Polarization multiplexing QPSK signal transmission in optical wireless-over fiber integration system at W-band

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We propose and experimentally demonstrate a novel scheme to realize polarization-division-multiplexing quadrature-phase-shift-keying (PDM-QPSK) signal transmission over fiber, wireless and fiber at W-band (75−110 GHz). The generation of polarization multiplexing millimeter-wave (mm-wave) wireless signal is based on the photonic technique. After 20-km fiber transmission, polarization diversity and heterodyne beating are implemented to convert the polarization components of the polarization-multiplexing signals from the optical baseband to W-band so that up to 16 Gb/s mm-wave signals can be delivered over 2-m 2×2 multiple-input multiple-output (MIMO) wireless link. At the receiver base station (BS), polarization combination reconstructs the PDM-QPSK signal which is then launched into another 20-km fiber. In the experiment, coherent detection is introduced to improve receiver sensitivity and constant modulus algorithm (CMA) is applied for polarization de-multiplexing. The bit-error-ratio (BER) for 16-Gb/s PDM-QPSK signal delivery is below the forward-error-correction (FEC) threshold of 3.8×10^{-3} with the optical signal-to-noise ratio (OSNR) above 11.8 dB.

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Large-capacity optical wireless integration system in millimeter-wave (mm-wave) bands is being intensively researched due to its huge bandwidth, low transmission loss, and broad coverage[1−14]. High-speed wireless-over fiber transmission such as 100-G and 400-G integration systems have been experimentally demonstrated by utilizing the technologies of polarization division multiplexing (PDM), photonic mm-wave generation and multiple-input multiple-output (MIMO)[8−10]. However, the transmission distance has been limited because the wireless receiver demodulated the high-speed mm-wave signals in the electrical domain directly. Moreover, in such cases, the wireless receiver which is mainly composed of electrical devices would be more complicated with the increasing capacity and frequency of the radio-frequency (RF) signals. References [13,14] has proposed a RF transparent optical-wireless-over fiber system in which the mm-wave signals are up-converted into the optical domain at the receiver base station (BS), to achieve long distance transmission without relay. And in the scheme, coherent detection and advanced digital signal processing (DSP) could be adopted to improve the receiver sensitivity and bit error ratio (BER) performance, respectively. Furthermore, it can be used to provide high-speed communication when the natural disasters such as earthquake and tsunamis occur[12]. However, there is no wireless and long distance fiber transmission in Ref. [14] and how to deliver polarization multiplexing signals in such systems is still a problem which should be addressed.

In this letter, we propose a novel scheme to deliver the PDM quadrature-phase-shift-keying (QPSK) signal in the optical wireless-over fiber system and long distance transmission has been demonstrated. In the experiment, the W-band (75−110 GHz) is employed to carry the transmitted data to simulate the practical communication scene. And to integrate wireless and fiber-optic network seamlessly, photonic generation of the polarization-multiplexing mm-wave wireless signal is introduced at the transmitter BS. For the polarization components of PDM-QAM signals, the Jones matrixes of the first and the second 20-km fiber for transmission, and the channel gain matrix for 2×2 MIMO wireless delivery are all given by a 2×2 matrix. Therefore, the constant modulus algorithm (CMA) could be applied to realize polarization de-multiplexing in the optical wireless-over fiber system. We experimentally demonstrate up to 16 Gb/s signals transmission over the fiber, wireless and fiber link. The deployed 2-m wireless delivery and (20+20) km single-mode fiber-28 (SMF-28) transmission in the full link cause no optical signal-to-noise ratio (OSNR) penalty. The BER for 16-Gb/s PDM-QPSK signals delivery is below the forward-error-correction (FEC) threshold of 3.8×10^{-3} with the OSNR above 11.8 dB.

Figure 1 shows the principle of the novel scheme for PDM-QPSK optical wireless-over fiber transmission system. At the transmitter central station (CS), polarization multiplexing is realized for the optical QPSK signals. After the first fiber transmission, polarization diversity is utilized to obtain the x- and y-polarization components of PDM-QPSK signal and local free-running light. Then heterodyne beating technology is employed to up-convert the x- and y-polarization components from optical baseband to W-band. Hence, the delivery of PDM-QPSK signal over 2×2 MIMO wireless link could be achieved through two pairs of transmitter and receiver horn antennas (HAs).

Let the Jones matrix of the first span of fiber for transmission be given as

$$\mathbf{J}=\begin{pmatrix}\sqrt{\alpha}\mathrm{e}^{\mathrm{i}\delta} & -\sqrt{1-\alpha}\\ \sqrt{1-\alpha} & \sqrt{\alpha}\mathrm{e}^{-\mathrm{i}\delta}\end{pmatrix}, \quad (1)$$

where α and δ denote the power splitting ratio and the phase difference between the two polarization modes, respectively. Assuming that the original x- and y-polarization components could be expressed as $(E_{\mathrm{in},x}, E_{\mathrm{in},y})^{\mathrm{T}}$, the state of polarization (SOP) of the output is given as

$$\begin{pmatrix}E_x\\ E_y\end{pmatrix}=\mathbf{J}\begin{pmatrix}E_{\mathrm{in},x}\\ E_{\mathrm{in},y}\end{pmatrix}. \quad (2)$$

Hence, there is significant crosstalk between the original signals in the two orthogonal polarization states after fiber transmission.

For the 2×2 MIMO wireless delivery, the channel response is a 2×2 gain matrix, which means that the received signals by Rx1 contains both components from Tx1 and Tx2. As the Jones matrix mentioned above, the gain matrix can be denoted as

$$\mathbf{H}=\begin{pmatrix}h_{xx} & h_{xy}\\ h_{yx} & h_{yy}\end{pmatrix}, \quad (3)$$

where h_{xy} and h_{yx} denote the interference between x- and y-polarization components under wireless condition. Taking the fiber transmission from the receiver BS to the receiver CS into account, the input of receiver CS is given as

$$\begin{pmatrix}E_x^{'}\\ E_y^{'}\end{pmatrix}=\mathbf{J}^{'}\mathbf{H}\begin{pmatrix}E_x\\ E_y\end{pmatrix}=\mathbf{J}^{'}\mathbf{HJ}\begin{pmatrix}E_{\mathrm{in},x}\\ E_{\mathrm{in},y}\end{pmatrix}, \quad (4)$$

where $\mathbf{J}^{'}$ denotes the Jones matrix of the second span of fiber. As $\mathbf{J}^{'}$, $\mathbf{H}$ and $\mathbf{J}$ are all 2×2 matrix, the whole transmission function is still a 2×2 matrix for the SOP of the original PDM-QPSK signal. Furthermore, the channel gain matrix only contributes to the loss of the transmitted signal, so the impact of the fiber, wireless and fiber transmission on the SOP can be equivalent to a Jones matrix of a new fiber which is composed of two spans of fiber. Thus, the classic CMA equalization with a 2×2 butterfly structure can be used at the receiver CS to realize PDM-QPSK signal polarization de-multiplexing after coherent detection.

Figure 2 shows the schematic of the PDM-QPSK signal transmission optical wireless-over fiber system at W-band which can achieve the capacity up to 16 Gb/s.

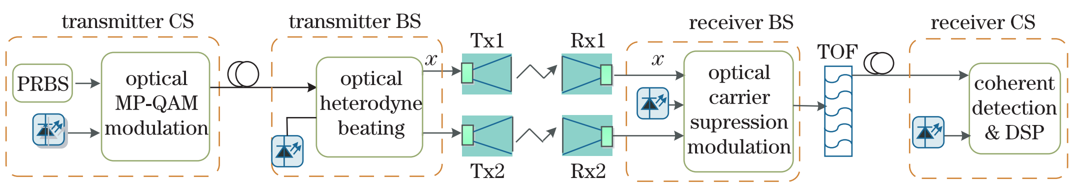

Fig. 1. (Color online) Principle of our optical-wireless-optical system for PDM-QPSK signal transmission.

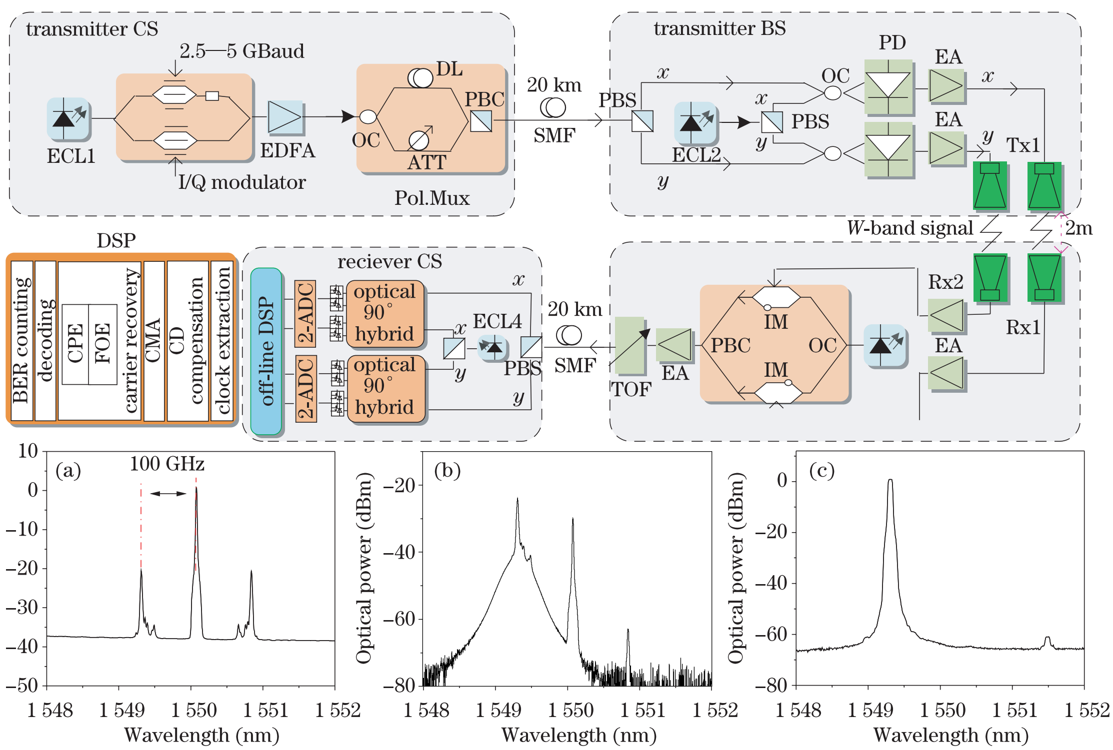

Fig. 2. (Color online) Experimental setup for the polarization multiplexing signal transmission optical wireless-over fiber system; optical spectra (0.02 nm resolution) (a) after the IM and (b) after the TOF; (c) optical spectrum (0.1-nm resolution) of the LO for coherent detection.

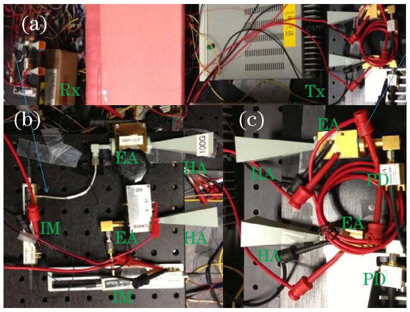

Fig. 3. (Color online) Photos of the (a) PDM-QPSK transmission link, (b) transmitter, and (c) receiver.

In the experiment, the laser source is fully tunable C-band external cavity lasers (ECLs) with line-width smaller than 100 kHz. At the transmitter CS, the lightwave from ECL1 is set at λ_1 (1549.384 nm). The in-phase/quadrature (I/Q) modulator is composed of two parallel Mach-Zehnder modulators (MZMs) which are driven by an electrical binary data with pseudo-random binary sequence (PRBS) length of $(2^{15}-1)$ to generate up to 10-Gb/s optical QPSK signals. After amplification by an erbium-doped fiber amplifier (EDFA), the QPSK signal is halved into two branches by a polarization maintaining optical coupler (PM-OC). The upper branch is a span of fiber for optical delay, while the lower branch is an optical attenuator for power balance. Then the outputs of these two branches are recombined by a polarization beam combiner (PBC), realizing polarization multiplexing. The generated PDM-QPSK signal is launched into 20-km SMF-28 which has 5-dB fiber loss.

At the transmitter BS, the ECL2 at λ_2 (1550.1433 nm) has a frequency offset of f_{RF}(100 GHz) relative to the wavelength of ECL1 and its power is 4-dB higher than received PDM-QPSK signal. Two polarization beam splitters (PBSs) are adopted to realize polarization separation of the optical PDM-QPSK signal and local free-running light. And two OCs are deployed for heterodyne beating. It is worth noting that the x- or y-polarization component of the PDM-QPSK signal after 20-km SMF transmission don't have only original x- or y-polarization signal because the polarization state cannot be maintained in the fiber. It means that each output of the PBS for PDM-QPSK signal contains both original x- and y-polarization signals. And in this letter, x- and y-polarization are just for simplification. Two photo detectors (PDs) with 90-GHz 3-dB bandwidth are utilized to convert the x- and y-polarization components from optical baseband to W-band. Two W-band electrical amplifiers (EAs) with output power of ∼10 dBm and gain more than 25 dB are following for power amplification. Then the generated mm-wave signals are delivered over 2×2 wireless link through two pairs of transmitter and receiver HAs. Each pair of HAs is for 2-m wireless distance transmission and each HA is of a gain of 25 dB.

The receiver BS consists of an ECL, two W-band EAs, and two intensity modulators (IMs), a PBC, an EDFA, and a tunable optical filter (TOF). The received wireless signals are first amplified by two EAs. Then they are fed into two IMs to modulate the optical carrier at λ_3 (1550.07 nm) emitted from ECL3. The optical output from IMs has a central carrier at λ_3 and two sidebands at $\lambda_3 \pm \lambda_{\mathrm{RF}}(\lambda_{\mathrm{RF}} = c/f_{\mathrm{RF}}$, where c is the velocity of light), which means that the RF signals have been up-converted into the optical domain. Each IM with 3-dB bandwidth of ∼36 GHz and insertion loss of 5 dB, is direct-current (DC)-biased at optical-carrier-suppression (OCS) point[15−17]. That is to say, each IM has minimal output when there is no mm-wave signal driving the modulators. In fact, due to the limited DC extinction ratio, the center carrier cannot be fully suppressed. Moreover, since the response of the IMs is weak with the signal at ∼100 GHz, large sidebands can't be generated. Therefore, there is a higher center carrier related to the sidebands, as shown in Fig. 2(a). After the frequency shift from the wireless W-band to optical baseband, a PBC is used to reconstruct the PDM-QPSK signals. Then a TOF is employed to filter out the lower sideband (the extracted optical spectrum is shown in Fig. 2(b)) so that homodyne beating with the local oscillator (LO) could be adopted at the receiver CS. Figure 3(a) shows the photo of PDM-QPSK transmission optical wireless-over fiber link at W-band. Figures 3(b) and (c) show the photos of transmitter and receiver in the full link.

At the receiver CS, the LO is at $\lambda_3 - \lambda_{\mathrm{RF}}$ (as shown in Fig. 2(c)). Similarly, two PBSs are utilized to achieve polarization diversity of the received PDM-QPSK signal and the LO. Then x- or y- polarization of PDM-QPSK signal, together with x- or y- polarization of the LO, is optically mixed in an optical 90° hybrid and photo-detected by two balanced PDs. Then, the obtained I and Q signals for x- or y- polarization component are sampled and off-line processed by adopting advanced DSP algorithm.

Figures 4(a)−(e) respectively show the measured x-polarization constellations for the 10-Gb/s PDM-QPSK signal over 2-m wireless and (20+20)-km fiber transmission at 13-dB OSNR before clock extraction, after clock extraction, after CMA equalization, after frequency-offset estimation (FOE) and after carrier phase estimation (CPE), while Figs. 4(f)−(j) show the corresponding y-polarization constellations. As we can see from the constellations shown in Figs. 4(c) and (h), the received signals converge to a circle with same radius after recovered by the classic CMA equalizer. In spite of the wireless transmission, CMA algorithm still has good modulus decision performance, which certifies the CMA algorithm is an effective way for polarization de-multiplexing in our PDM-QPSK optical wireless-over fiber transmission system.

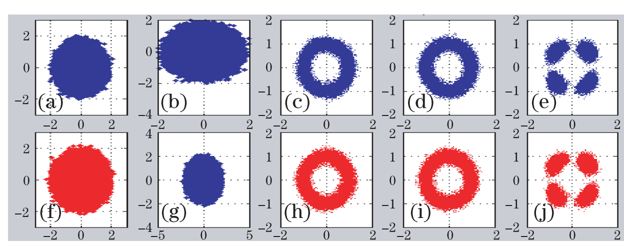

Fig. 4. (Color online) Constellations of x-polarization (a) before clock extraction, (b) after clock extraction, (c) after CMA equalization, (d) after FOE, and (e) after CPE; y-polarization (f) before clock extraction, (g) after clock extraction, (h) after CMA equalization, (i) after FOE, and (j) after CPE in the off-line DSP.

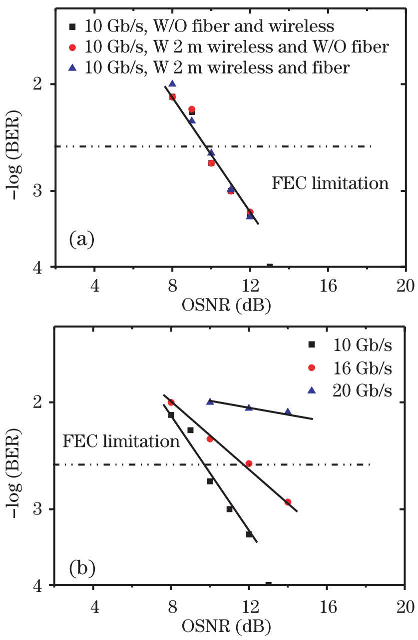

Fig. 5. (Color online) (a) BER versus OSNR for 10-Gb/s PDM-QPSK signal transmission, (b) BER versus OSNR for the 10−20-Gb/s PDM-QPSK signal over 2-m wireless delivery and (20+20)-km fiber transmission.

Figure 5(a) gives the BER versus OSNR for the 10-Gb/s PDM-QPSK signal under different transmission conditions in the optical wireless-over fiber integration system. The results show that both 2-m wireless delivery and (20+20)-km SMF-28 transmission in the system cause no OSNR penalty. This is because nonlinear effect of fiber and wireless transmission is very small due to the short transmission distance.

Figure 5(b) denotes the BER versus the OSNR for the PDM-QPSK signal transmission with 2-m wireless delivery and (20+20) km SMF-28 transmission at the bit rate of 10, 16, and 20 Gb/s, respectively. In our experiment, there are more conversions of optical to electrical and electrical to optical signal, introducing large path effect which results in more taps to recover the original data. Thus, the CMA tap number is set as 29 for 10-Gb/s signal, and 39 for 16-Gb/s signal, which are higher than the CMA tap number 13 for commercial 100G PDM-QPSK products. More CMA tap number is required with the increasing transmission bit rate. From Fig. 5(b), we can see that the BER for 16-Gb/s signal transmission is below the FEC limitation when the OSNR is above 11.8 dB, while for 10-Gb/s signal transmission, the OSNR should be larger than 9.7 dB so the BER is below the 3.8×10^{-3}. Moreover, due to the limited bandwidth of the optical and electrical components, there is an error floor at 1×10^{-3} for 16-Gb/s signal and at 2×10^{-2} (above the software defined FEC threshold) for 20-Gb/s signal, respectively. Therefore, to recover the transmitted signal at the receiver CS, the speed of the proposed system has to be smaller than 20 Gb/s.

In conclusion, a novel architecture is proposed and experimentally demonstrated to deliver PDM-QPSK signal over fiber, wireless and fiber link. In our experiment, mm-wave PDM-QPSK signal is generated by photonic technique and coherent detection is used to improve receiver sensitivity. By utilizing polarization diversity and heterodyne beating, we solve the problems how to deliver polarization multiplexing W-band mm-wave QPSK signal and how to realize polarization de-multiplexing at the receiver CS. We demonstrate 16-Gb/s polarization multiplexing signal transmission over (20+20)-km fiber and 2-m wireless distance with BER below the FEC threshold.

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