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Generation of 1.024-Tb/s Nyquist-WDM phase-conjugated twin vector waves by a polarization-insensitive optical parametric amplifier for fiber-nonlinearity-tolerant transmission

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Abstract: We experimentally demonstrate the generation of 1.024-Tb/s Nyquist-WDM phase-conjugated vector twin waves (PCTWs), consisting of eight 128-Gb/s polarization-division-multiplexed QPSK signals and their idlers, by a broadband polarization-insensitive fiber optic parametric amplifier. This novel all-optical signal processing approach to generate WDM-PCTWs enables a 2-fold reduction in the needed optical transmitters as compared to the conventional approach where each idler is generated by a dedicated transmitter. Digital coherent superposition of the twin waves at the receiver enables more than doubled reach in a dispersion-managed transmission link. We further study the impact of polarization-mode dispersion on the performance gain brought by the phase-conjugated twin waves, showing a gain of ~3.8 dB in signal quality factors.

OCIS codes: (190.4970) Parametric oscillators and amplifiers; (190.5040) Phase conjugation; (060.2330) Fiber optics communications.

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1. Introduction

Fiber nonlinearity imposes major impairments that limit the achievable transmission distance of optical communication systems [1,2]. Various techniques have been proposed to mitigate nonlinear impairments with the use of optical signal processing [3,4] and more recently also digital signal processing (DSP) [5–7]. It was recently shown that co-propagating phase-conjugated twin waves (PCTWs) experience anti-correlated nonlinear distortions, and nonlinearity mitigation can be achieved by coherently superimposing the twin waves at the receiver [8], effectively trading spectral efficiency for ultra-long-haul performance. It has been shown that longer transmission distance can be obtained by using lower-level modulation formats with lower spectral efficiency [9]. When the PCTW approach is applied to QPSK signals, it provides more than doubled reach with halved spectral efficiency, which may be beneficial in certain ultra-long-haul applications [10]. A 406.6-Gb/s superchannel consisting of eight QPSK signals, each with its twin wave modulated at the same wavelength but on the orthogonal polarization, was transmitted over a distance of 12,800 km in a TrueWave reduced slope (TWRS) fiber link. To further mitigate inter-channel nonlinear impairments, it was suggested to form wavelength-division-multiplexed (WDM) PCTWs where one polarization of the entire WDM spectrum is the phase-conjugated and spectrally-inverted copy of the other polarization [8,10]. To generate such broadband WDM-PCTWs, fiber optic parametric amplifiers (OPAs) [11,12] are well suited. Recently, we reported the generation of the first Tb/s WDM-PCTWs [13], consisting of eight Nyquist-WDM [14] 128-Gb/s polarization-division-multiplexed (PDM or vector) QPSK signals and their corresponding idlers that are converted by using a broadband polarization-insensitive (PI) OPA. Through all-optical processing, this approach halves the number of transmitters needed for all-digitally generated PCTW transmission. The converted idlers exhibit similar quality as the signals, and provide over 3.8 dB performance gain when coherently superimposed with the signals after nonlinear transmission, enabling the 1.024-Tb/s Nyquist-WDM signals to be transmitted over 40 × 100-km dispersion-managed TWRS spans; this more than doubles the distance achieved without digital coherent superposition (DCS) of the PCTWs. Here, we present this study in more depth, and investigate the impact of polarization-mode dispersion (PMD) on the performance gain of the DCS of the PCTWs, showing the benefit of the DCS in improving the worst-case signal qualities and in tightening the performance distribution.

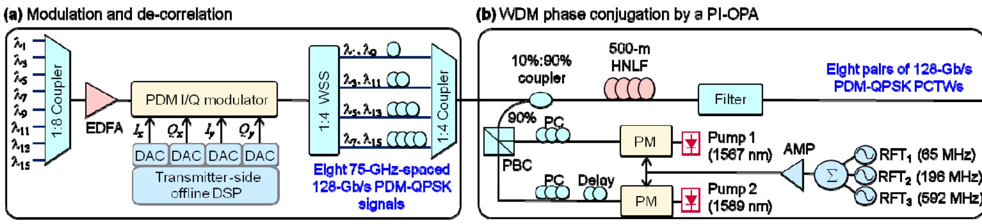

Fig. 1. (a) Experimental setup for the modulation and de-correlation of 8 128-Gb/s PDM-QPSK signals; (b) PI-OPA setup for simultaneous optical phase conjugation of the signals. EDFA: erbium-doped fiber amplifier; DAC: digital-to-analog converter; WSS: wavelength-selective switch; PC: polarization controller; PM: phase modulator; AMP: electronic amplifier; RFT: radio-frequency tone; HNLF: highly nonlinear fiber;

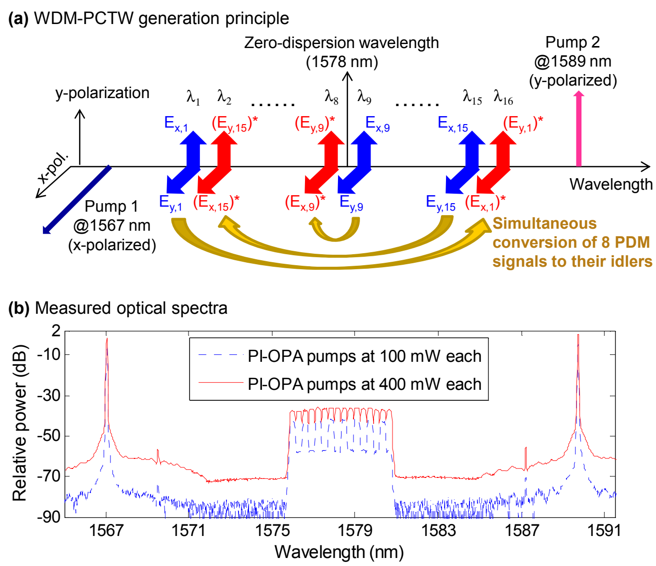

Fig. 2. (a) Illustration of the principle of the generation of the WDM-PCTWs by a PI-OPA; (b) Measured optical spectra of the converted idlers, together with the signals and the pumps.

2. Generation of WDM-PCTWs

Figure 1 shows the schematic of the experimental setup used for the generation of WDM-PCTWs. In the modulation stage (a), eight 75-GHz spaced external cavity lasers were modulated by one PDM inphase/quadrature (I/Q) modulator. The four drive signals for the modulator were provided by four 64-GSa/s digital-to-analog converters (DACs). The inputs to the DACs were provided by a field-programmable gate array with stored signal waveforms. Pseudo-random bit sequences of length 2^{15}-1 were first encoded and mapped to PDM-QPSK symbols. Root-raised-cosine filtering with a roll-off factor of 0.1 was used. The oversampling ratio was two, resulting in 32-Gbaud signals. To accurately represent real-world applications, sufficient de-correlation between modulated channels is needed [15,16]. We first used a 1:4 wavelength-selective switch (WSS) to separate the signals into four paths with different path

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lengths. The delay difference between any two of the four paths was at least 100 symbol periods. The de-correlated signals were then combined by a 1:4 coupler before entering the PI-OPA for the simultaneous generation of their idlers. The configuration of the PI-OPA is shown in Fig. 1(b). We used two pumps at 1567 nm and 1589 nm, each having a linewidth of <100 kHz. They were phase-modulated to suppress stimulated Brillouin scattering (SBS) by two $LiNbO_3$ phase modulators (PMs), each of which was driven by the sum of three RF tones (RFTs) at 65.2, 196.1, and 592.6 MHz. Note that the frequencies were fine-tuned around their nominal frequencies having a ratio of 1:3:9 to maximally suppress SBS. After modulation, the two pumps were suitably delayed to achieve optimum counter-phasing in order to obtain the highest phase coherence in the OPA process. Their polarizations were then controlled by two polarization controllers (PCs) and combined by a polarization beam combiner (PBC). The orthogonally polarized pumps were combined with the input PDM (vector) signals through a 10%:90% coupler, whose 90% port was connected to the pumps and 10% port to the signals. The combined signals and pumps were launched into a 500-m highly nonlinear fiber (HNLF), whose zero-dispersion wavelength, nonlinear coefficient, and dispersion slope were 1578 nm, 20 W^{-1} km^{-1}, and 0.02 ps nm^{-2} km^{-1}, respectively. Finally, a bandpass filter was used to remove the residual pumps, so that only the signals and their corresponding idlers would subsequently be launched into a transmission link.

Figure 2 shows the WDM-PCTW generation principle in more detail. The mean frequency of the two pumps was tuned to be 18.75 GHz lower than the center frequency of channel 9 (λ_9), so that after phase conjugation of the eight 75-GHz-spaced signals, eight 75-GHz-spaced idlers were generated with a spacing of 37.5 GHz from the signals. Consequently, signal field $E_{x(y),n}$ (n being the channel index) was converted to idler field $(E_{y(x),17-n})^*$, where * denotes the complex conjugate. Thus, Nyquist-WDM PCTWs with 32-Gbaud signals and idlers fully de-correlated and spaced at 37.5-GHz spacing (compatible with the flexible-grid WDM standard, ITU-T G.694.1) were formed. The PI-OPA produced a gain of 10 dB, resulting in a small power difference between the converted idlers and the amplified signals of <0.5 dB. Figure 2(b) shows the optical spectra at the output of the HNLF measured at two different pump powers (measured at the input of the HNLF), 400 mW and 100 mW. Clearly, the PI-OPA achieved the simultaneous phase conjugation of the WDM signals with sufficient optical power (for the subsequent transmission) and good power uniformity.

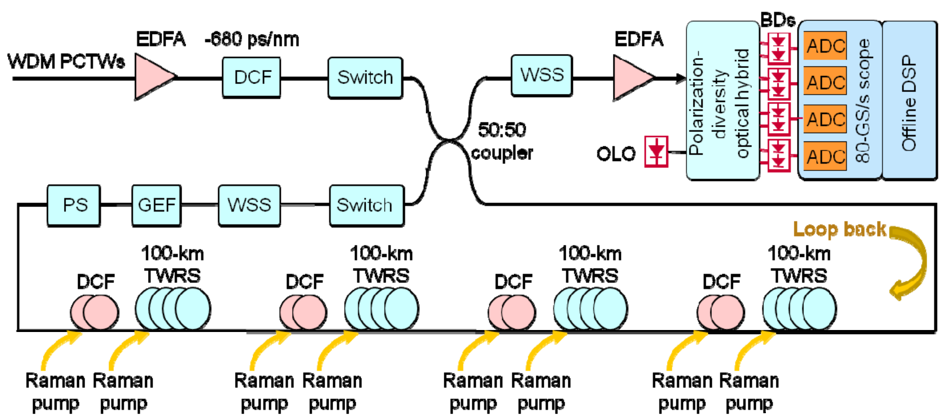

Fig. 3. Experimental setup for the re-circulating transmission link and offline-DSP based digital coherent receiver. EDFA: erbium-doped fiber amplifier; DCF: dispersion-compensating fiber; TWRS: TrueWave reduced slope fiber; WSS: wavelength-selective switch; GEF: gain-equalization filter; PS: polarization scrambler; OLO: optical local oscillator; BDs: balanced detectors; ADC: analog-to-digital converter.

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3. Experimental setup and back-to-back performance

To test the nonlinear transmission performance of WDM-PCTWs, we used a commonly deployed dispersion-managed TWRS fiber link, which for coherent systems typically exhibits more severe nonlinear distortions than a dispersion-unmanaged link [5]. Figure 3 shows the link setup. The WDM PCTWs were pre-compensated by a dispersion-compensating fiber (DCF) with −680 ps/nm dispersion, before entering a re-circulating fiber loop consisting of 4 × 100-km TWRS spans with 5.5-ps/nm/km dispersion coefficient, each compensated by a DCF to have a residual dispersion per span of ~30 ps/nm. Backward Raman amplification was used to compensate both the span loss (~22 dB) and the DCF loss (~5 dB). A 1-kHz polarization scrambler (PS) and gain-equalizing filter (GEF) were used in the loop setup. The receiver setup is a typical digital coherent receiver setup with offline digital signal processing (DSP) [8,17]. Similar to [17], all the signals and idlers, which contained repetitive patterns with a pattern length of 2^{15} symbols, were detected and stored before offline DSP. For digital coherent superposition (DCS), the recovered field of a signal, $E_{x(y),n}$, was coherently added with that of its idler, $(E_{y(x),17\text{-}n})^*$ after digital constellation, phase recovery, and pattern synchronization [8,17]. Figure 4(a) shows the baseline performance of both signals and idlers after the broad-band PI-OPA. Over one million bits were recovered for each measurement, and no errors were found. We thus use the constellation noise variance to estimate the Q^2-factor. Sample recovered signal and idler constellations are shown in Fig. 4(b). Remarkably, the converted idlers exhibit similar quality as the signals: the differences between the signals and their corresponding idlers are less than 0.4 dB. Moreover, the Q^2-factors of all 16 signals and idlers are within 0.6 dB of each other. This underlines the attractiveness of the broadband PI-OPA for the generation of WDM PCTWs.

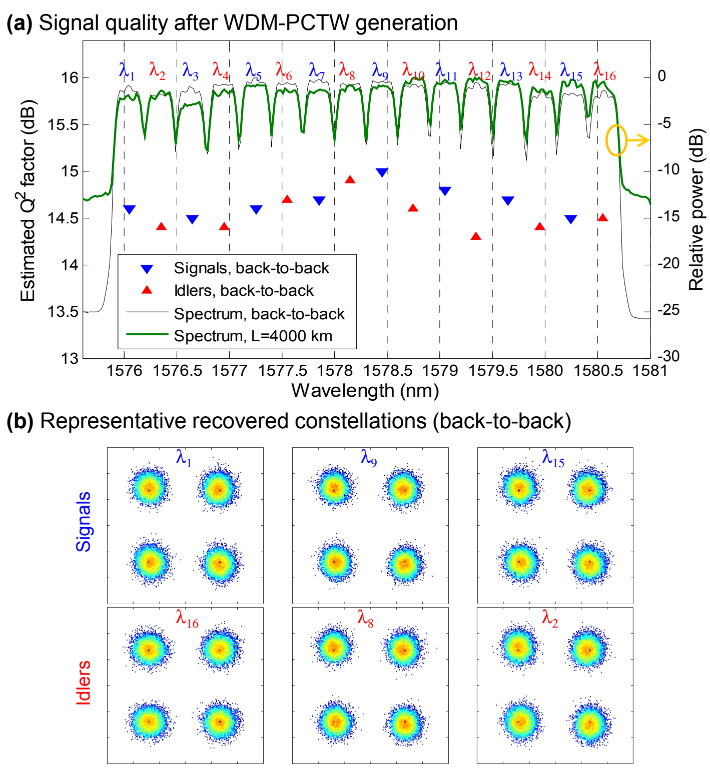

Fig. 4. (a) Estimated Q^2-factor for signals and idlers after broadband phase conjugation by the PI-OPA; (b) Representative recovered constellations of signals and idlers.

4. Transmission results

Figure 5(a) shows the mean transmission performance as a function of signal launch power per channel. Each data point shown in the figure was obtained by averaging over five different BER measurements in order to reduce the PMD-induced BER fluctuations. The statistical performance behavior due to PMD will be discussed in the following section. At low signal launch powers, the gain in Q^2 is 3 dB, as expected from linear path diversity considerations. At the optimal signal launch power (~-7 dBm), the DCS of the PCTWs provides a typical performance gain of 3.6 dB. Note that the DCS of signals alone only provides a performance improvement (at optimal signal launch power) of ~2 dB, due to correlated signal-to-signal nonlinear distortions [17]. The gain is increased to 4.2 dB at −6 dBm signal launch power, and could be even higher if the baseline performance was further improved, e.g., by increasing the optical signal-to-noise ratio (OSNR) of the transmitter. Figure 5(b) shows the transmission performance as a function of transmission distance. In dispersion-managed transmission, doubling the reach usually leads to a Q^2-factor reduction of more than 3 dB [18]. DCS of the PCTWs provides a more favorable decrease of Q^2 with distance. At 8.5-dB Q^2-factor (corresponding to a BER of 3.8×10^{-3}), a typical threshold of 7%-overhead hard-decision forward error correction (FEC) [19], DCS of the PCTWs more than doubles the transmission reach, from ~2200 km to 4800 km. Figure 6 shows the measured Q^2-factors (derived from measured BER values) for all the 16 channels after 4000-km transmission. Without DCS, half of the measured BERs exceed 2.4×10^{-2}. With DCS, all the BERs are below the HD-FEC threshold of 3.8×10^{-3}.

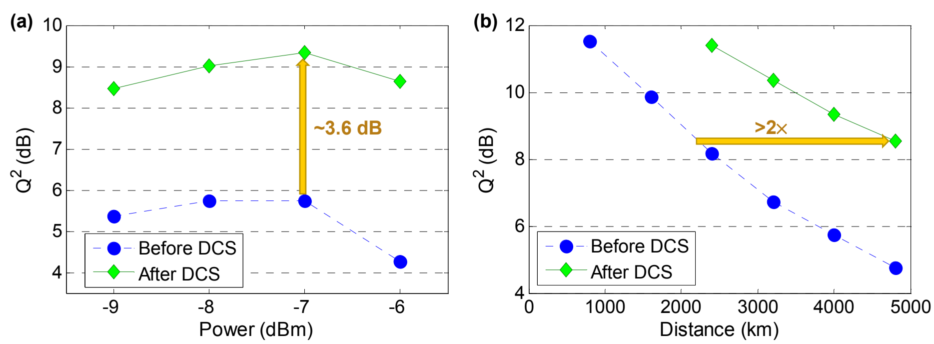

Fig. 5. (a) Measured mean Q^2-factor (derived from BER) vs. signal launch power per channel (P_{in}) at 4000 km; (b) Measured mean Q^2-factor vs. transmission distance with $P_{in} = -7$ dBm.

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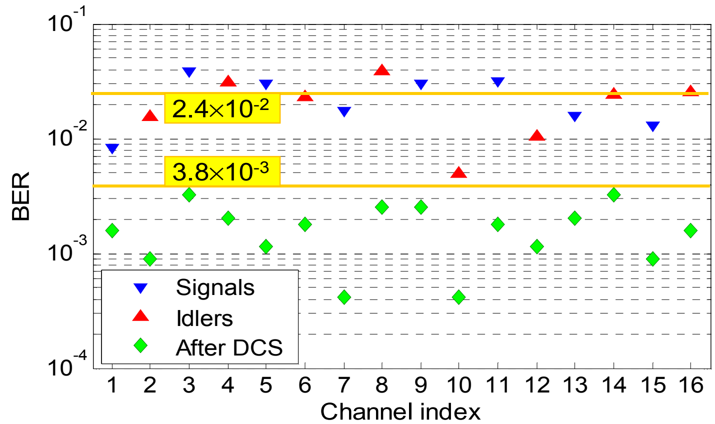

Fig. 6. Measured BER as a function of channel index after 4000-km transmission over 40 dispersion-managed 100-km TWSR fiber spans at P_{in} = −7 dBm.

5. Impact of PMD

It was speculated in earlier work that the benefit of PCTW transmission might be reduced by polarization-mode dispersion (PMD). The dispersion-managed TWRS link tested here had a mean PMD coefficient of ~0.15 ps/km$^{1/2}$, leading to a mean differential group delay (DGD) of ~9.5 ps after 4000-km transmission. To study the resulting statistical performance behavior, we made 13 separate measurements of a signal (λ_9) and its idler (λ_8), which capture different instantaneous PMD values due to the use of the loop PS. For the DCS case, we coherently superimposed each of the measured signal fields with each of the measured idler fields, effectively resulting in 169 measurements. Figure 7 shows the histograms of the measured Q^2-factors. The distributions of the signal and idler Q^2-factors spread over about 4 dB, ranging from 5 dB to ~9 dB. This is reasonable as large instantaneous DGD may reduce the nonlinear penalty, and lead to better overall signal quality when the DGD is compensated [20–22], e.g., by a coherent receiver in this case. Interestingly, after the DCS of the PCTWs, the Q^2-factor distribution becomes better confined, to a 2.5-dB range. The lowest Q^2-factor after DCS of the PCTWs is 9 dB, which is ~3.8 dB higher than that of the lowest signal Q^2-factor (~5.2 dB). The gain could be even higher if the baseline performance was further improved by using more powerful EDFAs to increase the optical OSNR of the transmitter. This indicates that in the presence of large PMD, PCTW transmission is still beneficial in that (i) it uses diversity (via different-wavelength signal and idler) to limit the performance variation, and (ii) it tends to become most effective when the nonlinear distortions are the largest (or when nonlinearity mitigation is most needed) due to small instantaneous DGD. This PCTW approach provides the flexibility of trading half the spectral efficiency with more than 3 dB improvement in performance, leading to system cost savings in certain applications [8,10].

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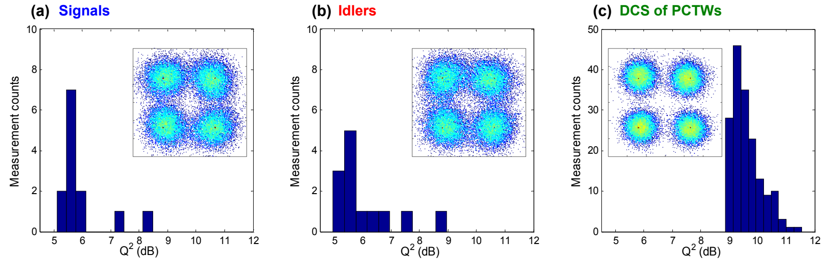

Fig. 7. Histograms of sample measured Q^2-factors (derived from the BER) for the signals (a), the idlers (b), and the DCS of the signals and their corresponding idlers (c). Distance: 4000 km. $P_{in} = -7$ dBm. Insets: representative worst-case constellations.

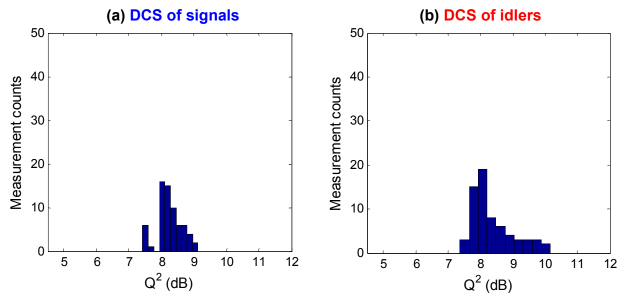

Fig. 8. Histograms of sample measured Q^2-factors for the DCS of the signals (a) and the DCS of the idlers (b), clearly indicating worse overall performance than the DCS of the signals and their corresponding idlers as shown in Fig. 7(c). Distance: 4000 km. $P_{in} = -7$ dBm.

To further verify the performance advantage of DCS of PCTWs as compared to DCS of just signals [17] or idlers, we show in Fig. 8 the histograms of the measured Q^2-factors after DCS of the signals in different wavelength channels (a) and after DCS of the idlers in different channels (b). The lowest Q^2-factor obtained after DCS of the signals or the idlers is ~7.5 dB, resulting in a gain of ~2.3 dB with respect to the lowest signal Q^2-factor. This gain is ~1.5 dB lower than that obtained by DCS of PCTWs, clearly showing the benefit of using PCTWs for DCS.

Note that an OPA was recently used to convert a single-wavelength 112-Gb/s PDM-QSPK signal to its idler at a different wavelength [23]. At the receiver, DCS of the signal and the idler was conducted, and a performance gain of 2.4 dB was observed. We attribute the higher gain (~3.8 dB) observed in the work reported here to the fact that (i) the essential dispersion-symmetry condition needed for achieving the optimal PCTW performance [8] was satisfied in our work, and (ii) the WDM-PCTW approach made one polarization of the entire WDM spectrum to be the phase-conjugated and spectrally-inverted copy of the other polarization, thereby further mitigating inter-channel nonlinear effects [10].

6. Conclusions

We have experimentally generated 1.024-Tb/s Nyquist-WDM PCTWs consisting of eight 128-Gb/s PDM-QPSK signals and their corresponding idlers, converted by a broadband PI-OPA. This novel all-optical signal processing approach in conjunction with modest electronic DSP has been shown to provide the performance gain offered by WDM-PCTW and offers a 2-fold reduction in the needed optical transmitters as compared to the conventional approach. It is also shown that in the presence of large PMD, the DCS of PCTWs effectively improves the worst-case signal qualities and tightens the performance distribution. The WDM-PCTWs based transmission scheme may also be compatible with the emerging class of low-noise phase-sensitive amplifiers [12,24] to improve signal immunity to both nonlinear distortions and amplified spontaneous emission noise for future optical transmission systems.

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