Demonstration of an optical phase conjugation based dual-hop PDM-QPSK free-space optical communication link

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The dual-hop free-space optical (FSO) communication link for polarization-division multiplexing quadrature phase-shift keying (PDM-QPSK) signals is proposed and experimentally demonstrated in an atmospheric chamber with the optical phase conjugation (OPC) compensating the turbulence-induced signal distortions. The phase fluctuations can be effectively reduced by the OPC, as the error vector magnitudes are 10.03% and 8.28% decreased for x- and y-polarization. At the bit error rate of 1×10^{-3}, the power penalty of the dual-hop link with OPC is 2.85 or 2.34 dB lower than that of each polarization without OPC.

Introduction: Free-space optical (FSO) communications have been well concerned owing to the high-speed and large capacity data transmission, broad unlicensed spectrum, easy and quick deploy-ability, and enhanced security [1–4]. Despite of great potentials of FSO communications, its performance is strongly influenced by the atmospheric turbulence, which will lead to the random wavefront distortion and serious signal degradation [5]. To compensate the turbulence-induced signal distortions, we have demonstrated the optical phase conjugation (OPC) in the dual-hop FSO communication links [6]. Although many works used OPC with the free space optics, they focused on achieving the laser target-aiming and improving the energy concentration of the laser spot in the imaging systems [7]. The OPC has a simple structure, short response time, and a minor limitation of the affordable spatial frequencies owing to its all-optical characteristics [8]. The signal phase distortion can be conjugated and compensated as the optical carrier propagating back through the atmospheric channel.

Polarization-division multiplexing (PDM) is a valid technology to enhance the transmission capacity and improve the spectral-efficiency by transporting two different data streams using the orthogonal polarization states [9, 10]. However, for FSO communications, the turbulence can change each information-carrying dimension of the signal containing its polarization state, and may lead to the crosstalk between two orthogonal polarized signals [11]. Although we have illustrated the validity of OPC compensation for the non-multiplexing FSO link [6], its compatibility with PDM-FSO links is still uncertain. In this letter, the compensation of OPC is demonstrated for the turbulence-induced signal distortion in a dual-hop FSO transmission with 10 Gb/s PDM quadrature phase-shift keying (QPSK) signals. The experimental results show that the PDM-QPSK signals can be effectively demodulated in the weak turbulence regime (generated by an atmospheric chamber).

Experimental scheme: The scheme of the OPC-based dual-hop FSO transmission for PDM-QPSK signals is depicted in Figure 1. At terminal 1, the optical carrier is launched by a distributed feedback laser with a wavelength of 1550.1 nm. The QPSK signal is generated by modulating two 2.5 Gb/s 2^{15}-1 pseudo-random binary sequences (PRBSs) through an electro-optical I/Q modulator (Fujitsu FTM7962). After being modulated, it is separated into two paths via a 3-dB optical coupler. For one path, a time-delay is introduced by the optical delay line (ODL) to eliminate their correlation. As for the other path, a variable optical attenuator (VOA1) is used to tune the optical power for balancing the two path powers. The polarization states of the two paths are adjusted by the polarization controllers (PC2 and PC3) since they need to be orthogonal. A polarization beam combiner (PBC) is inserted to recombine the two paths and generate the 10 Gb/s PDM-QPSK signal. And then, the signal is amplified to 13 dBm and collimated into free-space through circulator 1 and collimator 1 (Thorlabs F810FC-1550). The propagation channel is established in a 1.5-m-long atmospheric chamber and the turbulence is demoed by introducing a temperature difference between its upper and lower plates, whose distance is about 0.3 m. As the temperature difference increases, the turbulence will get stronger. The turbulence generated in the chamber belongs to the weak turbulence regime, while the Rytov variances σ_R^2 are measured to be 0.0062 for the temperature difference ΔT of 100 °C and 0.1231 for 250 °C [12]. Namely, the atmospheric channels with the temperature difference of 100 and 250 °C are comparable to the 1-km-long outdoor channel with the atmospheric refraction-index structure parameter C_n^2 of 3.11×10^{-16} and 6.18×10^{-15} $m^{-2/3}$. After transmitting through the atmospheric chamber, the distorted signal is delivered to the OPC unit when it is received by the collimator 2 (Thorlabs F810FC-1550) at terminal 2.

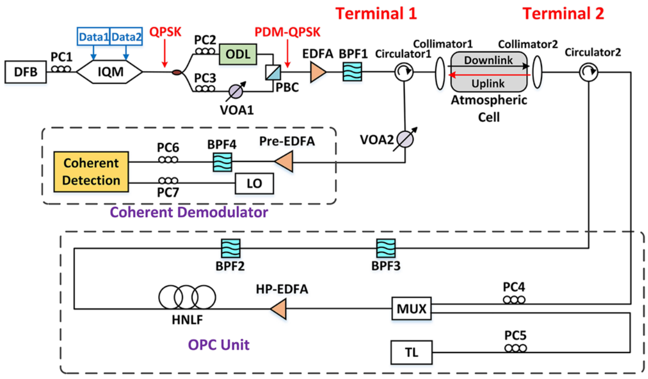

Fig. 1 *Experimental scheme of the PDM-QPSK dual-hop FSO transmission with the OPC compensation*

The OPC is generated by the degenerate four-wave mixing (DFWM) process. The distorted signal is combined with a continuous-wave pump and amplified using a high-power erbium-doped fiber amplifier (HP-EDFA) to a total power of 23.2 dBm. Then, they are launched into a 110-m-long highly nonlinear fiber (HNLF). In the HNLF, the DFWM process occurs to generate the OPC wave. By adjusting PC5, the pump polarization is changed to an appropriate angle to ensure the conversion efficiencies of the two polarization signals nearly the same [13]. The converted OPC wave will carry the PDM-signal and the conjugated distorted phase. After being filtered by the band-pass filters (BPF2 and BPF3), the OPC wave reflects to free-space through circulator 2 and collimator 2 and propagates back through the atmospheric channel. At terminal 1, a polarization and phase-diverse coherent detection can be realized by the coherent demodulator including a pre-amplifier (Pre-EDFA), a band-pass filter, a local oscillator, and a coherent lightwave signal analyser. A variable optical attenuator (VOA2) is used to change the received power of the signal for BER performance measurement.

Results and discussion: The attenuations of the downlink and uplink transmission are 13.2 and 12.9 dB, respectively, which can be attributed to the atmospheric propagation losses and the coupling losses between free-space and the fibers. Figure 2 shows the measured optical spectrum after the HNLF for the OPC. The OPC wave is generated at 1546.9 nm whose conversion efficiency is −17.5 dB, and the power is measured to be −0.4 dBm.

As shown in Figure 3, at the temperature difference ΔT of 250 °C and the received power of −32 dBm, the constellation diagrams of the PDM-QPSK signal are tested for the dual-hop link with OPC together with those for the back to back (BTB) transmission, the single-trip link, and the dual-hop link without OPC. In contrast to the BTB transmission with root-mean-square (RMS) error vector magnitudes (EVMs) of 32.39% and 31.84% (for x- and y-polarization signals), the RMS EVMs of the single-trip link and the dual-hop link without OPC are measured to be 37.86%, 36.45%, 43.64%, and 41.08%, respectively. The phase

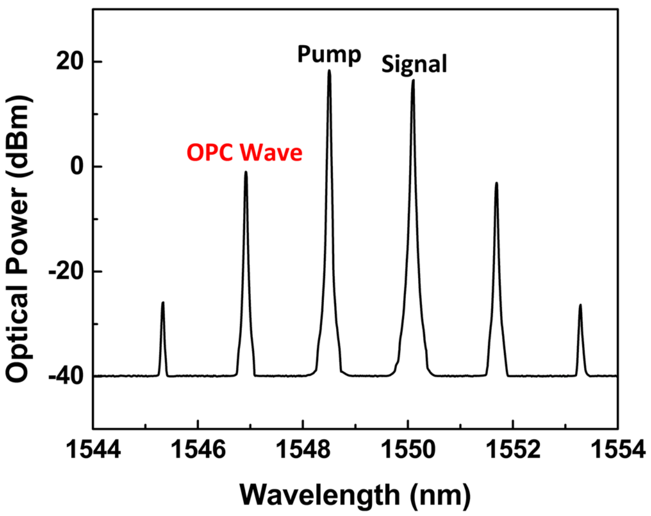

Fig. 2 *Optical spectrum of the OPC wave generation at the end of the HNLF*

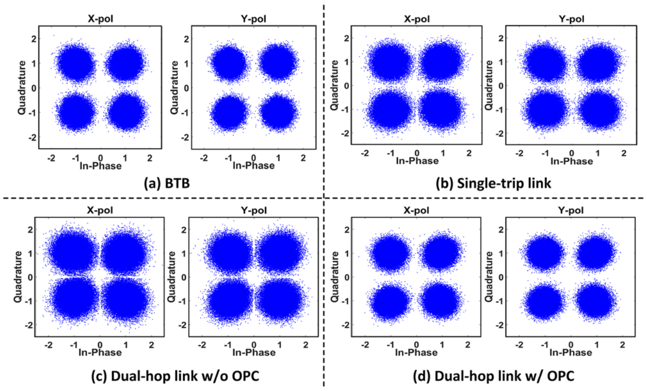

Fig. 3 *Constellation diagrams for PDM-QPSK signals of (a) the BTB, (b) the single-trip link transmission, (c) the non-compensation dual hop link transmission, and (d) the OPC-compensated dual-hop link transmission*

fluctuations of the single-trip signals increase compared with the BTB signals and the performances of the non-compensation dual-hop link are even worse, which are caused by the accumulation of the turbulence-induced signal degradation. As for the dual-hop link with OPC, the RMS EVMs are obtained to be 33.61% and 32.80%, which are 10.03% and 8.28% decreased in contrast to the link without OPC. It is exhibited that the phase fluctuation of the received signal can be effectively reduced by the OPC.

Figure 4 shows the BER performances for the BTB transmission, the single-trip link, the dual-hop link without OPC, and the dual-hop link with OPC under the conditions of $\Delta T = 0,\ \ 100,\ \ 250\ ^{\circ}$C. As shown in Figure 4a, with the temperature difference $\Delta T = 0\ ^{\circ}$C, due to the negligible turbulence, the performance differences between the FSO transmissions are insignificant. When the temperature difference ΔT rises to 100 °C, as shown in Figure 4b, a considerable improvement can be obtained by the OPC compensation, and the improvement is larger for the link under the temperature difference of $\Delta T = 250\ ^{\circ}$C, as shown in Figure 4c. At the BER of 1×10^{-3}, the measured sensitivities for the two orthogonal signals of FSO transmissions are summarized in Table 1. For the BTB case, the sensitivities of the *x*- and *y*-polarization signals are −35.70 and −36.06 dBm, respectively. Under the condition of ΔT = 250°C, the power penalties of the single-trip link for the two polarization signals are 2.23 and 2.21 dB, while they are 3.72 and 3.42 dB for the non-compensation dual-hop link. In contrast to the single-trip link, due to the double-pass propagation through the atmospheric turbulence, the dual-hop link without OPC suffers more from the turbulence effect and leads to a worse BER performance. The power penalties for the OPC-compensated dual-hop link are 0.87 and 1.08 dB, while 2.85 and 2.34 dB penalty improvements can be obtained compared with the non-compensation dual-hop link. The power penalties are significantly improved, which indicates that the signal degradations are mitigated,

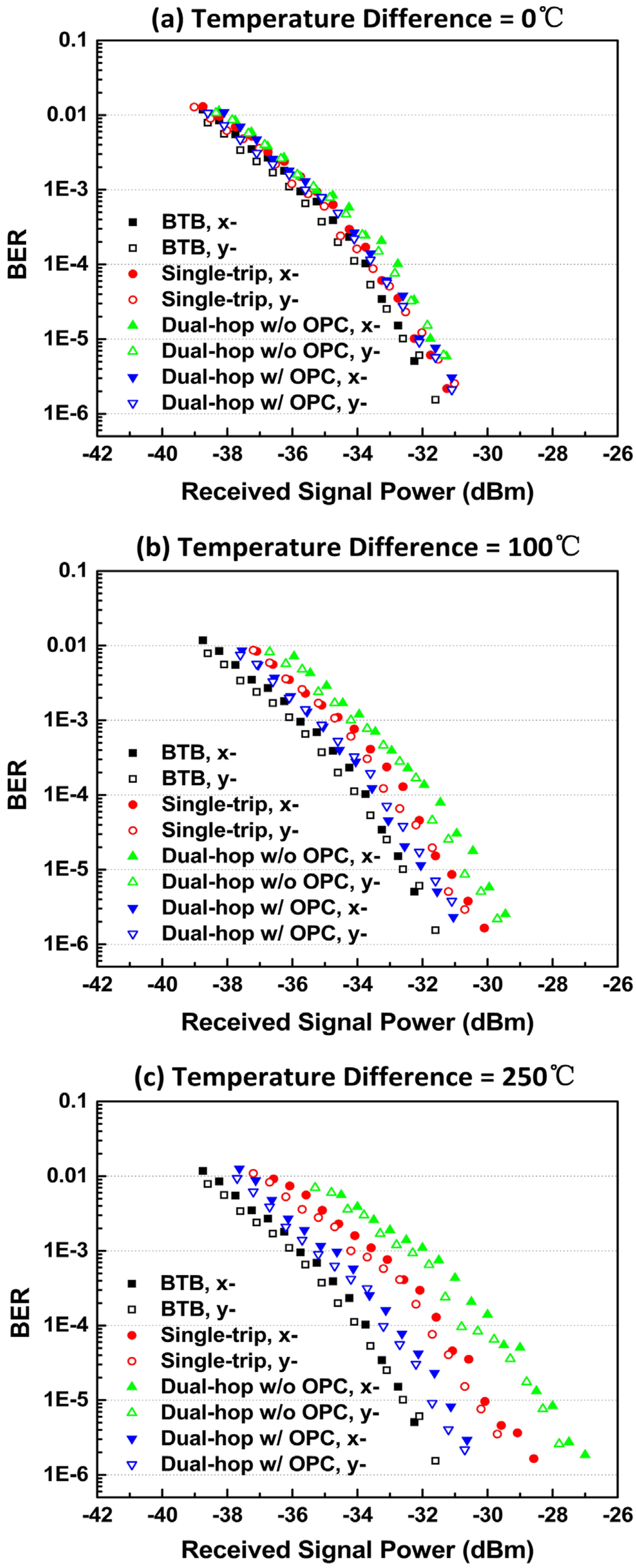

Fig. 4 *BER performance of the PDM-QPSK signals for the BTB transmission and three different FSO transmissions at the temperature differences of (a) 0 °C, (b) 100 °C, and (c) 250 °C, respectively*

and the phase distortions caused by turbulence are well compensated. Although our experiment is performed in laboratory, an outdoor long-distance turbulent channel can be simulated by the atmospheric chamber. Therefore, the OPC compensation has the potential to be used in real outdoor FSO links. In future FSO communication networks, the OPC unit can be applied to the relay node to guarantee the availability of the backhaul link. It can also be used in the FSO self-healing ring as a protection structure [14].

Table 1. Received sensitivities and power penalties for the PDM-QPSK signals of FSO transmissions at the BER of 1×10^{-3}

Temperature difference	Signal polarization	Sensitivity (dBm) Single-trip	Dual-hop w/o OPC	Dual-hop w/ OPC
0°C	*x*-	−35.26	−34.87	−35.48
	y-	−35.55	−35.11	−35.54
100°C	*x*-	−34.35	−33.69	−35.32
	y-	−34.79	−33.91	−35.11
250°C	*x*-	−33.47	−31.98	−34.83
	y-	−33.85	−32.64	−34.98
/	/	Power penalty (dB)		
0°C	*x*-	0.44	0.83	0.22
	y-	0.51	0.95	0.52
100°C	*x*-	1.35	2.01	0.38
	y-	1.27	2.15	0.95
250°C	*x*-	2.23	3.72	0.87
	y-	2.21	3.42	1.08

Conclusion: The OPC compensation has been experimentally demonstrated for the turbulence-induced signal distortions in the dual-hop PDM-QPSK FSO link. The EVMs and BER performances have been tested in contrast to the single-trip link and the non-compensation dual-hop link in an atmospheric chamber. The OPC compensation can mitigate the signal phase fluctuations, as the error vector magnitudes are decreased by 10.03% and 8.28% for the *x*- and *y*-polarization signals. At the BER of 1×10^{-3}, the power penalties of OPC-compensated dual-hop link are 2.85 and 2.34 dB lower than those of the link without OPC, when the temperature difference ΔT is 250 °C.

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