A dual-polarization coherent communication system with simplified optical receiver for UDWDM-PON architecture

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Abstract: A dual-polarization coherent heterodyne optical communication system using a simplified and low-cost demodulation scheme, for high-capacity UDWDM-PON access networks, is proposed and demonstrated. In this scheme, the signal light and reference light occupying each of the polarization modes are emitted simultaneously from the transmitter. The random phase fluctuations between the signal light and reference light are obviated completely by means of the application of the phase-correlated orthogonal lights. When the signal light in the each polarization mode is modulated with M-amplitude-shift keying (M-ASK) or M^2-quadrature amplitude modulation (M^2-QAM), the phase-stable intermediate frequency (IF) signal with M-ASK or M^2-QAM modulation in the corresponding polarization mode is available for conversion in the electrical domain by beating the modulated signal light with the un-modulated reference light. A new IF signal with M^2 or M^4-QAM can be synthesized by the IF signals in both modes as long as the power ratio and time delay between the two-modes optical signals are set at the proper values. This is achieved without using polarization demultiplexing and complicated algorithms and the synthesized IF signal can be received and demodulated directly. A proof-of-concept transmission link with dual-polarization 2-ASK is demonstrated. The experimental results are consistent with theoretical predictions.

OCIS codes: (060.1660) Coherent communications; (060.2840) Heterodyne; (060.4230) Multiplexing; (060.5625) Ratio frequency photonics.

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1. Introduction

The dual-polarization coherent optical communication scheme has been adopted widely in transmission core networks (TCNs) in various forms to increase spectral and power efficiency [1]. In this scheme, almost all the degrees of freedom of the light wave including the amplitude, phase, and polarization are utilized simultaneously to carry the data [2]. It is well-known that the phase coding on the lightwave cannot be detected directly by the photodetector (PD). Therefore, a continuous wave (CW) and coherent reference light is required to interfere with the signal light on a PD. The phase information will be down-converted from the optical domain to the electrical domain by means of the beating between the signal light and reference light, that is commonly referred to “coherent detection” [3]. In theory, to obtain reliable data decoding of the complex field, random phase and polarization fluctuations between the reference light and signal light must be avoided. In general this is difficult to achieve with un-correlated sources of reference light and signal light [2]. Consequently, narrow-linewidth optical local oscillator (LO) sources and complicated digital signal processing (DSP) integrated circuits have to follow the coherent receiver to suppress and compensate these random fluctuations [4], [5]. In the receiving terminal, a series of high speed analog-to-digital converters (ADCs) are needed following an analog coherent receiver to convert the received signal to the digital domain. The ADCs must then be interfaced to a DSP processor unit which performs chromatic dispersion (CD) compensation, polarization control and equalization (PCE), carrier phase recovery (CPR), and finally forward error correction (FEC) decoding [3].

Recently, to meet the growing demand on data traffic coherent detection was introduced in ultra-dense wavelength-division multiplexing passive optical networks (UDWDM-PON) as it allows high transmission capacity with enhanced spectral efficiency [6-9]. However, considering the cost and power consumption of the ONU, these methods are difficult to be deploy in the near future. There are two cost effective ways to implement ONU for the

UDWDM-PON: 1) remove or replace the narrow-linewidth optical LO in the ONU and 2) reduce the hardware implementation complexity of the DSP unit. In fact, a series of papers addressing this issue have been published so far. For example in ref. [10] and [11], the homodyne coherent receivers with the simplified DSP unit was demonstrated for UDWDM-PON applications using commercial distributed feedback laser diode (DFB-LD) as a LO instead of the narrow-linewidth external cavity laser (ECL). Unfortunately, only low order modulation formats with single polarization mode has been demonstrated by using these methods. To reduce ONU cost, a single polarization, coherent optical communication link with LO-free homodyne conversion to the electrical domain has been implemented by removing the narrow-linewidth ECL at the OLT [12]. Nevertheless, the complex signal processing algorithms (e.g. PCE, CPR, FEC etc.) are still necessary for phase and polarization estimation in the DSP unit. In addition, cost reduction can be achieved with slower ADCs at the expense of under-sampling by the receiver and use of serial-to-parallel converters [13], [14]; still this approach is not efficient in terms of filter complexity in the DSP unit.

In this work, a novel dual-polarization coherent heterodyne optical communication system using a simplified demodulation scheme is proposed and demonstrated which can be scaled to future UDWDM-PON because of its low-cost and higher power efficiency. In our method, the signal light and reference light in the each polarization mode arise from the same laser source. The random phase fluctuation (RPF) between the signal light and reference light can be avoided completely due to the application of the phase-correlated orthogonal lights (POLs). When the signal lights in the transverse electric (TE) and transverse magnetic (TM) modes are modulated with M-ary amplitude-shift keying (M-ASK) or M^2-quadrature amplitude modulation (M^2-QAM), two phase-stable intermediate frequency (IF) signals with M-ASK or M^2-QAM modulation in the TE and TM modes will be generated respectively in the optical domain due to the beating between the signal lights and reference lights. If the power ratio and time delay between the two aforementioned IF signals are set at the proper values in the OLT, the third IF signal with M^2 or M^4-QAM can be synthesized as the signal lights and reference lights in both polarization modes are fed into the PD installed in the ONU. Since the synthesized IF signal can be received and demodulated directly, polarization demultiplexing is not used in the proposed system, which means that the PCE algorithm will become unnecessary in the DSP unit. In addition, the CPR algorithm and FEC decoding are also not needed in view of that the RPFs are controlled in optical domain. Accordingly we can achieve a LO-free ONU with simplified DSP unit. This paper is organized as follows. We first discuss the concept and architecture of the proposed scheme in Section 2. Then, a proof-of-concept experiment is described in Section 3 for the case in which a dual-polarization 2-ASK optical signal is heterodyne detected and demodulated. A discussion on future implementation and conclusion follows.

2. Architecture and Principle

2.1 Architecture of the proposed system

According to the schematic diagram shown in the Fig. 1, we will firstly give a brief description for the architecture of the proposed coherent dual-polarization optical communication system based on POLs. The POLs which are characterized by a pair of linearly polarized lights with different optical frequency, correlated phases and orthogonal polarization directions, can be obtained from the phase-correlated orthogonal lights generator (POLG) and used to generate the phase-matched signal light and reference light (the operational principle of the POLG will be introduced in Section 3). For one (TE or TM) of the dual-polarization modes, the transmitter consists of a POLG, a polarization sensitive electrical optical modulator (EOM 1 or 2) and a polarizer. The desired property of the polarization sensitive EOMs is that the injected light will be modulated with maximum modulation efficiency (ME) if its polarization direction is parallel with the externally applied electric field

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(EAEF), and will not be modulated if its polarization direction changes into the orthogonal direction. As displayed in Fig. 1, in the OLT, a 3-dB optical coupler is connected with the POLG to split the POLs for the TE and TM modes application. A polarization beam combiner (PBC) is used to combine the TE and TM modes. The power ratio and time delay between the optical signals in the dual-polarization modes are controlled by the variable optical attenuator (VOA) and the optical delay line (ODL) after the optical coupler. The dual-polarization coherent optical signals are delivered to ONU via the single mode fiber (SMF). The ONU includes a photodetector (PD) appropriate for the signal bandwidth, an electrical local oscillator (ELO), an electrical phase shifter (PS), two mixers, and a DSP unit. Note that except for data decision circuit all of the complicated algorithms such as PCE, CPR, and even FEC are not required in the baseband data unit. Additionally, all optical components in the OLT are connected by polarization maintaining fibers (PMFs). The principles of modulation, signal synthesizing, and formal conversion will be elaborated in subsection 2.2.

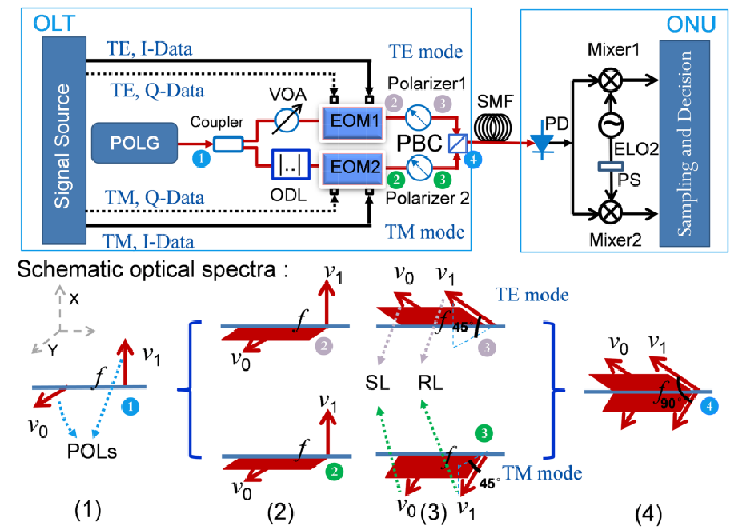

Fig. 1. Schematic diagram of the proposed coherent dual-polarization optical communication system; insets (1)-(4) correspond to schematic representations of the modulation optical spectra at different positions of the link. OLT: optical line terminal; TE: transverse electric; TM: transverse magnetic; POLG: phase-correlated orthogonal lights generator; VOA: variable optical attenuator; ODL: optical delay line; EOM: electrical optical modulator; PBC: polarization beam combiner; SMF: single mode fiber; PD: photodetector; ELO: electrical local oscillator; ONU: optical network unit. SL: signal light, RL: reference light, POLs: phase-correlated orthogonal lights.

2.2 Operational Principle

The normalized optical fields of the POLs are given by

$$\begin{bmatrix} E_{0,y}(t) \\ E_{1,x}(t) \end{bmatrix} = \begin{bmatrix} e^{j(2\pi\nu_0 t)} \\ e^{j(2\pi\nu_1 + \varphi_1)} \end{bmatrix} \tag{1}$$

where ν_0 and ν_1 are optical frequencies of the lights, and φ_1 is the initial phase difference between the orthogonal lightwaves. Here, the polarization direction of the light ν_0 is defined as Y-axis which is in parallel with the slow axis of the PMF as well as the EAEF applied on the EOM. Inset (1) of Fig. 1 shows the corresponding schematic optical spectrum of the POLs. Due to the aforementioned property of the EOM, for the upper branch, i.e. the TE mode, the modulated-light-wave output from the EOM1 (See inset (2) of Fig. 1) could be expressed as

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$$\begin{bmatrix} E_{0,y}(t) \\ E_{1,x}(t) \end{bmatrix} = \begin{bmatrix} (A_{m,I,TE} + jA_{m,Q,TE})e^{j(2\pi v_0 t)} \\ e^{j(2\pi v_1 + \varphi_1)} \end{bmatrix} \qquad (m = 1, 2, \cdots, M) \tag{2}$$

and

$$A_m = (2m - 1 - M)d\,, \tag{3}$$

$A_{m,I,TE}$ and $A_{m,Q,TE}$ are the signal amplitudes applied on the I and Q channels in the TE mode, M is the number of symbol in I or Q channel, d is the amplitude interval between A_m and A_{m+1}. Aligning the polarization direction of the light v_0 with the principal axis of polarizer 1 at an angle of 45°, the optical field of the light waves output from polarizer 1 could be written as

$$E_{45^\circ,TE}(t) = \frac{\sqrt{2}}{2}((A_{m,I,TE} + jA_{m,Q,TE})e^{j(2\pi v_0 t)} + e^{j(2\pi v_1 + \varphi_1)}) \qquad (m = 1, 2, \cdots, M)\ , \tag{4}$$

whose schematic optical spectrum is displayed in inset (3) of Fig. 1. Eq. (4) shows that signal light v_0 and reference light v_1 with identical polarization direction for the TE mode application have been obtained after polarizer 1. Moreover, the phase correlation between the signal light and reference light is never damaged in the whole process of signal modulation due to the fact that these two lights are always transmitted along the same optical path. Likewise, the optical field of the signal light and reference light in the TM mode (after polarizer 2) could be written as

$$E_{45^\circ,TM}(t) = \frac{\sqrt{2}}{2}k((A_{m,I,TM} + jA_{m,Q,TM})e^{j(2\pi v_0 t)} + e^{j(2\pi v_1 + \varphi_1)}) \qquad (m = 1, 2, \cdots, M) \tag{5}$$

where $A_{m,I,TM}$ and $A_{m,Q,TM}$ are the signal amplitudes applied on the I and Q channels in the TM mode, k is the amplitude coefficient which can be controlled by the VOA in the OLT. The schematic representation of synthesized optical spectrum is shown in inset (4) of Fig. 1. When the signal lights and reference lights in both modes are fed to the PD via the SMF, the photocurrent could be presented as

$$\begin{aligned} I(t) &= I_{TE}(t) + I_{TM}(t) \\ &\propto E_{45^\circ,\mathrm{TE}} \cdot E^*_{45^\circ,\mathrm{TE}} + E_{45^\circ,\mathrm{TM}} \cdot E^*_{45^\circ,\mathrm{TM}} \\ &= 1 + \frac{1}{2}(A^2_{m,I,TE} + A^2_{m,Q,TE} + k^2 A^2_{m,I,TM} + k^2 A^2_{m,Q,TM}) \\ &+ A_{m,I,TE}\cos(2\pi ft + \varphi_1) - A_{m,Q,TE}\sin(2\pi ft + \varphi_1) \\ &+ kA_{m,I,TM}\cos(2\pi ft + \varphi_1 + \Phi) - kA_{m,Q,TM}\sin(2\pi ft + \varphi_1 + \Phi) \end{aligned} \tag{6}$$

As we can see, the resultant current I(t) is the sum of the I_{TE}(t) and I_{TM}(t) which are the photocurrents converted from the coherent optical signals in the dual-polarization modes. Except for the direct-current and baseband terms, the last four terms in the expanded formula correspond to the two IF signals from the beating between signal light and reference light in the TE and TM modes. Φ is the phase difference between the IF signals, which can be adjusted by the ODL in the OLT. The photo detection output after high-pass filtering is

$$\begin{aligned} S(t) \propto\ & A_{m,I,TE}\cos(2\pi ft + \varphi_1) - A_{m,Q,TE}\sin(2\pi ft + \varphi_1) \\ & + kA_{m,I,TM}\cos(2\pi ft + \varphi_1 + \Phi) - kA_{m,Q,TM}\sin(2\pi ft + \varphi_1 + \Phi) \end{aligned} \tag{7}$$

It can be seen from Eq. (7) that a new IF signal S(t) which carries all the information transmitted from OLT is synthesized from the original IF signals. As for the demodulation of the new IF signal, there are two cases which need to be analyzed and explained separately.

In the first case, the signal lights in the TE and TM modes are modulated with M-ASK. We have

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$$S(t) \propto A_{m,I,TE}\cos(2\pi ft+\varphi_1)+kA_{m,I,TM}\cos(2\pi ft+\varphi_1+\Phi) \tag{8}$$

When $\Phi=\pi/2$ and $k=1$, Eq. (8) can be rewritten as

$$S(t) \propto A_{m,I,TE}\cos(2\pi ft+\varphi_1)-A_{m,I,TM}\sin(2\pi ft+\varphi_1) \tag{9}$$

Eq. (9) represents the M^2-QAM implementation of the IF signal S(t). The first and second rows in Fig. 2 display the transfer relationship between the dual-polarization optical coherent signals and synthesized IF signal as the modulation in both modes is 2- or 4-ASK. It is evident that information dropout or distortion will not happen if the synthesized IF signal is demodulated by the receiver as illustrated in Fig. 1 without having to make use of polarization demultiplexing.

In the second case, the signal lights in the TE and TM modes are modulated with M^2-QAM. As $\Phi=0$ and $k=M$, Eq. (7) can be expressed as

$$\begin{aligned} S(t) \propto\ & (A_{m,I,TE}+MA_{m,I,TM})\cos(2\pi ft+\varphi_1) \\ & -(A_{m,Q,TE}+MA_{m,Q,TM})\sin(2\pi ft+\varphi_1) \end{aligned} \tag{10}$$

It can be seen that the IF signal with M^4-QAM is obtained. Therefore, all the codes transmitted by the OLT can be recovered by using the receiver in Fig. 1 without polarization demultiplexing. The corresponding graphic analysis is described in the third row of Fig. 2 as M=2.

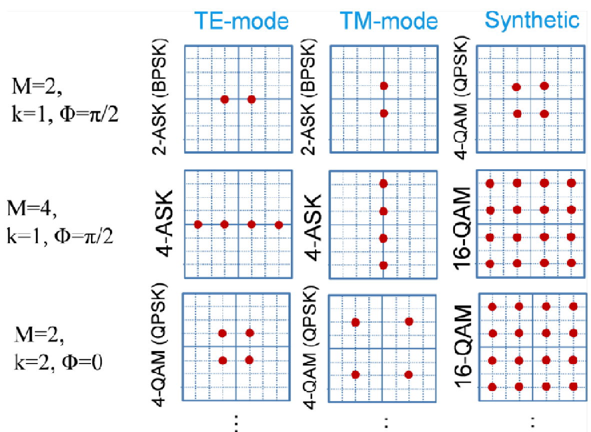

Fig. 2 Transfer relationship between the TE/TM mode optical coherent signals and the synthesized IF signal

In these two cases, the CPR algorithm and FEC decoding need not be executed in the ONU due to the fact that the RPF is controlled in optical domain. In addition the PCE algorithm also becomes unnecessary in the DSP unit because the polarization demultiplexing need not be executed in the proposed system.

3. Proof-of-concept experiment

3.1 Experiment setup

In order to verify the feasibility of our proposed scheme, a proof-of-concept transmission link with dual-polarization 2-ASK, i.e. binary phase shift keying (BPSK), modulation has been established. The experimental setup is displayed in Fig. 3 where we used two polarization-sensitive $LiNbO_3$ Mach-Zehnder modulators (MZM 2 and 3). In general, the ME of the $LiNbO_3$ is in the direction of the EAEF (Y-axis), namely the principal axis of the crystal which is around 3.58 times that in the orthogonal direction (X-axis) due to the electro-optical properties of the $LiNbO_3$ crystal [15]. As the Y-axis component of the injected light is

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modulated, the modulation for the X-axis component of the light is insignificant. Therefore, the optical 2-ASK (BPSK) modulation can be realized on the incident light at ν_0 of the POLs as the MZM2 and 3 are biased at null, i.e. the minimum transmission point (MITP) [16]. The phase-correlated signal light and reference light emerge after the polarizer in each mode.

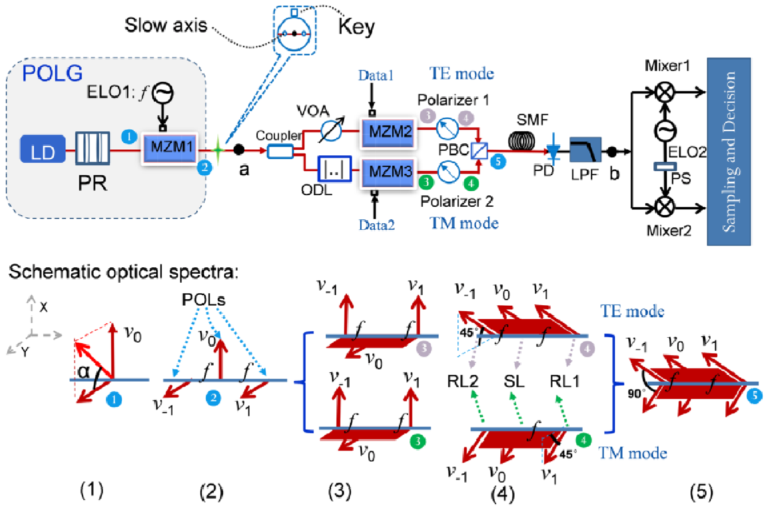

Fig. 3. Experiment setup of the dual-polarization 2-ASK coherent communication system; insets (1)-(5) are schematic representations of the optical spectra at different positions in the link. LD: laser diode; PR: polarization rotator; MZM: Mach-Zehnder modulator, LPF: low pass filter.

There are several methods for generating the POLs [17-19]. Here, we introduce a relatively simple method. The POLG consists of a commercial DFB-LD with around 2-MHz linewidth, a polarization rotator (PR), an ELO (ELO1) and a $LiNbO_3$ MZM (MZM1). Linearly polarized light with frequency of ν_0 emitted from the LD enters into the MZM1 via the PR, whose polarization direction is aligned at an angle α with respect to the principal axis of the MZM crystal. The PR comprises a quarter-wave plate and a rotatable polarizer which is used to control the angle of α. We also make use of the polarization sensitivity of MZM1 in the POLG. As the Y-axis component of the injected light is modulated in accordance with optical-carrier-suppression (OCS) at frequency f, the modulation for the X-axis component of the light is insignificant, as discussed above. Therefore, ±1st order optical subcarriers (OSs) ν_{-1} and ν_1 will be generated and the optical carrier (OC) ν_0 will be suppressed in the Y-axis direction. The OC ν_0 in the X-axis direction is reserved for heterodyne mixing (See the inset (2) of Fig. 3). Naturally, the orthogonal OC and OSs are POLs because they have the matched phases. The power ratio between the OC and OSs is controlled by adjusting the angle α. According to the principle described in Section 2, in order to obtain the phase-correlated signal light and reference lights at their respective optical frequency ν_0 and ν_1, the -1st order OS ν_{-1} should be removed by an optical filter before the POLs enter into the EOMs. However, this is not a necessary step in a real system because both OSs are pure tones and carry no information. In fact, the OS ν_{-1} can be transferred into an additional reference light (RL2, see inset (4) of Fig. 3) to increase the power of the synthesized IF signal as it passes through the polarizer after the EOM. Meanwhile, a low-pass filter (LPF) is used after the PD to filter out the pure microwave frequency at $2f$ which is generated by the beating between ν_{-1} and ν_1. This ensures that we can observe the regular eye diagrams of the IF-signal without the overlapping idle microwave.

It should be noted that, in this experiment, the key for connecting the polarization maintaining fiber and the POLG output port was modified so as to shift alignment with the slow axis of the PMF from 0° to 90°. This is to ensure that the OC ν_0, rather than the OSs ν_1 and ν_{-1}, can enter into the MZM2 and 3 along the principal axes of the modulators. In addition, the principal axis of polarizer 1 and 2 are rotated at 45º with respect to the slow axis of the PMF at the input ports of the polarizers. Hence, as the POLs pass through polarizer 1 or 2, the polarization direction of the OC v_0 also becomes aligned at 45º with respect to the X and Y axes. The synthesized IF signal was received and sampled by the real-time oscilloscope (OSC). The frequency down-conversion and demodulation of the signal were carried out off-line. An electrical spectrum analyzer (ESA) and optical spectrum analyzer (OSA) were used to investigate the electrical and optical spectra. Eye diagrams were observed with a sampling OSC. Points "a" and "b" marked in Fig. 3 are the test positions.

3.2 Experimental results

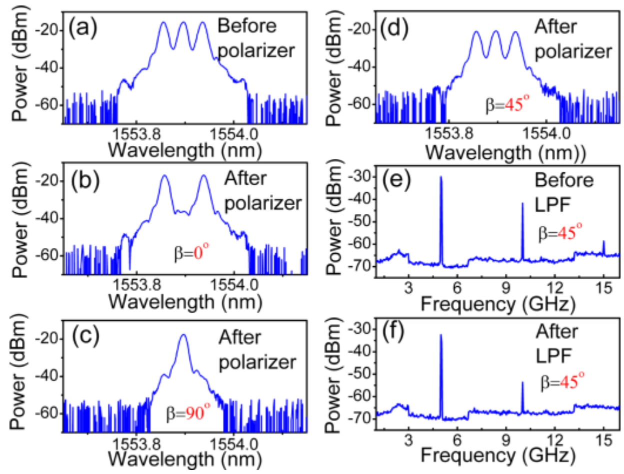

Fig. 4. Optical spectra of the POLG output measured before (a) or after the polarizer is set at β=0° (b), 90° (c), and 45° (d), electrical spectra of the POLG before (e) and after (f) the LPF with β=45°. β is the angle between the polarization direction of the OC v_0 and the principal axis of the polarizer.

Considering that the conventional channel spacing of the UDWDM-PON is 12.5 GHz, the frequency of ELO1 was set at 5 GHz. In order to investigate the performance of the POLG, a polarization controller (PC) and polarizer were inserted immediately after it. β is defined as the angle between the polarization direction of the OC v_0 and the principal axis of the polarizer. The optical and electrical spectra were measured and recorded at the test point "a". Fig. 4(a) shows the optical spectrum before the polarizer with α=39°. As expected, generally equal amplitude OC and OSs are generated. The optical spectra shown in Fig. 4(b)-(c) illustrate that the OC or the OSs can be selected when the angle β is set at 0° or 90° by adjusting the PC. These data imply that there is a good orthogonality between the OC and the OSs. At β=45°, half of optical power will be obstructed by the polarizer. This is shown in Fig. 4(d), where the power of the OC and OSs has decreased by 3 dB simultaneously. In the electrical domain, two pure microwave signals are retrieved (See Fig. 4(e)) by the beating between OC and OS lights, indicating excellent phase-correlation between the OC and OSs. Fig. 4(f) shows that the 2f microwave signal at 10 GHz is filtered out by the LPF and can be removed nearly completely by a better LPF.

When a 2.5 Gbit/s nonreturn-to-zero (NRZ) pseudo-random bit sequences (PRBSs) was applied to MZM2 or 3, a clear eye diagram IF-signal with 2-ASK (BPSK) modulation was obtained at test point "b" for each TE or TM mode (See Fig. 5(a)-(b)). The corresponding received optical power was around -15 dBm. When two independent NRZ-PRBSs at 2.5 Gbit/s were applied on the MZM 2 and 3 simultaneously, we can set k=1 and Φ=π/2 (i.e. verify Eq. (9)) by adjusting the VOA and ODL. It can be seen from Fig. 5(c) that an IF signal with 4-QAM was synthesized as expected. The eye diagram was recorded at an optical power of about -13 dBm. After 25-km SMF transmission, the received optical power dropped to around -18 dBm. In this case, the eye diagram shown in Fig. 5(d) is still clear, which indicates that signal distortion induced by chromatic dispersion (CD) and polarization mode dispersion (PMD) is insignificant in the experiment and the synthesized IF signal can be demodulated directly without polarization demultiplexing.

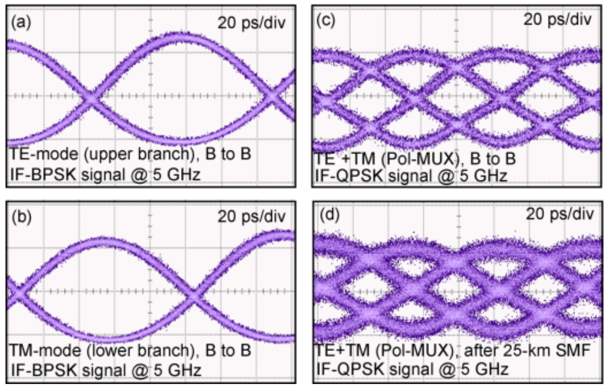

Fig. 5. Eye diagrams of the 5-GHz IF 2-ASK signal generated by beating between the phased-correlated signal light and reference light in TE mode (a), TM mode (b), and TE+TM modes (c)-(d). (a)-(c) were recorded as back-to-back (B-to-B) transmission, (d) was recorded after 25-km SMF transmission.

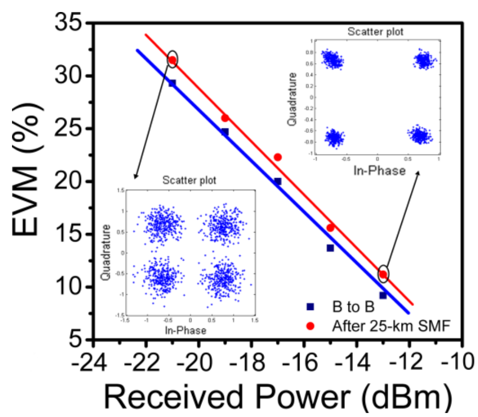

Fig. 6 EVM versus received optical power for synthesized IF signal as 2-ASK modulation at the TE and TM mode. Inset: the constellations after 25-km SMF transmission.

The synthesized IF signal was demodulated and recovered off-line. Fig. 6 shows that the error vector magnitude (EVM) performances versus different received optical powers for back-to-back (B to B) and 25-km SMF transmission. The power penalty is about 0.3 dB as the EVM is as low as 10%. The CD induced penalty is negligible considering the relatively short transmission distance and low bit rate. Thus, we infer that the power penalty mainly comes from the PMD. The insets in Fig. 6 display the constellations of the demodulated data after 25-km SMF transmission at different received power with corresponding EVMs of 32% and 11% respectively.

4. Discussion and conclusion

Due to the bandwidth limitation of the real-time OSC in our lab, only 5 Gb/s dual-polarization 2-ASK communication link was achieved in our experiment. However, the 16-QAM synthetic IF signal can be obtained after the PD as 4-ASK or 4-QAM modulation is achieved in each

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mode (See the second and third rows of Fig. 2). In the dual polarization 4-ASK scheme, two 4-level electrical signals should be applied to MZM 2 and 3. In contrast, four 2-level electrical signals must be applied to two I-Q modulators (if these are substituted for MZM2 and 3) to implement a dual polarization 4-QAM communication system. It seems that the hardware structure of dual polarization 4-ASK scheme is simpler than that of dual polarization 4-QAM scheme. Nevertheless, the baseband terms in Eq. (6) will include the amplitude information as the dual polarization 4-ASK scheme is adopted. The contingent spectrum overlap between the baseband terms and the IF terms in the frequency domain will induce the signal-to-signal beat interference (SSBI) which will degrade the signal-to-noise ratio of the transmission channel. Therefore, the dual polarization 4-QAM communication system is a better alternative considering no SSBI occurs in this scheme. Besides, as mentioned above, the ME along the principal axis of the $LiNbO_3$ crystal is around 3.58 times of that in the orthogonal direction. Therefore, as the multi-level electrical signal with large peak-to-peak voltage is applied to the $LiNbO_3$ MZM or I-Q modulator in order to realize higher order modulation formats, the, though small, co-lateral modulation of the reference light may no longer be ignorable. Fortunately, the pilot tone vector modulator (PTVM) described in [12] is the optimal EOM for our proposed scheme, which has the perfect polarization dependent property. If the PTVM is used, this problem may be solved.

In practice, one POLG which includes only one PR can handle many multiplexed wavelengths from different sources (or one array laser source). As long as the wavelengths are in the C or L bands, there should be negligible difference in the ME of MZM1. After the POLG demultiplexing can separate the wavelengths to realize the signal modulation. Moreover, since all of patchcords in the proposed OLT are polarization maintaining fiber, the external environmental factors hardly impact the angle α and the polarization state of the light. Additionally, because α could be calculated precisely according to polarization dependent loss (about 4 dB) and the half-wave voltage of MZM1, the PR could be replaced by a PMF patchcord with a specially designed connector key [16].

Since the frequency f of the IF signal is not higher than 5 GHz considering the narrow channel spacing of the UDWDM architecture (12.5 GHz generally), the corresponding IF signal wavelength in the delay line (ODL) is longer than 6 cm. Therefore, the phase delay, Φ, determined by the length of the delay line is insensitive to the external factors including the temperature and vibration. Moreover, the relatively low frequency of the heterodyne IF signal also suggests that the proposed scheme is insensitive to the CD and PMD for a fiber length of 25-km. However, the signal distortion induced by the PMD should be re-evaluated as the transmission distance is dramatically increased. This issue will be addressed in future work. In addition, the phase noise of the ELO should be improved in order to ensure the transmission performance if a higher order modulation format is applied.

In conclusions, we have proposed and demonstrated a dual-polarization coherent self-heterodyne UDWDM-PON system with simplified demodulation scheme. Because of the application of the POLs, the phase-correlated signal lights and reference lights in the TE and TM modes can be generated and emitted from OLT together. When the signal light in the each mode is modulated with M-ASK or M^2-QAM, the phase-stable IF signal with M-ASK or M^2-QAM will be generated in the corresponding mode due to beating between the signal light and reference light. The theoretical analysis shows that a new IF signal including all the information can be synthesized by the IF signals in both modes as the power ratio and time delay between the two-modes optical signals are set at the proper values in the OLT. The synthesized IF signal can be received and demodulated without using polarization demultiplexing and DSP algorithms. A proof-of-concept transmission link with dual-polarization 2-ASK has been demonstrated. Comparing with other relevant competing approaches described in [10]-[14], our method can realize a dual-polarization coherent optical

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signal transmission without increasing the complexity and cost of the receiver, which means that the cost and power consumption of the ONUs can be reduced dramatically in the next generation UDWDM-PON.

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