Polarization crosstalk canceller for forward-pumping distributed Raman amplification

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Abstract: This paper proposes a novel polarization crosstalk canceller (PCC) based on receiver digital signal processing (DSP) in polarization division multiplexed digital coherent transmission utilizing forward-pumping distributed Raman amplification (DRA). The PCC consists of 1-tap adaptive filters with a butterfly configuration controlled by the recursive least square algorithm. The PCC offsets the crosstalk between two polarization tributaries caused by the time-varying polarization fluctuation due to the relative intensity noise of the forward-pumping sources. The proposed PCC is applied to the long-haul dual-polarization QPSK transmission experiment with forward-pumping DRA, and confirmed to improve the transmission performance.

Keywords: Optical fiber communication, distributed Raman amplification, RIN transfer

Classification: Transmission Systems and Transmission Equipment for Communications

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1 Introduction

Large capacity long-haul optical transmission systems based on coherent reception and polarization division multiplexing (PDM) have been extensively deployed in optical transport networks in order to support the ever-increasing data traffic. Distributed Raman amplification (DRA) is a powerful technique to extend the attainable distance and the repeater spacing in such large capacity transmission. In particular, first-order backward-pumping schemes have been widely deployed in commercial networks to improve the received optical signal to noise ratio (OSNR) without increasing nonlinear impairments [1, 2].

Forward-pumping scheme is very attractive in order to extend the benefits of DRA. By using forward-pumping in addition to conventional backward-pumping, signal power variation along the fiber can be reduced, and thus receiver OSNR improvement and suppression of nonlinear distortion can be expected.

In forward-pumping configuration, however, signal and pump lights propagate with the same direction through the fiber, and the relative intensity noise (RIN) of the pump light degrades the signal quality. It is well known that the RIN-induced pump power fluctuation directly transfer to the signal. This effect, called RIN transfer, was extensively investigated in intensity-modulation direct-detection system [3].

The pump RIN also causes signal phase and polarization fluctuations due to cross-phase modulation (XPM) and cross-polarization modulation (XPolM), respectively [4, 5]. In coherent communication systems, the phase and polarization fluctuations deteriorate the signal quality severely, and thus hinder the implementation of the forward pumping scheme. The compensation of RIN-induced phase noise was demonstrated by employing pilot subcarrier and digital signal processing (DSP) at the receiver in repeaterless coherent transmission [6]. On the other hand, the suppression of RIN-induced XPolM have not demonstrated to the best of our knowledge.

In this paper, we propose a novel method that cancel the time-dependent polarization crosstalk in polarization division multiplexed digital coherent transmission with forward-pumping DRA. The polarization crosstalk canceller (PCC) consists of 1-tap adaptive filters with a butterfly configuration, which are controlled by the recursive least square (RLS) algorithm. The performance of the proposed PCC is examined in the dual polarization-QPSK (DP-QPSK) long-haul transmission experiment employing first order forward-pumping DRA with polarization division multiplexed semiconductor laser diodes (LDs).
2 Polarization crosstalk canceller

Fig. 1 shows the receiver DSP configuration containing the proposed PCC. The first part is a conventional digital coherent DSP consisting of chromatic dispersion (CD) compensation, polarization demultiplexing and equalization based on adaptive equalizers (AEQ), and carrier phase recovery (CPR). The CPR output signals for both $x$- and $y$-polarization ($E_x$ and $E_y$) contain time-dependent polarization fluctuation that cannot be tracked by the AEQ. Thus $E_x$ and $E_y$ are processed by the proposed PCC to suppress polarization crosstalk. We used 1-tap adaptive equalizers with a butterfly configuration as shown in Fig. 1. The PCC output signals $E'_x$ and $E'_y$ for $n$-th symbol are expressed as

$$E'_x(n) = w_{xx}^*(n-1) E_x(n) + w_{xy}^*(n-1) E_y(n) \quad (1)$$
$$E'_y(n) = w_{yx}^*(n-1) E_x(n) + w_{yy}^*(n-1) E_y(n) \quad (2)$$

where $*$ represents complex conjugate, and $w_{ij}(n)$ ($i, j$ denote $x$- or $y$-polarization) are PCC tap coefficients.

![Fig. 1. Receiver DSP configuration employing the proposed PCC.](image)

We employed the RLS algorithm in the decision-directed mode in order to update the tap coefficients [7]:

$$w_{ij}(n) = w_{ij}(n-1) + k_{ij}(n) \left[ D_i^* (n) - E_i'^*(n) \right] \quad (3)$$
$$k_{ij}(n) = \frac{P_{ij} (n-1) E_i(n)}{\lambda + P_{ij} (n-1) |E_i(n)|^2} \quad (4)$$
$$P_{ij}(n) = \frac{1}{\lambda} P_{ij} (n-1) - \frac{1}{\lambda} k_{ij}(n) E_i'^*(n) P_{ij} (n-1) \quad (5)$$

where $\lambda (0 < \lambda \leq 1)$ is the forgetting factor and $D_i(n)$ is the decision output signal for $i$-polarization.

Because of the fast convergence and small mean-square error properties of the RLS algorithm, the time-dependent polarization crosstalk due to RIN of the forward pump can be effectively suppressed by the PCC. In addition, it should be noted that if the length of the tap coefficients is $M > 1$, $k_{ij}(n)$ are $M$-by-1 vector and $P_{ij}(n)$ are $M$-by-$M$ matrix. In this case, however, we adopted 1-tap equalizers ($M = 1$). Therefore $k_{ij}(n)$ and $P_{ij}(n)$ have scalar values and thus the computational complexity of the PCC is effectively suppressed.
3 Experimental setup

The performance of the proposed PCC was examined in the long-haul DP-QPSK transmission experiment. Fig. 2 shows the experimental setup, which utilizes a recirculating loop configuration with first order forward-pumping DRA.

![Fig. 2. Experimental setup.](image)

A 1531.1-nm CW light was modulated by an IQ modulator driven by an arbitrary waveform generator (AWG) to create a 9.6-Gbaud Nyquist-pulse-shaped QPSK signal with a roll-off factor of 0.1. The modulated signal was then polarization division multiplexed by a PDM emulator with a 260-symbol delay between the two polarization tributaries, and launched into a recirculating loop.

The recirculating loop consisted of an 80-km standard single-mode fiber (SMF) with an average loss of 0.20 dB/km, a dynamic gain-equalizing filter (DGE), an EDFA (shown by triangles), and an acousto-optic switch. The SMF was pumped by first-order forward pumps consisting of two Fabry-Perot LDs with a fiber bragg grating (FBG-LD). The wavelength of FBG-LDs was 1435 nm and the RIN was around $117 \text{ dB/Hz}$. We employed polarization division multiplexing in order to eliminate polarization-dependent Raman gain. The pump light was coupled with the signal by the wavelength-division multiplexing (WDM) filter (shown by the square). We also utilized a loop-synchronous polarization scrambler (LSPS) to minimize the polarization dependence specific to the recirculating loop experiments. The DRA on-off gain was 13.5 dB. Note that we intentionally set such high on-off gain to show the benefit of the PCC. However, this reduced the total attainable distance due to the additional degradation caused by the RIN-induced phase fluctuation.

The output signal from the recirculating loop was received by a polarization-diversity integrated coherent receiver (ICR) and sampled by a 25-GS/s digital storage oscilloscope (DSO) with an analog bandwidth of 6 GHz. The digitized signals were stored, and processed offline: First, chromatic dispersion (CD) was compensated by a frequency-domain fixed equalizer, and then polarization-demultiplexing and equalization was done by 31-tap adaptive FIR filters controlled by the decision-directed LMS algorithm with a step-size parameter of $1 \times 10^{-3}$, which was the optimum value for the case without the PCC. After carrier-phase recovery, the time-dependent polarization-crosstalk was cancelled by the proposed 1-tap PCC controlled by the RLS algorithm. The forgetting factor $\lambda$ was optimized to 0.89 in
this experiment. Finally Q factors were calculated from bit error counting over one million bits.

4 Results and discussion

Fig. 3(a) shows the Q-factors as a function of the transmission distance. The fiber input power was set to \(-14\) dBm that was almost the optimum taking account of nonlinear signal distortion. The Q-factor decreases as the transmission distance increases. When the PCC is activated, we can confirm that the Q-factors improved by 1.2 to 1.7 dB. This corresponds to transmission distance extension of about 640 km.

We also evaluated the performance of PCC at the transmission distance of 1,600 km by activating the tap weight control with the following different conditions:

Case-1 $w_{xx} = w_{yy} = 1, w_{xy} = w_{yx} = 0$ (without PCC)
Case-2 $w_{xx}$ and $w_{yy}$: Control on, $w_{xy} = w_{yx} = 0$
Case-3 $w_{xy}$ and $w_{yx}$: Control on, $w_{xx} = w_{yy} = 1$
Case-4 $w_{xx}, w_{xy}, w_{yx}$, and $w_{yy}$: Control on (with PCC)

Case-1 corresponds to the case without the PCC. In Case-2, a 1-tap equalizer suppresses the residual amplitude and phase fluctuations of each polarization that are not suppressed by the preceding AEQ and CPR, and the polarization crosstalk is not cancelled. In Case-3, only the polarization crosstalk between two polarization tributaries is cancelled. Case-4 is the full equalization case.
The measured Q-factors were 7.6 dB for Case-1, 7.7 dB for Case-2, 8.9 dB for Case-3, and 9.1 dB for Case-4, as plotted in Fig. 3(a). These results show that the Q-factor degradation due to polarization crosstalk was effectively suppressed by the PCC. On the other hand, the degradation due to the residual phase fluctuations caused only small impacts on the transmission performance.

Fig. 3(b) and (c) show the constellation diagrams after 1600-km transmission without using the PCC for $x$- and $y$-polarization, respectively, and Fig. 3(d) and (e) show the results with the PCC. We can confirm that the broadening of the signal distribution due to polarization crosstalk observed in Fig. 3(b) and (c) is successfully reduced by the PCC as shown in Fig. 3(d) and (e).

5 Conclusion

We have proposed the DSP-based PCC for polarization division multiplexed digital coherent transmission using forward-pumping DRA. The PCC is based on 1-tap adaptive filters with a butterfly configuration controlled by the decision-directed RLS algorithm. The performance of the proposed PCC was examined in the 9.6-Gbaud DP-QPSK long-haul transmission experiment. It was confirmed that the PCC effectively cancelled the polarization crosstalk, and 1.2 to 1.7 dB improvement in Q-factor was obtained.

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