We experimentally demonstrate a W-band optical-wireless transmission system over 160-m wireless distance with a bit rate up to 40 Gb/s. The optical-wireless transmission system adopts optical polarization-division-multiplexing (PDM), multiple-input multiple-output (MIMO) reception and antenna polarization diversity. Using this system, we experimentally demonstrate the 2 × 2 MIMO wireless delivery of 20- and 40-Gb/s PDM quadrature-phase-shift-keying (PDM-QPSK) signals over 640- and 160-m wireless links, respectively. The bit-error ratios (BERs) of these transmission systems are both less than the forward-error-correction (FEC) threshold of 3.8 × 10⁻³.

Not only high-speed but also long-haul wireless transmission links are required in order to meet the demand of mobile backhauling between the wireless macro stations as well as emergency services when large-capacity long-haul optical cables are cut during natural disasters such as earthquakes and tsunamis [1]. Recently, the W-band (75–110 GHz), with inherent wider bandwidth available at higher frequencies, has attracted increasing interest as a candidate radio-frequency (RF) band to provide multi-gigabit wireless links for mobile data transmission [1–9]. Meanwhile, the W-band has relatively small atmospheric loss [10] and good directionality, and is thus a potential RF band to offer long-haul wireless links for mobile data transmission as well. It is well known that it is challenging to generate millimeter-wave (mm-wave) frequencies at W-band based on bandwidth-limited electrical components. A more attractive solution for W-band mm-wave generation would be the employment of photonic techniques, which can also effectively promote the seamless integration of wireless and fiber-optic networks. Experimentally demonstrated 100-Gb/s and 400-Gb/s wireless signal delivery at W-band were reported adopting photon mm-wave generation, but the wireless transmission distance is no more than 2 m [5–9]. Up to 15-m wireless signal delivery at W-band was also reported at the cost of a relatively low bit rate of 50 Gb/s [6]. It is evident that, however, even tens of meters of wireless transmission distance cannot effectively meet the demand of the aforementioned mobile backhauling and emergency communications.

In this Letter, we propose and experimentally demonstrate a high-speed long-haul wireless transmission link at W-band enabled by photonic mm-wave generation and antenna polarization diversity, which can support 40-Gb/s polarization-division-multiplexing quadrature-phase-shift-keying (PDM-QPSK) signal wireless transmission over 160 m and 20-Gb/s PDM-QPSK signal wireless transmission over 640 m. The mm-wave wireless signals are generated by heterodyne mixing of an optical PDM-QPSK signal with a free-running lightwave at different wavelengths, and after 20-km single-mode fiber-28 (SMF-28) transmission, delivered over a 2 × 2 multiple-input multiple-output (MIMO) wireless link. Analog down-conversion and coherent demodulation are performed for the received mm-wave signals at the receiver. The product of the transmission distance and the bit rate is 6400 Gb · m/s or 12800 Gb · m/s, which is a record number for optical-wireless integration transmission to the best of our knowledge.

The experimental setup for the PDM-QPSK signal transmission optical wireless system at W-band is shown in Fig. 1. At the transmitter central office (CO), the optical QPSK signal is generated by an in-phase/quadrature (I/Q) modulator driven by an electrical binary data with a pseudo-random binary sequence (PRBS) length of 2¹⁵ – 1. The tunable external cavity laser 1 (ECL1) used as an optical source has a linewidth of about 100 kHz and an operating wavelength of 1548.691 nm. The two parallel Mach–Zehnder modulators (MZMs) in the I/Q modulator are both biased at the null point and driven at the full swing to achieve zero-chirp 0- and π-phase modulation. The phase difference between the upper and lower branches of the I/Q modulator is controlled at π/2. Then the generated optical QPSK signal is amplified by a polarization-maintaining Erbium-doped fiber amplifier (EDFA) and polarization multiplexed by a polarization multiplexer (PM). The PM is composed of a polarization-maintaining optical coupler (OC) to halve the signal into two branches, an optical delay line to provide a 150-symbol delay, an optical attenuator to balance the power of two branches, and a polarization beam combiner to recombine the signals. The generated PDM-QPSK optical baseband signal is launched into 20-km SMF-28, which has 5-dB fiber loss. At the transmitter base station (BS), ECL2 (with a linewidth of about 100 kHz) at 1549.3750 nm functions as a local oscillator (LO), and has a frequency offset of 85.5 GHz relative to the wavelength of ECL1. Two polarization beam splitters (PBSs) are adopted to realize polarization separation of the optical PDM-QPSK signal and local free-running light. The diversity optical PDM-QPSK signal and LO is
heterodyne beat through two OCs, enabling the mm-wave at a frequency of 85.5 GHz.

Then, two optical mm-wave signals are converted into two electrical mm-wave signals by two photo detectors (PDs) (90-GHz 3-dB bandwidth). The two electrical mm-wave signals pass through two parallel 100-GHz narrowband electrical amplifiers (both denoted by EA1 and manufactured by Ducommun) each with 23-dB gain and 4-dBm saturation output power [11,13], and then are simultaneously sent into a $2 \times 2$ MIMO wireless link based on antenna polarization diversity (H- and V-polarization). That is, one pair of transmitter and receiver cassegrain antennas (CAs) is horizontally polarized, while the other pair is vertically polarized. Each CA has 2-foot diameter, 50.8-dBi gain, and 0.4-deg half-power-beamwidth. The wireless transmission distance is variable from 80 to 640 m. Because of the large antenna polarization isolation between H- and V-polarization CAs (35 dB), the adoption of antenna polarization diversity effectively avoids wireless crosstalk and offers an easy CA installation and adjustment [8]. We finished this field demonstration in Handan Campus of Fudan University. We put the antenna on the ground with very flat area over 800-m straight-line distance from east to west [see the Google map shown in Fig. 2(a)]. The transmitter antennas are put on a moving car with 1.5-m height, while the position of the receiver antennas is fixed. A picture of the antennas in RX is shown in Fig. 2(b). Note that the received wireless signal is sensitive to the antenna position, and the degree of the sensitivity depends on the wireless transmission distance. With the increase of the wireless transmission distance, the received wireless signal becomes less sensitive to the antenna position because of larger wireless coverage range.

The X- and Y-polarization wireless links are parallel, and two transmitter (receiver) CAs have a 1.1-m separation. At the receiver, the received mm-wave signal is amplified by two parallel W-band electrical amplifiers (both denoted by EA2 and manufactured by Ducommun) with 35-dB gain, 100-GHz 3-dB bandwidth, 4-dBm saturation output power, and 4.5-dB noise figure. Figure 3 shows the frequency response of EA1 and EA2. Then the 85.5-GHz wireless mm-wave signal is down-converted into a 10.5-GHz electrical intermediate-frequency (IF) signal in analog domain. For the X- and Y-polarization branches, a 12.5-GHz sinusoidal radio-frequency (RF) signal first passes through an active frequency doubler ($\times 2$) and an EA in serial, and then is halved into two branches by a power divider. Next, each branch passes through a passive frequency tripler ($\times 3$) and an EA in serial. As a result of this cascaded frequency doubling, an equivalent 75-GHz RF signal is provided for each mixer. Each RF mixer, manufactured by Quinstar, has 7-dB conversion loss and 30-GHz bandwidth. Thus, two IF signals at $f_{\text{IF}} = 10.5$ GHz are obtained after analog down-conversion. Each IF signal is amplified by a band-pass low-noise amplifier (denoted by EA3, and has 35-dB gain, 22-dBm saturation output power and 40-GHz bandwidth) after the mixer. The analog-to-digital conversion is achieved using a 2-channel real-time digital oscilloscope (OSC) with the sampling rate of 50 GSa/s and the

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**Fig. 1.** Experimental setup for the PDM-QPSK signal transmission optical wireless system at W-band.

**Fig. 2.** (a) Aerial photograph of 640-m straight-line link range at Handan Campus in Fudan University. (b) Picture of antennas in RX.

**Fig. 3.** Frequency response of EA1 (black) and EA2 (red).
electrical bandwidth of 16 GHz. The captured data is then post-processed offline using a desktop computer.

According to the Friis transmission equation, we estimate the received power for a given transmit power $P_T$, the gains of antennas, and the transmission distance $d$. The received power $P_R$ is given by

$$P_R(\text{dB}) = P_T + G_T + G_R - 20 \log(4\pi d / \lambda) - L_F - L_A \times d,$$

(1)

where $\lambda$ is the transmission wavelength, $G_T$ and $G_R$ are respectively the transmit and receive antenna gain, and $L_F$ is the loss of antenna feedline. $L_A$ is the atmospheric loss factor. $L_A$ at W-band is 0.5 dB/km [10]. The atmospheric loss can be ignored when the wireless transmission distance reaches hundreds of meters. In our experiment, $P_T$ is 4 dBm, $G_T$ and $G_R$ are both 50.8 dBi, and $L_F$ is 3 dB, which results in the predicted received power of −6.54, −12.56, and −24.60 dBm over a range of 80, 160, and 640 m at an 85.5-GHz center frequency, respectively.

Note that the wireless transmission distance is mainly limited by the limited transmit power and limited receiver sensitivity at the receiver. The adopted devices, such as CA, amplifier, mixer, and PD, can also limit the wireless transmission distance in some degree due to limited bandwidth, limited gain, and other imperfect characteristics.

Figure 4 shows the optical spectrum (0.01-nm resolution) after heterodyne beating at the transmitter BS. 85.5-GHz frequency spacing exists between the signal and the LO. Figures 5(a) and 5(b) show the received X-polarization electrical spectrum for the 40-Gb/s PDM-QPSK signal 2 × 2 MIMO wireless delivery over 160 m and 20-Gb/s PDM-QPSK signal 2 × 2 MIMO wireless delivery over 640 m after analog down-conversion, respectively. The corresponding received optical power is 5.5 dBm.

Figures 6(a)–6(e) show the measured X-polarization constellations for the 40-Gb/s PDM-QPSK signal over 160-m wireless and 20-km SMF transmission when the received optical power is 5.5 dBm before clock extraction, after clock extraction, after CMA equalization with tap length of 21, after frequency-offset estimation (FOE), and after carrier phase estimation (CPE), respectively. The corresponding BER is $2.59 \times 10^{-3}$. Figures 6(f)–6(j) show the measured Y-polarization constellations for the 20-Gb/s PDM-QPSK signal over 640-m wireless and 20-km SMF transmission when the received optical power is 5.5 dBm before clock extraction, after clock extraction,

Fig. 4. Optical spectrum (0.01-nm resolution) after polarization diversity at the transmitter BS.

Fig. 5. Electrical spectrum after analog down-conversion for (a) the 40-Gb/s PDM-QPSK signal wireless delivery over 160 m and (b) 20-Gb/s PDM-QPSK signal wireless delivery over 640 m.

Fig. 6. Received X-polarization constellations for 40-Gb/s PDM-QPSK signal wireless delivery over 160 m: (a) before clock extraction, (b) after clock extraction, (c) after CMA equalization, (d) after FOE, and (e) after CPE. Received Y-polarization constellations for 20-Gb/s PDM-QPSK signal wireless delivery over 640 m: (f) before clock extraction, (g) after clock extraction, (h) after CMA equalization, (i) after FOE, and (j) after CPE.

Fig. 7. BER versus the wireless transmission distance for 40-, 36-, 32-, and 20-Gb/s PDM-QPSK signals. Insets (a) and (b) give the received constellations at the BERs of $1 \times 10^{-3}$ and $4 \times 10^{-4}$, respectively.
after CMA equalization with tap length of 21, after FOE, and after CPE, respectively. The corresponding BER is $2.8 \times 10^{-3}$.

Figure 7 gives the measured BER versus the wireless transmission distance for 40-, 36-, 32-, and 20-Gb/s PDM-QPSK signals, respectively. It is clearly shown that the BER performance becomes worse with the increase of the wireless transmission distance under the same transmission rate, and also becomes worse with the increase of transmission rate under the same wireless transmission distance. Insets (a) and (b) in Fig. 7 give the received constellations at the BERs of $1 \times 10^{-5}$ and $4 \times 10^{-4}$, respectively.

In conclusion, we experimentally demonstrated different transmission rates wireless $2 \times 2$ MIMO signal at W-band optical-wireless transmission system over different transmission distance. The optical-wireless transmission system adopts optical polarization multiplexing, antenna polarization diversity, heterodyne beating, and MIMO reception. We have realized 40-Gb/s signal transmission over 160-m wireless distance and 20-Gb/s over 640-m wireless distance in this $2 \times 2$ MIMO wireless system at W-band. The transmission system can transfer longer distances and higher rate if better electrical components with more transmit power and wider bandwidth are adopted.

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References