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# Over 100 Gb/s mm-wave delivery with 4600 m wireless distance based on dual polarization multiplexing

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With the rapid development of network services and the emergence of emerging technologies such as big data, Internet of vehicles, and 5G communications, the traffic of digital mobile devices and various network services has increased dramatically, which puts forward higher requirements on the transmission capacity and wireless distance of data communication [1–3]. Radio over fiber (ROF) technology is an emerging wireless broadband access technology that integrates the advantages of fiber optic communication with large bandwidth and anti-electromagnetic interference, as well as the advantages of wireless mobile communication with low cost and good mobility [4–10]. As shown in Figure 1(a), the basic architecture of an ROF system usually consists of central stations and base stations. In the central station, the data is modulated onto the optical carrier through an electro-optical modulator (Mod), and the modulated signals are subjected to a series of changes and processing in the optical domain. Then the processed optical signals are transmitted to the base station employing fiber optic remote technology. In the base station, a photodiode (PD) is used to convert the optical signals into electrical signals, and the antennas are used to propagate the radio wave signals.

*Research target.* Recently, we have made significant strides in achieving high-speed wireless millimeter wave signal transmission utilizing the photonics-aided ROF system, particularly in the W-band (75–110 GHz). More specifically, we have been able to achieve data transmission of 80 Gb/s over a 300 m point-to-point wireless link [5], 20 Gb/s over a 1700 m link [6], 54 Gb/s over a 2500 m link [7], and 47.5 Gb/s over a 4600 m link [8]. Despite these impressive results, it is worth noting that the wireless distance in the aforementioned demonstrations is relatively short, and communication capacity remains relatively low. More importantly, the systems all have relatively low spectral efficiency (SE). In this study, we have experimentally built a W-band communication system based on dual-polarization multiplexing that can achieve 119 Gb/s net data rate transmission over 4600 m with SE of 9.9 bit/s/Hz.

*Framework.* Polarization division multiplexing (PDM) technology is one of the technical approaches to solve the shortage of communication frequency band resources, which can realize frequency band reuse. The same antenna emits two different polarized waves of the same frequency, and different polarized waves can carry different information. In order to reduce the mutual interference of the two polarized waves, the orthogonally polarized waves are usually selected. PDM technology can not only increase the communication capacity but also significantly improve SE [9]. Figure 1(b) displays the framework of our proposed dual-polarization multiplexing communication system. The critical components of the system include a pair of transmitters, receivers, ortho-mode transducers (OMTs) and conical antennas (CAs). First, the transmitter1 (TX1) emits the $x$-polarized waves into the vertical channel (Ch.V). The transmitter2 (TX2) emits the $y$-polarized waves into the horizontal channel (Ch.H). As shown in the insets of Figure 1(b), the directions of $x$-polarized and $y$-polarized waves are mutually orthogonal. Then, the linearly polarized waves of Ch.V and Ch.H are transmitted into an ortho-mode transducer (OMT1) for polarization multiplexing to generate dual-polarized signals. It is worth noting that the OMTs can be used to couple two orthogonal linearly polarized signals simultaneously while providing polarization isolation between the transmitter and receiver. The dual-polarized signals output from OMT1 are transmitted into the wireless space through a conical antenna (CA1). After the wireless transmission, the dual-polarized wireless signals are received

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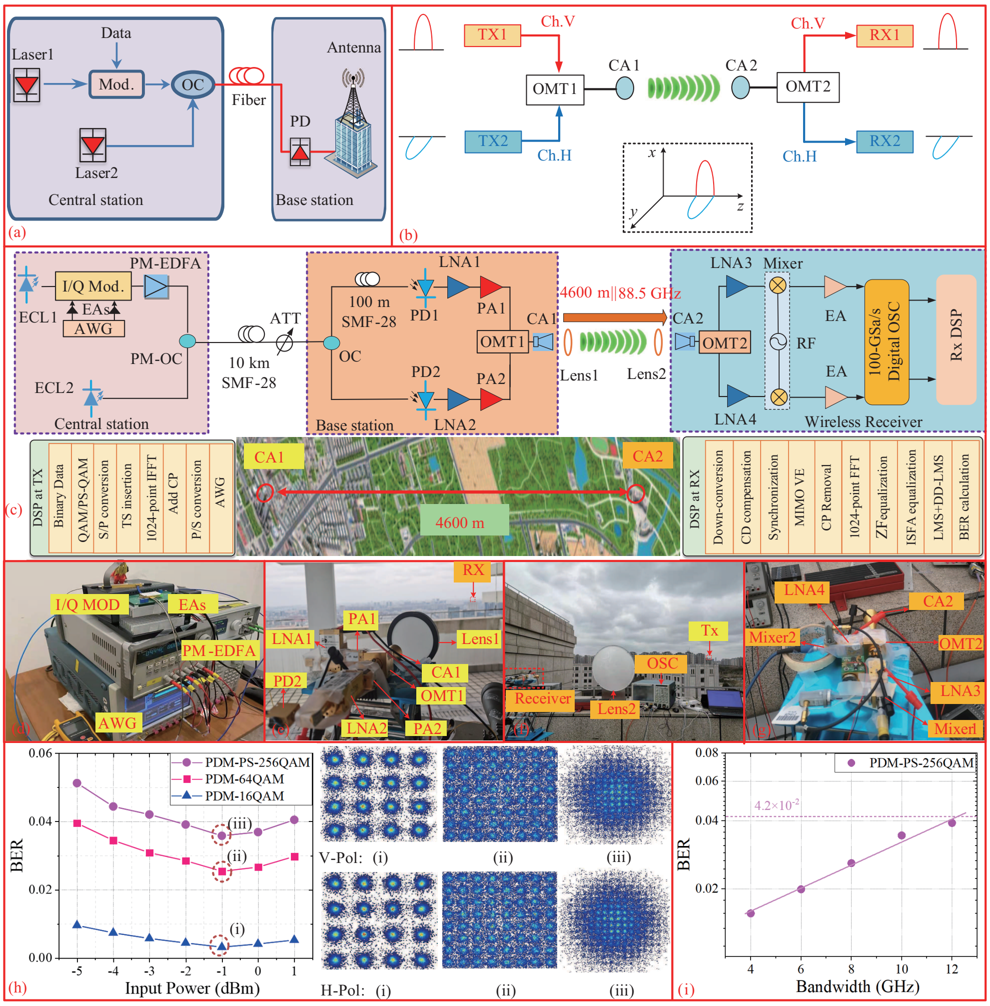

**Figure 1** (Color online) (a) Basic architecture of a ROF system. (b) Framework of our proposed dual-polarization multiplexing wireless communication system. (c) Arrangement of the PDM point-to-point transmission system setup in the W-band. Scenes of the transmitter side in this experiment: (d) the central station; (e) the base station. Scenes of the receiver side of the wireless link in this experiment: (f) the receiver side; (g) the wireless receiver. (h) BER versus input optical power of PDs for 10 GHz signals. (i) BER versus bandwidth for PDM-PS-256QAM signals.

by the other conical antenna (CA2). Then the received signals are de-multiplexed into Ch.V and Ch.H by the other ortho-mode transducer (OMT2). Finally, the linearly polarized signals of Ch.V and Ch.H are received by receiver1 (RX1) and receiver2 (RX2), respectively.

*Experimental setup.* Figure 1(c) illustrates the arrangement of the PDM point-to-point transmission system setup in the W-band [10]. In the central station, a pair of external cavity lasers (ECLs) referred to as ECL1 and ECL2 with linewidths < 100 kHz emit continuous waves with a frequency separation of 88.5 GHz. We use Matlab software to generate orthogonal frequency division multiplexing (OFDM) signals in the electrical domain offline [8]. Then the OFDM signals are loaded into an arbitrary waveform generator (AWG). In the I/Q mod, the continuous waves generated by the ECL1 are modulated by the OFDM signals output by the AWG. A polarization-maintaining Erbium-doped fiber amplifier (PM-EDFA) is utilized to compensate for the insertion loss of the I/Q mod. The polarization-maintaining optical coupler (PM-OC) is utilized to connect the compensated optical signals with the continuous waves generated by ECL2.

The coupled optical signals are transmitted over 10 km single mode fiber-28 (SMF-28). An optical attenuator (ATT) undertakes the function of adjusting the power of optical signals in the optical fiber before entering the base station. Next, an OC is used to divide the optical signals output by the ATT into two paths. The signals in one of the paths enter 100 m SMF-28 acting as an optical delay line (DL), which can eliminate the correlation between two paths by providing over 1000 symbols delay. The optical signals are converted to the H-polarized millimeter waves by PD1. A low noise amplifier (LNA1, gain 30 dB) and a power amplifier (PA1, output 16 dBm) are used to amplify the electrical millimeter wave. The signals produced by PD2 are also enhanced by the combination of a low noise amplifier (LNA2, gain 30 dB) and a power amplifier (PA2, output 16 dBm) in the other path. After that, the boosted V-polarized signals and the H-polarized signals are multiplexed by OMT1. Figures 1(d) and (e) display the scenes of the transmitter side in this experiment.

The dual-polarized millimeter waves are transmitted to the wireless space through CA1 with a gain of 25 dBi and Lens1 with a gain of 9 dBi. After that, the wireless signals are transmitted over a point-to-point wireless link up to 4600 m. In the wireless receiver, the combination of CA2 and Lens2 with a total gain of 56 dBi is used to receive radio wave signals. Subsequently, the received signals are divided into the H-polarized and V-polarized signals by OMT2. The signals in the two polarization directions are amplified by LNAs with 30 dB gain, respectively. They are then down-converted by mixers driven by a radio frequency (RF) source with 75 GHz to generate 13.5 GHz intermediate frequency (IF) signals. Before the digital storage oscilloscope (OSC), the IF signals are amplified by EAs with a gain of 26 dB. Figures 1(f) and (g) display the scenes of the receiver side of the wireless link in this experiment.

The digital signal processing (DSP) algorithms at the receiving side mainly include I/Q multiple-input and multiple-output (MIMO) Volterra equalizer (VE), zero-forcing (ZF) equalization, the intra-symbol frequency-domain averaging (ISFA), cascaded least mean squares (LMS) and decision-directed least mean squares (DD-LMS) algorithms.

The Friis formula is as follows:

$$P_R = P_T + G_T + G_R - 20\log\frac{4\pi df}{c} - L_m,$$

where $P_T$ represents the transmit power with a value of 16 dBm, $G_T$ represents the transmit antenna gain with a value of 34 dBi, and $G_R$ is the receive antenna gain with a value of 56 dBi. $d$ represents the wireless distance with a value of 4.6 km. $c$ represents the light speed. $L_m$ stands for atmospheric loss. This experiment was conducted on a sunny day with a temperature of 3°C and a humidity of 25%. Therefore, the atmospheric loss $L_m$ over a 4600 m wireless link at 88.5 GHz is 2.3 dB. After calculation, the estimated received power $P_R$ is $-40.93$ dB. In our experiment, the measured received power is $-41.96$ dBm. Considering the insertion loss between devices, the actual received wireless signal power is close to the power budget result.

*Measurement results.* The three curves in Figure 1(h) show the bit error rate (BER) versus input optical power of PDs for 10 GHz PDM 16-ary quadrature-amplitude-modulation (PDM-16QAM, 8 bit/symbol), PDM 64-ary quadrature-amplitude-modulation (PDM-64QAM, 12 bit/symbol) and PDM probabilistic-shaped 256-ary quadrature-amplitude-modulation (PDM-PS-256QAM, 14.14 bit/symbol). Gradually, the BER of three kinds of signals decreases because the signal-to-noise ratio (SNR) of the system improves when the input optical power exhibits a raise from $-5$ to $-1$ dBm. However, the BER of signals increases instead with increasing input power because the PDs and LNAs are affected by the saturation effect. The insets (i)–(iii) in Figure 1(h) respectively show the signal constellations of three kinds of signals in the vertical-polarization (V-pol) and horizontal polarization (H-pol) direction with $-1$ dBm input optical power.

Figure 1(i) displays the curve illustrating the relationship between BER and bandwidth of the transmitted signals with $-1$ dBm optical power for PDM-PS-256QAM signals. As the bandwidth of signals increases, there is a subsequent increase in BER of signals. In order to keep the BER of PDM-PS-256QAM signals less than the 25% forward error correction (FEC) threshold of $4.2 \times 10^{-2}$, the maximum bandwidth of signals is 12 GHz with the BER of $3.89 \times 10^{-2}$. Note that we adopted LNAs and PAs with better performance in this experiment, which enables the system to support larger bandwidth [8]. In the experimental operation, we have carried out a finer operation to keep the main lobe direction of the receiving antenna and the transmitting antenna on the same axis as possible. Meanwhile, we optimized the position between the lens and CA. All of the above contribute to the improvement of system performance.

The fast Fourier transformation (FFT) points and inverse fast Fourier transformation (IFFT) points of OFDM are all 1024, and the cyclic prefix (CP) length is 64. From the 1024 subcarriers, 990 subcarriers are active and the others are set to null. When the bandwidth of the transmitted signals is 12 GHz, the subcarrier spacing of OFDM data is 0.011 GHz and 990 subcarriers are active excluding CP in each frame of OFDM data. Each frame of OFDM data is composed of twenty-eight symbols, where one of the symbols is allocated for use as a training symbol (TS). Therefore, the data rate of the communication system is $0.011 \times 990 \times 14.14 \times 27/28 = 148.5$ Gb/s. Considering the 25% FEC overhead, the maximum net rate and SE are 119 Gb/s and 9.9 bit/s/Hz, respectively.

*Conclusion.* A high-speed long-haul W-band wireless transmission system based on dual-polarization multiplexing has been demonstrated, which can realize up to 119 Gb/s wireless delivery over a 4600 m link at 88.5 GHz. This achievement pushes the W-band ROF technology closer to the practical deployment of high-speed B5G and 6G wireless communication.

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**Supporting information** Videos and other supplemental documents. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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