Reduction of Nonlinear Inter-channel Crosstalk Penalty for DQPSK signal in Carrier Phase Locked WDM

Fumikazu Inuzuka, Kazushige Yonenaga, Shuto Yamamoto, Etsushi Yamazaki, Atsushi Takada
NTT Network Innovation Laboratories, NTT Corporation, *1-1 Hikari-no-oka, Yokosuka, Kanagawa, 239-0847 JAPAN*,
inuzuka.fumikazu@lab.ntt.co.jp

Abstract *This paper shows reduction of nonlinear inter-channel crosstalk penalty for DQPSK signal in carrier phase locked WDM. Experimental results show that carrier phase locking successfully suppresses the OSNR penalty caused by four-wave-mixing crosstalk.*

Introduction

The capacity of wavelength division multiplexing (WDM) systems has been recently increased by using the highly spectrum-efficient signal formats such as differential quadrature-phase-shift keying (DQPSK), multi-level quadrature amplitude modulation (QAM), polarization division multiplexing (PDM), and orthogonal frequency division multiplexing (OFDM). In these transmission systems, one of the most important limiting factors is fiber nonlinearity. In particular, four-wave-mixing (FWM) is a dominant factor in dense WDM systems utilizing dispersion-shifted fiber (DSF) with a narrow channel spacing. Recently, using the optical phase locking of WDM carriers [1], a way to reduce the waveform distortion induced by nonlinear inter-channel crosstalk such as FWM was proposed and was experimentally demonstrated with intensity modulation format [2, 3]. The optical phase locking of WDM carrier is achieved by using optical phase lock loop (OPLL) at a transmitter. This technique for DQPSK may not be applicable, because the carrier oscillation component disappears from DQPSK signals.

In this paper, the suppression of inter-channel FWM crosstalk (FWM-XT) is experimentally demonstrated for DQPSK using the optical phase locking of WDM carrier. The OPLL at the transmitter is achieved by using vertical-polarized light to a polarization-axis of an optical modulator. Experiments show successful suppression of the FWM-induced optical signal-to-noise ratio (OSNR) penalty.

Carrier phase locking and FWM-XT in DQPSK

Since individual laser sources are used in conventional WDM, phase differences among the optical carriers have no correlation with each other. In this condition, optical phase of FWM-XT generated in the transmission fiber has no correlation with optical phase of the signal light. Therefore, electric field of FWM-XT and that of the signal are composed with their phase difference random. The waveform distortion is a non-deterministic effect in conventional WDM, and the symbol distance is decreased. When the relative phases of WDM carriers are locked, FWM-induced distortion become deterministic. Therefore, the symbol distance is increased at a given angle between signal and FWM-XT light.

In carrier phase locked WDM, the normalized electric field of the DQPSK signal before a receiver is written as

$$E_r(t) = E_0\, e^{i(\omega_s t + \phi_0 + \phi_s(t))} + \Delta E\, e^{i(\omega_s t + \Delta\phi_{FWM} + \Delta\phi_s(t))}. \quad (1)$$

In (1), E_0 represents the signal electric field amplitude, ω_s represents signal angular frequency, ϕ_0 represents signal phase, ΔE represents electric field amplitude of FWM light, and $\Delta\phi_{FWM}$ represents FWM light phase. The differentially encoded phase information of signal and FWM light are represented by $\phi_s(t)$ and $\Delta\phi_s(t)$. With these assumption and definitions, when detecting DQPSK signals, the inphase and quadrature components can be obtained by (2) and (3):

$$I_I = \frac{1}{2}\left[\begin{array}{l} E_0{}^2 \cos\left(\phi_s(t) - \phi_s(t-\tau) - \phi_I\right) + \Delta E^2 \cos\left(\Delta\phi_s(t) - \Delta\phi_s(t-\tau) - \phi_I\right) \\ + 2E_0 \Delta E \cos\left(\dfrac{\phi_s(t) - \phi_s(t-\tau) + \Delta\phi_s(t) - \Delta\phi_s(t-\tau)}{2} - \phi_I\right) \\ \cdot \cos\left(\dfrac{\phi_s(t) + \phi_s(t-\tau) - \Delta\phi_s(t) - \Delta\phi_s(t-\tau)}{2} + \phi_0 - \Delta\phi_{FWM}\right) \end{array}\right] \quad (2)$$

$$I_Q = \frac{1}{2}\left[\begin{array}{l} E_0{}^2 \cos\left(\phi_s(t) - \phi_s(t-\tau) - \phi_Q\right) + \Delta E^2 \cos\left(\Delta\phi_s(t) - \Delta\phi_s(t-\tau) - \phi_Q\right) \\ + 2E_0 \Delta E \cos\left(\dfrac{\phi_s(t) - \phi_s(t-\tau) + \Delta\phi_s(t) - \Delta\phi_s(t-\tau)}{2} - \phi_Q\right) \\ \cdot \cos\left(\dfrac{\phi_s(t) + \phi_s(t-\tau) - \Delta\phi_s(t) - \Delta\phi_s(t-\tau)}{2} + \phi_0 - \Delta\phi_{FWM}\right) \end{array}\right] \quad (3)$$

In (2) and (3), τ is the duration of one symbol, and ϕ_I and ϕ_Q are the phase shift within an optical delay interferometer in the inphase and quadrature branches, respectively. In figure 1, a constellation diagram of DQPSK signal induced by FWM-XT is obtained in numerical calculation with $\phi_0 - \Delta\phi_{FWM} = 0$ and pseudo-random binary sequence (PRBS) 2^7-1 data-pattern used for experiment. When $\phi_0 - \Delta\phi_{FWM} = n\pi/2$ (n=0,1,2,…), the symbol distance become a shortest case.

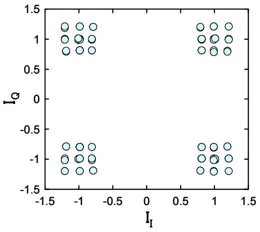


Fig.1: Constellation of DQPSK signal induced by FWM-XT with $\phi_0 - \Delta\phi_{FWM} = 0$

Experiment configuration

Figure 2 shows the experimental configuration. A continuous wave (CW) laser source is modulated by a

10-GHz electric sinusoidal wave through a phase modulator (PM) and three phase-locked carriers are generated with the frequency spacing of 10 GHz. The three carriers are separated into two optical paths by an arrayed waveguide grating (AWG) and an optical bandpass filter (OBPF). The carriers in each optical path are polarized with a 45-degree to a polarization-axis of DQPSK-modulator by a polarization rotator. The vertical polarizing light with carrier oscillation component is used for OPLL. All three-channels polarized horizontally are modulated with 10-Gb/s non-return to zero (NRZ)-DQPSK. To produce the NRZ-DQPSK signals, a DQPSK modulator is driven by two 5-Gb/s PRBS precoded data. Ch-2 and 3 in the bottom optical path are modulated by the same PRBS pattern with a 2^7-1 bits and Ch-1 is modulated by another pattern. The relative phases among the three channels are adjusted so that the FWM-XT onto Ch-1 becomes $\phi_0 - \Delta\phi_{FWM} = n\pi/2$. Ch-1, -2, and -3 are combined by polarization maintaining couplers. A part of the combined signal is split into horizontal and vertical polarization. OPLL using vertical polarization locks relative lightwave phases between Ch-1, -2 and -3. This makes FWM-induced waveform distortion deterministic. The coupled 3-channel WDM signal is launched into a 20-km DSF. Its zero-dispersion wavelength is 1550.95 nm and the wavelength of the center channel is 1550.88 nm. After the transmission, Ch-1 is extracted using an OBPF with 3-dB bandwidth of 12.5GHz and fed into the optical delay interferometer and balanced photo diode (BPD) followed by an error detector (ED).

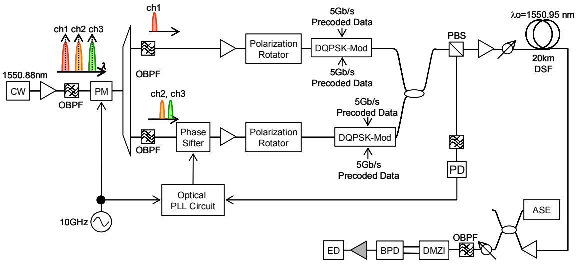


Fig.2: Experimental setup

Experiment results

Optical spectra before and after the transmission are shown in figure 3. Spectrum (b) and (c) show with/without a target channel after the transmission, respectively, and based on the difference we evaluate the signal to crosstalk ratio due to FWM in Ch-1 as -20.2 dB, when the launched power is set at -6.2 dBm/ch. Figure 4 shows the measured BER dependence on the OSNR at Ch-1. Figure 4 (a-1) and (b-1) show without phase locking in in-phase channel (I-ch) and quadrature channel (Q-ch), and (a-2) and (b-2) show with phase locking, respectively. The OSNR value is controlled by loading the appropriate amount of amplified spontaneous emission (ASE) noise at the receiver. The increase in the required OSNR value from the back-to-back target channel only case corresponds to the OSNR penalty caused by FWM-XT. Figure 5 (a) and (b) show the OSNR penalty as a function of the launched power per channel in I-Ch and Q-Ch, respectively. The OSNR penalty is evaluated at the BER of 1×10^{-4}. The optical phase locking suppresses the OSNR penalty by 3.1 dB and 1.6 dB at the launch power of -6.2 dBm/ch in I-Ch and Q-Ch, respectively. These results show that the carrier phase locking suppresses the FWM-induced OSNR penalty for DQPSK signal.

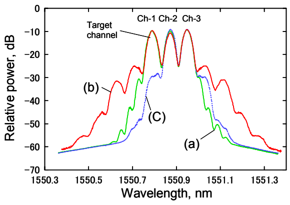
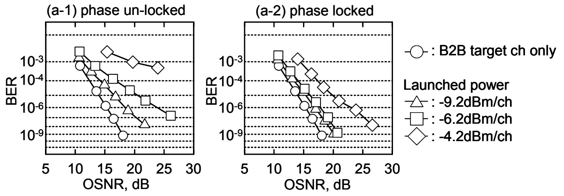


Fig.3: Optical spectrum. (a) Before transmission, (b) after transmission with target channel, and (c) after transmission without target channel.

(a) I-channel



(b) Q-channel

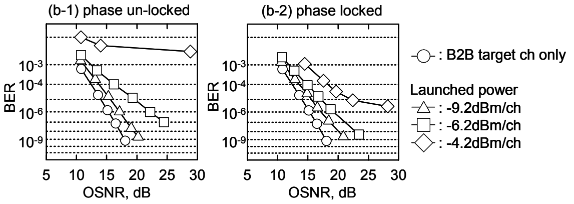


Fig.4: Measured BER dependence on OSNR at Ch-1, (a) I-channel, (b) Q-channel

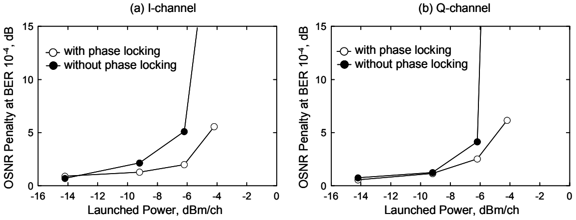


Fig.5: FWM-XT induced OSNR penalty at BER 1e-4 dependence on launched power, (a)I-channel, (b)Q-channel

Conclusion

The OSNR penalty induced by nonlinear inter-channel crosstalk is reduced by carrier phase locking for DQPSK. The experimental results show that the OSNR penalty caused by FWM-XT is successfully suppressed by 3.1 dB and 1.6 dB in I-Ch and Q-Ch, respectively. This work was supported in part by the National Institute of Information and Communication Technology (NICT) of Japan.

References:

[1] A.D. Ellis, et al., PTL, Vol. 17, No. 2, p. 504, 2005.
[2] E. Yamazaki et al., PTL, vol. 19, No. 1, p. 9, 2007.
[3] F. Inuzuka et al., OFC2007, OTuO5.