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127.8 Gb/s OFDM-PDM-PS256QAM W-Band Signal Delivery over 10 km SMF-28 and 4.6 km Wireless Distance

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Abstract: *We experimentally demonstrated a record-breaking delivery of 127.8 Gb/s OFDM-PDM-PS-256QAM signal over 10 km SMF-28 fiber and 4.6 km wireless distance at W-band, employing polarization multiplexing technology and advanced DSP algorithms. ©2022 The Authors*

Introduction

With the rapid development of new technologies such as artificial intelligence, Internet of Things, and VR/AR, the explosive growth of information has brought more challenges to the transmission capacity of current communication systems[1-8]. The W-band millimeter wave (75 GHz-110 GHz) has received a lot of attention due to the advantages of small atmospheric attenuation and large bandwidth. In addition, photonics technology is a very promising way to generate high-frequency millimeter waves, which is also a key technology in realizing the integration of optical fiber and wireless delivery [9-13].

In the photonics-aided radio-over-fiber (ROF) system at W-band, Xiao et al. achieved 20 Gb/s delivery over 1.7 km wireless distance [14], Li et al. achieved 54 Gb/s delivery over 2.5 km at W-band [15]. However, the wireless distances achieved in these experiments are relatively short, and the data rate is low with a low spectral efficiency. In order to meet the actual application requirements, kilometer-level wireless transmission, large-capacity (>100 Gb/s) and high spectral efficiency system are promising directions. We note that Ericsson and Deutsche Telekom have achieved the total data rate exceeding 100 Gb/s over 1.5 km by using 8×8 line-of-sight MIMO technology [16]. However, the data rate of each channel is less than 17 Gb/s in fact, and the product of single-channel transmission capacity and wireless distance is only 17 Gb/s× 1.5 km = 25.5 Gb/s•km. Besides, their proposed system is based on pure electricity to generate millimeter waves. Therefore, the bandwidth of signal is limited.

In this paper, we implement a high-speed, long-distance and high spectral efficiency photonics-aided polarization multiplexing ROF system at W-band, which can achieve the seamlessly-integrated delivery of 88.5 GHz OFDM-PDM-PS-256QAM signal over 10 km SMF-28 fiber and 4.6 km wireless link, with a data rate of up to 127.8 Gb/s and a spectral efficiency of 10.65 bit/s/Hz. The employment of polarization multiplexing technology and advanced DSP algorithms has greatly improved our wireless transmission distance and capacity. With the help of a pair of conical antennas (CAs) and dielectric lenses in all polarization directions, only one communication link is required in our system. As far as we know, this is the first demonstration of W-band PDM-PS-256QAM transmission over a wireless distance of more than 4 km, and a record product of single-channel transmission capacity and wireless distance (127.8 Gb/s × 4.6 km = 587.88 Gb/s•km) has also been achieved.

Experimental setup

Fig.1 shows the experimental setup of the photonics-aided W-band polarization multiplexing communication system. At the optical transmitter, two tunable external cavity lasers (ECL1 and ECL2) with <100 kHz linewidth are used as optical signal and local oscillator (LO) sources respectively, and the frequency separation between them is set to 88.5 GHz. The continuous wave (CW) generated by ECL1 is transmitted to the I/Q modulator with a 3 dB bandwidth of 30 GHz for modulation. The digital electrical OFDM signal is generated offline by Matlab software as shown in Fig. 1(a), and is then converted to the analog signal through an arbitrary waveform generator(AWG). The output signal of the AWG is amplified by a pair of parallel electric amplifiers (EAs), and is then used to modulat the CW.. The modulated optical signal is amplified by a polarization-maintaining Erbium-doped fiber amplifier (PM-EDFA) to compensate for the insertion loss of the modulator, and then coupled with the laser generated by ECL2 through a polarization-maintaining optical coupler (PM-OC). The coupled optical signal spectrum is shown in Fig. 1(b). The optical signal is then adjusted by an optical attenuator (ATT) after being transmitted over 10 km SMF-28. Note that

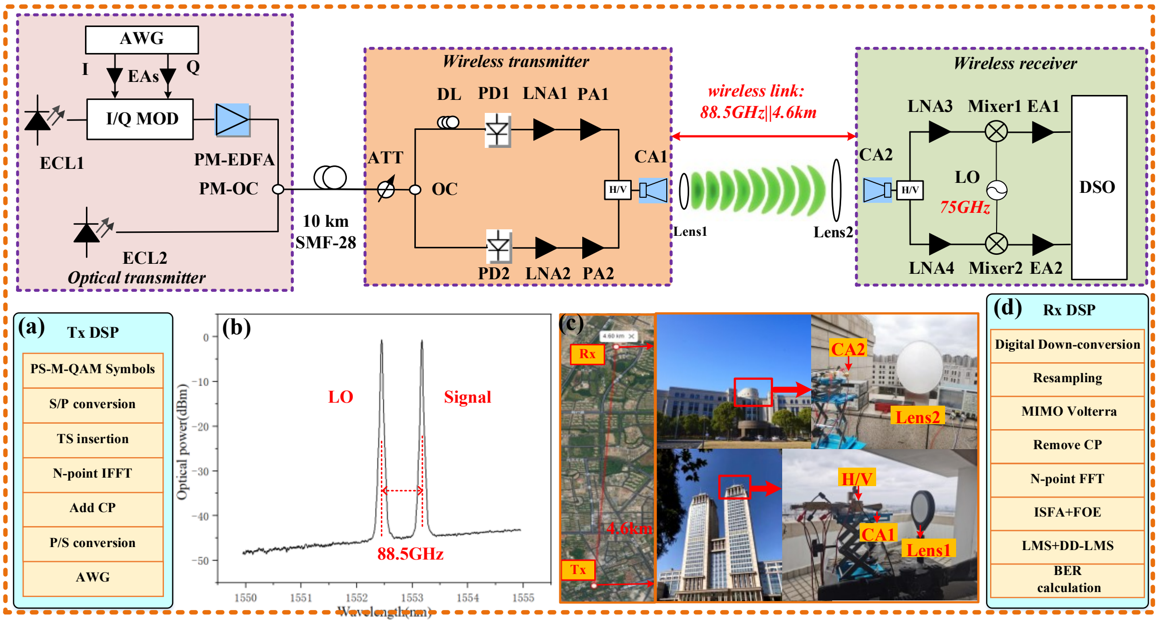

Fig. 1: The experimental setup of the photonics-aided W-band polarization multiplexing communication system; (a) block diagram of Tx DSP; (b) optical spectrums of the optical signal after PM-OC; (c) the experimental photos of 4.6km wireless transmission system (Tx and Rx are located between the two campuses of Fudan University); (d) block diagram of Rx DSP

the part of the experimental setup prior to 10 km SMF-28 is located indoors. The output signal from the ATT is first divided into two paths by an optical coupler (OC), one of which first goes through an optical delay line (DL, ~100m SMF-28), and then enters PD1 to realize photoelectric conversion to generate *H*- polarization W-band signal. Subsequently, the *H*-polarization W-band signal is boosted by a low noise amplifier (LNA1, gain 30 dB) and power amplifier (PA1, saturated output 18 dBm), finally enters the *H/V* polarization multiplexer with a polarization isolation ratio larger than 23 dB. The signal on the other path is directly heterodyne beat via PD2, and multiplexed by *H*/*V* polarization multiplexer after being amplified by LNA2 and PA2. The models of LNA2 and PA2 are identical to LNA1 and PA1. The DL in the system is used to remove the correlation of *H*- and *V*-polarization directions by providing an exact over 1000-symbol delay. The output signal of the *H*/*V* polarization multiplexer is transmitted into the wireless space through a W-band CA1 with a gain of 25 dBi.

A communication link with a wireless distance of 4.6 km (between Fudan Handan campus and Jiangwan campus) is set. Fig. 1(c) shows the photos of the transmitter, receiver, and transmission link. The transmitter is located on the roof of Guanghua Building on Handan Campus, with a height of 142 m. The receiver is located on the roof of the Physical Building of Jiangwan campus, with a height of 24 m. Our experiment was carried out on a sunny day in winter with a temperature of 3°C and a humidity of 25%. We know that CAs and lenses are usually used in short-distance (<100m) transmission systems, high-gain reflector antennas(such as Cassegrain antennas) are used in almost all long-distance transmission systems. In this experiment, we find that CAs combined with lenses can still achieve long-distance transmission up to the kilometer level. What's more, they have full polarization orientation, so only one communication link is needed in the system. The combined gain (G_T) of CA1 and Lens1 is about 34 dBi. The combined gain (G_R) of HA2 and Lens2 is about 56 dBi. We measure the transmit power of the wireless signal and the received power after free space transmission are 16 and -41.96 dBm, respectively. Next, we calculate the wireless link power budget of our proposed communication system, which can be defined by the Friis transmission equation,

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

Where transmit power P_T is ~ 16 dBm, the transmit antenna gain G_T is ~ 34 dBi, the receive antenna gain G_R is ~ 56 dBi, the wireless transmission distance d is ~ 4.6 km, c stands for the speed of light in vacuum, the atmospheric loss L_m is ~ 2.3 dB for 4.6 km wireless at 88.5 GHz. In summary, we can estimate the received power P_R of the system to be ~ -40.93 dBm, which is close to the power we measured considering some factors such as connection loss between the devices.

At the wireless receiver, the W-band signal is collected by Lens2 and received by CA2, then transmitted into the *H/V* polarization multiplexer and is divided into two orthogonal polarization directions. The separated W-band signal on *H*- and *V*-polarization direction is first boosted by a pair of LNAs (LNA3or LNA4) with a 30 dB gain, and then down-converted to a 13.5 GHz IF signal by a pair of mixers respectively, which are driven by a radio frequency (RF) signal whose frequency is 75 GHz. We use a pair of EAs (EA1or EA2) with a gain of 26 dB to amplify the IF signal, and finally use a digital storage oscilloscope (Tektronix, 100GSa/s, DSA73304D) to capture it. The DSP process at the receiving end is shown in Fig. 1(d). We use the I/Q MIMO structure Volterra equalizer (VNE) to compensate the non-linear damage and polarization crosstalk, the Intra-symbol frequency-domain averaging (ISFA) for channel estimation, as well as the cascaded LMS and DD-LMS algorithm structures as a hybrid time-frequency domain equalizer to obtain a better demodulation signal.

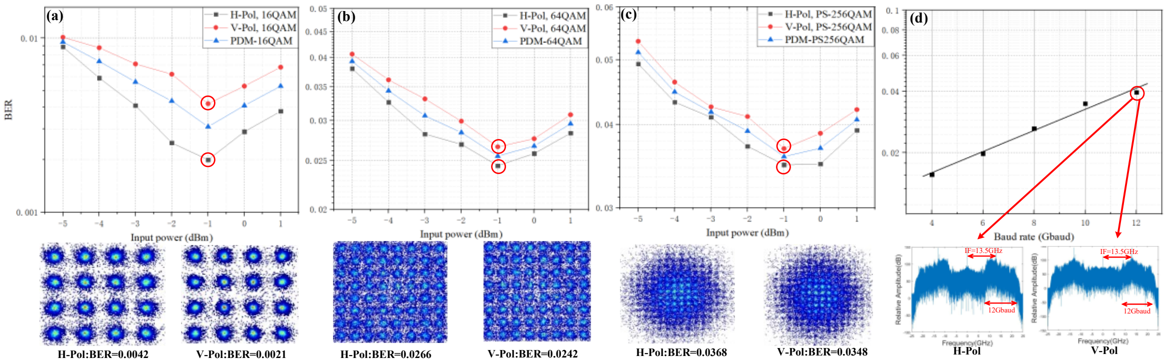

Fig. 2: (a) BER of PDM-16QAM signal vs. the input optical power of PD; (b) BER of PDM-64QAM signal vs. the input optical power of PD; (c) BER of PDM-PS-256QAM signal vs. the input optical power of PD; (d) BER of PDM-PS-256QAM signal vs. the baud rate

Results and Discussion

As shown in Figs. 2(a)-(c), we firstly transmit 10 Gbaud OFDM-PDM-16QAM (8 bit/symbol/Hz), OFDM-PDM-64QAM (12 bit/symbol/Hz), OFDM-PDM-PS-256QAM (14.14 bit/symbol/Hz) signal, respectively. We measure the relationship between the BER performance and the input power of PD. When the input power of PD increases from -5 dBm to -1 dBm, the BER performance is gradually optimized due to the improvement of SNR. When the input power continues to increase to 1 dBm, the BER performance gradually deteriorates due to the saturation effect of PD. We have achieved the minimum BER value of 3.2×10^{-3} for OFDM-PDM-16QAM, 2.54×10^{-2} for OFDM-PDM-64QAM, 3.58×10^{-2} for OFDM-PDM-PS-256QAM signal with -1 dBm input optical power into PD. And the demodulation constellations of *H*- and *V*-polarization OFDM signal are shown in the corresponding insets in Figs. 2(a)-(c).

In order to achieve a larger system transmission capacity, we adjust the baud rate of PDM-PS-256QAM signal from 4 to 12 Gbaud when the input optical power of PD is -1 dBm, as shown in Fig. 2(d). Due to the increase of the signal baud rate, the requirement for the system bandwidth increases, which leads to the deterioration of BER performance. Finally, we can achieve the minimum BER value of 3.89×10^{-2} for 12 Gbaud PDM-PS-256QAM signal, which is below the 25%SD-FEC threshold of 4.2×10^{-2}. The electrical spectrum of *H*- and *V*-polarization IF signal are shown in the corresponding insets in Fig.2(d), the channel SNR is about 25 dB. In addition, we add 64-point cyclic prefix (CP) to 1024 subcarriers to resist the inter symbol interference, so the overhead of CP in our OFDM structure is 64/(1024+64) ≈ 5.88%, and the maximum rate for PDM-PS256QAM signal in our system is12×14.14×(1-5.88%)=159.7 Gb/s. After removing the 25% SD-FEC overhead corresponding to the BER threshold of 4.2×10^{-2} [17], we can calculate the maximum net rate as 12×14.14×(1-5.88%)×1/1.25=127.8 Gb/s. In addition, the spectral efficiency of the system is 127.8/12=10.65 bit/s/Hz.

Conclusions

We have experimentally implemented a high-speed, long-distance and high spectral efficiency photonics-aided W-band polarization multiplexing ROF system, and up to 127.8 Gb/s OFDM-PDM-PS-256QAM signal transmission over 10 km SMF-28 fiber link and 4.6 km wireless link is achieved. This achievement significantly enhances the wireless distance performance and improves the transmission capacity for radio mobile data communications, which will have a great use stage in the beyond 5G.

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