generation of mm-wave frequencies based on photonic techniques is taken to overcome the bandwidth limitation of electrical components and effectively promote the seamlessly integrated wireless and fiber-optic networks.

3. Experimental Setup

The experimental setups for the short- and long-haul wireless delivery schemes are orderly elaborated in this section.

3.1 Demonstration of Short-Haul Wireless Delivery Scheme

The short-distance experiment setup is shown in Fig. 2 for high-speed transmission without bandwidth limitation, which excludes the components circled by the red dotted line.

Primarily, the isolation between the ortho-mode transducer devices used as a pair of panel antennas, H- and V-polarized respectively, is investigated experimentally. For single ortho-mode transducer device, the typical isolation is 30 dB, which is available in full bandwidth with 1.2:1 typical voltage standing wave ratio (VSWR). After pass through single ortho-mode transducer device, the average isolation is 27 dB.

At the transmitter, the lightwave with 1552.442-nm continuous wavelength (CW) emitted from the free-running ECL1 with linewidth of less than 100 KHz and output power of 14.5 dBm is first externally modulated by an I/Q modulator, driven by 9$\sim$15-Gbaud four-level electrical signal, I or Q component. The driving signal is a 16QAM signal generated by a pseudo random binary sequence (PRBS) with a length of 2^{14}-1, which is mapped with 16QAM, pre-equalized for the signal high-frequency component loss caused by EAs and I/Q modulator, converted by a digital-to-analog convertor (DAC) with 20-GHz electrical bandwidth and 80-GSa/s sampling rate, and amplified by an EA, orderly. The two parallel MZMs in the I/Q modulator are both biased at the null point and driven at the full swing.

After being amplified by a PM-EDFA and polarization multiplexed by a polarization multiplexer (Pol. Mux) composed of a PM-OC to separate the signal into two components, a variable optical DL to offer a delay of 100 symbols, a VOA to balance power of two components, and a PBC to recombine two components, a PDM-16QAM modulated optical baseband signal is generated. Subsequently, the generated PDM-16QAM modulated optical baseband signal is transmitted over 10 km SMF-28 which has average loss of 18 dB and chromatic dispersion (CD) of 17 ps/km/nm at 1550 nm in the absence of compensation for optical dispersion. The CW lightwave at 1551.766 nm emitted from ECL2 with linewidth of less than 100 KHz and output power of 14.5 dBm is employed as an optical LO. Two PBSs and two OCs are adopted for hybrid 90-degree polarization diversity of the received optical signal and the LO, implemented in optical domain before heterodyne beating. The X- and Y-polarization components after fiber transmission are discretional, which leads to a mix of both X- and Y- polarization signals existing at every output port of the PBS. The PDM-16QAM modulated optical baseband signal in either upper or lower path first directly passes through an optical attenuator (ATT) for power balance in case of generation of nonlinear effect in the subsequent PD. Then, a single-ended PD with 70-GHz 3-dB bandwidth and 1-dBm input power for optical-to-electrical conversion and up-conversion is adopted for the signal. Finally, the signal is amplified by a W-band low-noise EA with 0-dBm saturation output power, 25-dB gain, 90-GHz central frequency and 30-GHz 6-dB bandwidth. Thus, the generation of the PDM-16QAM modulated wireless mm-wave signal is done before delivery over a 0.6 cm 2×2 MIMO wireless link. For the proposed system, we make the ortho-mode transducer device a polarization multiplexer at the transmitter/demultiplexer at the receiver as well as a panel antenna without any additional antennas. By the two ortho-mode transducer devices, two orthogonal linearly-polarized signals are coupled or decoupled simultaneously at the transmitter or the receiver while polarization isolation is provided. The distance is kept 0.6 cm between the two WR-10 interfaced ortho-mode transducer devices with circular wave-guide flange, which means the wireless delivery distance is 0.6 cm. They are respectively used alone as a horizontally polarized panel antenna at the transmitter and a vertically polarized panel antenna at the receiver for avoidance of the crosstalk from the same antenna polarization.

At the receiver, two W-band parallel balanced mixers driven by the same electrical LO with 13-dBm output power and 75-GHz frequency are first employed to implement down-conversion in analog domain for the 100-GHz wireless mm-wave signals received and de-multiplexed by the ortho-mode transducer in both upper and lower paths. Then, it takes a 35-dB gain EA with DC$\sim$40-GHz operating range and 27-dBm saturation output power after each mixer to amplify the X- or Y-polarization component of the down-converted signal, before it is sent to the synchronous real-time digital OSC with 30-GHz electrical bandwidth and 80-GSa/s sampling rate for analog-to-digital conversion. Finally, offline baseband DSP is implemented after the OSC for clock recovery,

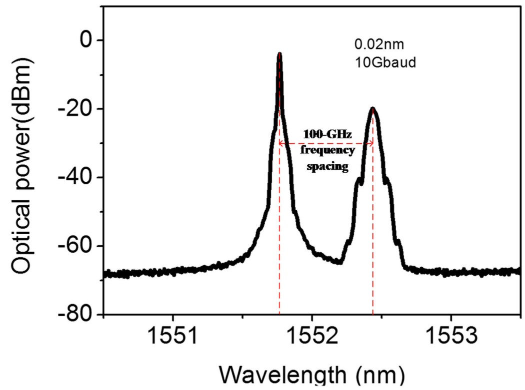


Fig. 3. Optical spectrum of signal and the LO after optical polarization diversity at the transmitter with 0.02 nm resolution.

down-conversion, CD compensation, CMA equalization, carrier recovery, differential decoding, and BER counting [18]–[26]. CMA equalization with the length longer than 81 taps is applied to de-multiplex polarization which ensures the BER less than 10^{-3} [9].

3.2 Demonstration of Long-Haul Wireless Delivery Scheme

As shown in Fig. 2 including parts of the highlighted components with red square dotted line, it is conspicuous that there are 2 major differences mentioned below between the short-distance wireless scheme and the long-haul setup with the wireless distance of 13 m. Firstly, for signal transmission rate and modulation format, 5$\sim$12-Gbaud QPSK is employed to substitute for 9$\sim$15-Gbaud 16QAM mapped from the original PRBS used as data stream. That is to say, QPSK mapping rather than QAM mapping is applied for modulation format. Secondly, a pair of 2-foot E-band Cassegrain antennas with higher gain of 48 dBi, with each antenna connected with an ortho-mode transducer, are deployed shown as insets 1 and 2 in Fig. 1. When it comes to 300-m and 1-km wireless link experimental setups, besides the two changes in the 13-m scheme, in either upper or lower path, a power amplifier (PA) with 30-dB gain and 20-dBm output power between the EA and the ortho-mode transducer as polarization multiplexer at the transmitter is added. Such experiments are implemented with the other devices and their parameters unchangeable. Note that for the 300-m and 1-km experiments, no obstacles exist between the two Cassegrain antennas with 2.5 m away from the ground.

4. Results and Discussion

In this part, the relevant results and diagrams of the experiments with our proposed schemes are respectively given and discussed.

4.1 Optical Spectrum of Signal and LO

The optical spectrum of the signal and the LO with 100-GHz frequency spacing and 20-dB power difference, after optical polarization diversity at the transmitter with 0.02-nm resolution, is shown in Fig. 3.

4.2 Electrical Spectra of PDM Signals

Fig. 4(a) and 4(b) respectively show the electrical spectra with pre-equalization detected by an OSC after down-conversion at the receive side, for Y-polarization of 10-Gbaud PDM-16QAM signal

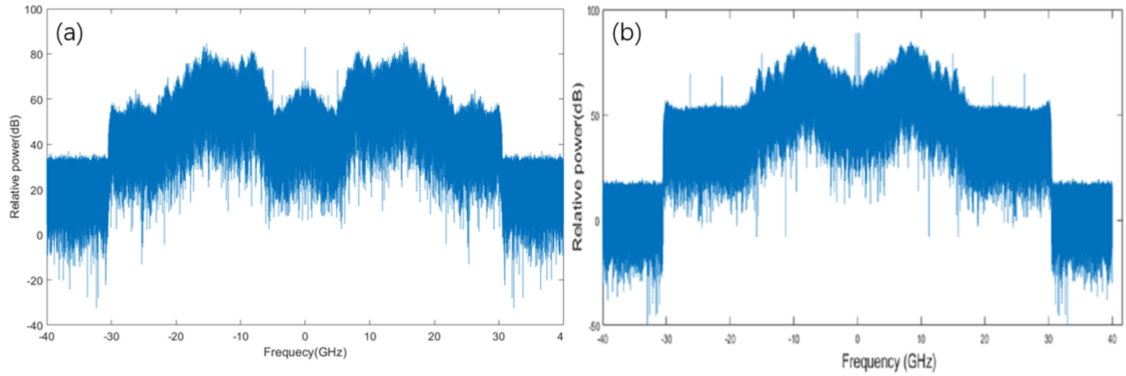


Fig. 4. Electrical spectra. (a) Y-polarization of 10-Gbaud PDM-16QAM signal. (b) Y-polarization of 10-Gbaud PDM-QPSK signal.

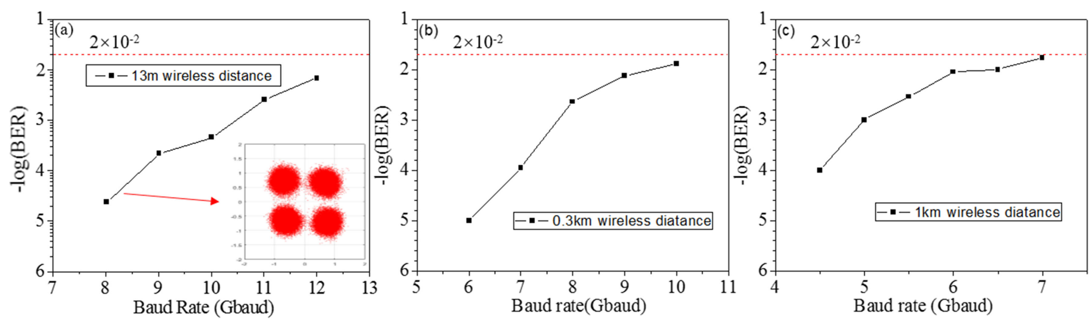


Fig. 5. BER versus transmission rate for PDM-QPSK signal over. (a) 13-m wireless link. (b) 300-m wireless link. (c) 1-km wireless link.

after 10-km SMF-28 transmission and 0.6-cm 2 × 2 MIMO wireless delivery and that of 10-Gbaud PDM-QPSK signal after 20-km SMF-28 transmission and 13-m 2 × 2 MIMO wireless link. The spectra for X-polarization of the signals are similar to their corresponding ones for Y-polarization.

4.3 Bit Error Ratio (BER) Performance

Figure 5(a)–(c) depict the relationship between BER and signal transmission rate for PDM-QPSK signal over 13-m, 300-m and 1-km wireless links in order.

Illustrated by Fig. 5(a) for 13-m wireless link scheme, the BER is 2.6×10^{-3} when the baud rate is 11 Gbaud. From the curve in Fig. 5(b), the BER is 2.3×10^{-3} at the signal baud rate of 8 Gbaud for 300-m wireless delivery scheme. As for the curve for 1-km wireless link scheme shown as Fig. 5(c), the corresponding BER is 2.9×10^{-3} if the signal baud rate is 5.5 Gbaud. Therefore, in order to keep BER less than 2×10^{-2}, 12-Gbaud signal at most can be provided in the 13-m wireless delivery scheme, and signal baud rate less than 10 Gbaud and 7 Gbaud can be applied respectively for 300-m and 1-km wireless link schemes.

Intuitively, as the baud rate grows, the BER increases. In other words, signal is not inappropriate to be delivered when it is too wide because the designed working frequency of the E-band Cassegrain antenna is 60∼90 GHz and the center frequency of the mm-wave is 84 GHz.

Insets (a) and (b) of Fig. 6 respectively indicate BER versus input power for 10-Gbaud PDM-16QAM signal delivered over 10-km fiber and 0.6-cm wireless link and 10-Gbaud PDM-QPSK signal delivered over 20-km fiber and 13-m wireless link under the condition of the electrical LO with 14.5-dBm output power.

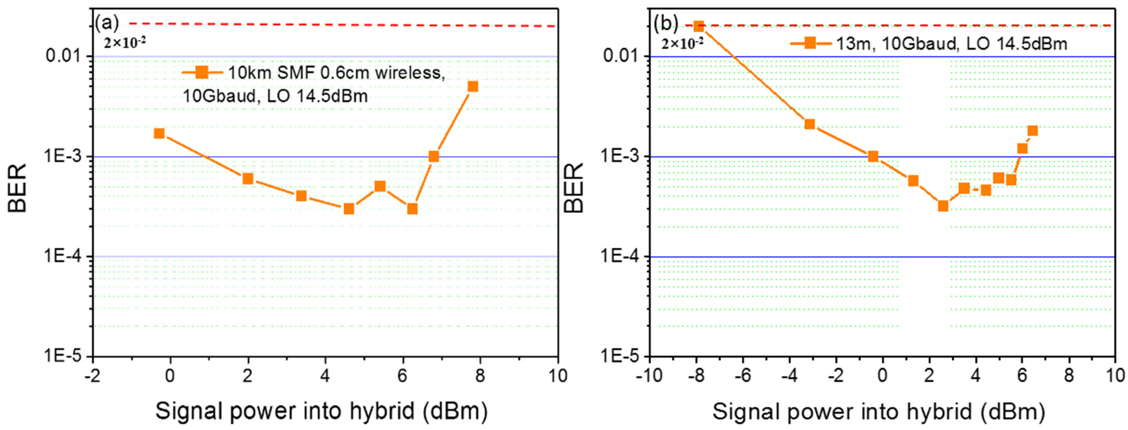


Fig. 6. BER versus input power. (a) The short-distance wireless link scheme (0.6 cm). (b) The long-distance wireless link scheme (13 m).

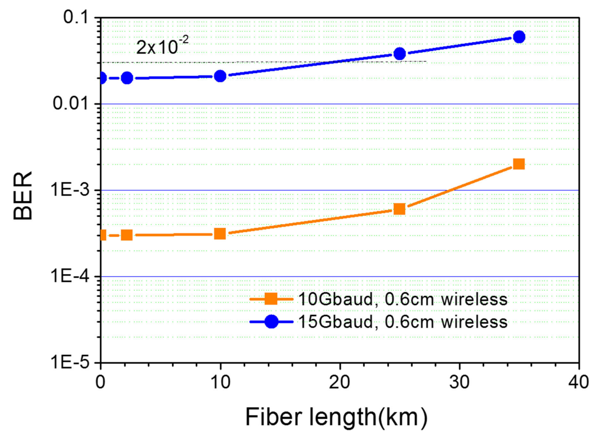


Fig. 7. BER versus fiber length for 10-Gbaud and 15-Gbaud PDM-16QAM signal.

Too large signal power will spell beat for the X- and Y-polarization optical signal in the PD which will generate nonlinear effect while too small power will lead to small signal to noise ratio at the receiver.

The values between 3.4 and 6.25 dBm for signal input power into hybrid are optimal for the 10-km SMF and 0.6-cm wireless link scheme while for the 20-km SMF and 13-m wireless delivery scheme, the value is 2.6 dBm, all of which can ensure the BER less than 10^{-3}.

By comparison of the curves obtained from the short- and long-haul wireless link schemes in Fig. 6(a) and 6(b), it can be calculated that at the same BER, 1.2-dB reduction at most for signal input power is done for the long-haul wireless delivery scheme, which contributes to superior tolerance to nonlinear effect.

The relationship of BER versus transmission length of fiber is shown in Fig. 7 with wireless delivery distance fixed at 0.6 cm, for 10-Gbaud (80-Gb/s) and 15-Gbaud (120-Gb/s) PDM-16QAM signal, in which the BER performance for 10-km fiber-length architecture less than the threshold for eFEC of 2×10^{-2} verifies the realization for the 15-Gbaud (120-Gb/s) PDM-16QAM delivery over 10-km fiber and 0.6-cm wireless communication system.

Insets 8(a) and 8(b) respectively exhibit BER versus CMA tap length for the 10-Gbaud PDM-16QAM signal over 10-km SMF-28 transmission and 0.6-cm 2×2 MIMO wireless delivery with 5-dBm input signal power and the 10-Gbaud PDM-QPSK signal over 20-km SMF-28 transmission

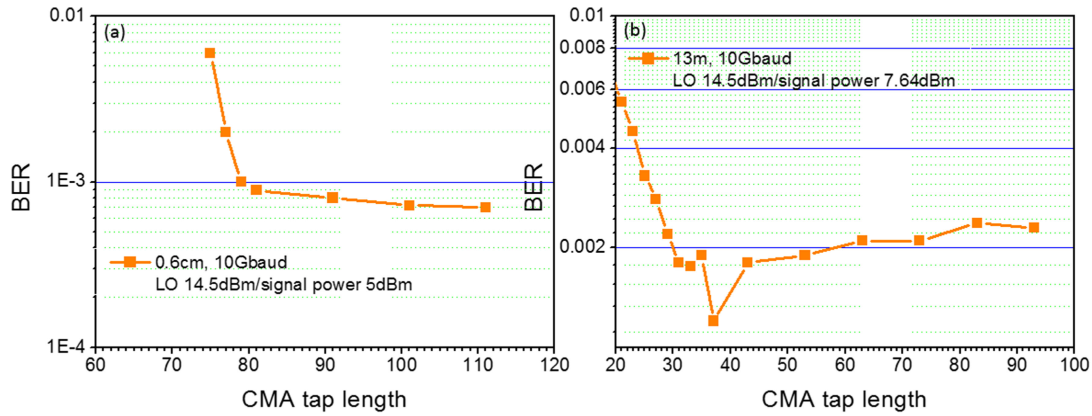


Fig. 8. BER versus CMA tap length at 10 Gbaud. (a) 0.6-cm wireless scheme with PDM-16QAM. (b) 13-m wireless scheme with PDM-QPSK.

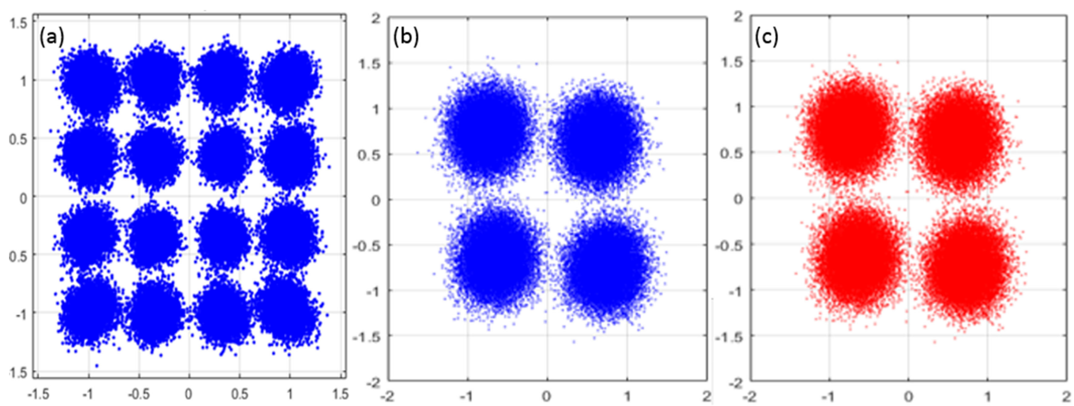


Fig. 9. Y-polarization constellation diagrams. (a) PDM-16QAM signal over 10-km SMF transmission and 0.6-cm wireless delivery. (b) and (c) PDM-QPSK signal over 20-km SMF transmission and 300-m/1-km wireless delivery.

and 13-m 2 $\times$ 2 MIMO wireless link with 7.64-dBm input power. For the 0.6-cm wireless delivery experiment, the CMA tap length larger than 81 is required for CMA equalization to guarantee BER less than 10^{-3}. In the 13-m wireless scheme, the optimal CMA tap length is 37. A properly larger CMA tap length is in need due to different-length fiber transmission for the optical signals before they are detected by the PD.

4.4 Received Constellation

As shown in Fig. 9(a)–(c), the Y-polarization constellation diagrams for the PDM-16QAM signal over 0.6-cm wireless delivery, the PDM-QPSK signal over 300-m and 1-km wireless deliveries are respectively represented. The constellation diagrams for X-polarization of the signals are similar to those for Y-polarization. Evidently, the PDM signals with short- and long-distance wireless link schemes can realize delivery by antenna polarization multiplexing based on the received constellation diagrams.

5. Conclusion

By antenna polarization multiplexing and photonic mm-wave generation techniques, the FWI transmission system at W-band, simpler to be installed and maintained, is experimentally demonstrated with the BER less than eFEC threshold of 2×10^{-2} with assistance of CMA equalization. In the scheme of the short-haul wireless delivery, up to 120-Gb/s (9∼15-Gbaud) PDM-16QAM signal delivery is realized over 10-km SMF-28 and 0.6-cm 2×2 MIMO wireless link. For the long-distance wireless scheme, 40-Gb/s (5∼12-Gbaud) PDM-QPSK signal is employed to be delivered over 20-km SMF-28 and 13-m/300-m/1-km 2×2 MIMO wireless link, respectively. The proposed system enabled by antenna polarization multiplexing with average isolation of 27 dB doubles the transmission capacity and diminished the demands of signal baud rate and performance for optical and wireless devices.

References

[1] X. Pang et al., "100 Gbit/s hybrid optical fiber-wireless link in the W-band (75-110 GHz)," *Opt. Exp.*, vol. 19, no. 25, pp. 24944–24949, 2011.
[2] D. Zibar et al., "High-capacity wireless signal generation and demodulation in 75- to 110-GHz band employing all-optical OFDM," *IEEE Photon. Technol. Lett.*, vol. 23, no. 12, pp. 810–812, Jun. 2011.
[3] A. Kanno et al., "Optical and radio seamless MIMO transmission with 20-Gbaud QPSK," in *Proc. 38th Eur. Conf. Exhib. Opt. Commun.*, 2012, Paper We.3.B.2.
[4] S. Koenig et al., "100 Gbit/s wireless link with mm-wave photonics," in *Proc. Opt. Fiber Commun. Conf. Expo. Nat. Fiber Optic Engineers Conf.*, 2013, Paper PDP5B.4.
[5] T. Nagatsuma et al., "Terahertz wireless communications based on photonics technologies," *Opt. Exp.*, vol. 21, no. 20, pp. 23736–23747, 2013.
[6] A. J. Seeds et al., "Coherent terahertz photonics," *Opt. Exp.*, vol. 21, no. 19, pp. 22988–23000, 2013.
[7] C. T. Lin et al., "2×2 MIMO radio-over-fiber system at 60 GHz employing frequency domain equalization," *Opt. Exp.*, vol. 20, no. 1, pp. 562–567, 2012.
[8] J. Yu, X. Li, and N. Chi, "Faster than fiber: Over 100-Gb/s signal delivery in fiber wireless integration system," *Opt. Exp.*, vol. 21, no. 19, pp. 22885–22904, 2013.
[9] X. Li, J. Yu, Z. Dong, J. Zhang, N. Chi, and J. Yu, "Investigation of interference in multiple-input multiple-output wireless transmission at W band for an optical wireless integration system," *Opt. Lett.*, vol. 38, no. 5, pp. 742–744, 2013.
[10] J. Zhang, J. Yu, N. Chi, Z. Dong, X. Li, and G. K. Chang, "Multichannel 120-Gb/s data transmission over 2×2 MIMO fiber-wireless link at W-band," *IEEE Photon. Technol. Lett.*, vol. 25, no. 8, pp. 780–183, Apr. 2013.
[11] X. Li, J. Yu, J. Zhang, Z. Dong, and N. Chi, "Doubling transmission capacity in optical wireless system by antenna horizontal- and vertical-polarization multiplexing," *Opt. Lett.*, vol. 38, no. 12, pp. 2125–2127, 2013.
[12] X. Li, Z. Dong, J. Yu, N. Chi, Y. Shao, and G. K. Chang, "Fiber-wireless transmission system of 108 Gb/s data over 80 km fiber and 2×2 multiple-input multiple-output wireless links at 100 GHz W-band frequency," *Opt. Lett.*, vol. 37, no. 24, pp. 5106–5108, 2012.
[13] Z. Dong, J. Yu, X. Li, G. K. Chang, and Z. Cao, "Integration of 112-Gb/s PDM-16QAM wireline and wireless data delivery in millimeter wave RoF system," in *Proc. Opt. Fiber Commun. Conf. Expo. Nat. Fiber Optic Engineers Conf.*, 2013, Paper OM3D.2.
[14] X. Li, J. Yu, J. Zhang, Z. Dong, F. Li, and N. Chi, "A 400G optical wireless integration delivery system," *Opt. Exp.*, vol. 21, no. 16, pp. 18812–18819, 2013.
[15] X. Li, J. Yu, N. Chi, and J. Zhang, "Optical-wireless-optical full link for polarization multiplexing quadrature amplitude/phase modulation signal transmission," *Opt. Lett.*, vol. 38, no. 22, pp. 4712–4715, 2013.
[16] X. Li, J. Yu, Z. Cao, J. Zhang, F. Li, E. Tangdiongga, and G. K. Chang, "Ultra-high-speed fiber-wireless-fiber link for emergency communication system," in *Proc. Opt. Fiber Commun. Conf.*, 2014, Paper M3D.6.
[17] X. Li, J. Yu, J. Xiao, and Y. Xu, "Fiber-wireless-fiber link for 128-Gb/s PDM-16QAM signal transmission at W-band," *IEEE Photon. Technol. Lett.*, vol. 26, no. 19, pp. 1948–1951, Oct. 2014.
[18] J. Yu et al., "Transmission of 200 G PDM-CSRZ-QPSK and PDM-16 QAM with a SE of 4 b/s/Hz," *J. Lightwave Technol.*, vol. 31, no. 4, pp. 515–522, Feb. 2013.
[19] J. Zhang et al., "Simplified coherent receiver with heterodyne detection of eight-channel 50 Gb/s PDM-QPSK WDM signal after 1040 km SMF-28 transmission," *Opt. Lett.*, vol. 37, no. 19, pp. 4050–4052, 2012.
[20] J. Yu and X. Zhou, "Ultra-High-Capacity DWDM transmission system for 100G and beyond," *IEEE Commun. Mag.*, vol. 48, no. 3, pp. S56–S64, Mar. 2010.
[21] X. Li and J. Yu, "2×2 multiple-input multiple-output optical-wireless integration system based on optical independent-sideband modulation enabled by an in-phase/quadrature modulator," *Opt. Lett.*, vol. 41, no. 13, pp. 3138–3141, 2016.
[22] X. Li, Y. Xu, and J. Yu, "Single-sideband W-band photonic vector millimeter-wave signal generation by one single I/Q modulator," *Opt. Lett.*, vol. 41, no. 18, pp. 4162–4165, 2016.
[23] J. Yu, "Photonics-Assisted millimeter-wave wireless communication," *IEEE J. Quantum Electron.*, vol. 53, no. 6, Dec. 2017, Art. no. 8000517.
[24] X. Li et al., "QAM vector signal generation by optical carrier suppression and precoding techniques," *IEEE Photon. Technol. Lett.*, vol. 27, no. 18, pp. 1977–1980, Sep. 2015.
[25] X. Li, J. Yu, and J. Xiao, "Demonstration of ultra-capacity wireless signal delivery at W-band," *IEEE/OSA J. Lightw. Technol.*, vol. 34, no. 1, pp. 180–187, Jan. 2016.
[26] X. Li et al., "Delivery of 54-Gbps 8QAM W-band signal and 32-Gbps 16QAM K-band signal over 20-km SMF-28 and 2500-m wireless distance," *IEEE/OSA J. Lightw. Technol.*, vol. 36, no. 1, pp. 50–56, Jan. 2018.