EVALUATION OF NONLINEAR IMPAIRMENT FROM NARROW-BAND UNPOLARIZED IDLERS IN COHERENT TRANSMISSION ON DISPERSION-MANAGED SUBMARINE CABLE SYSTEMS

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Abstract: We evaluated numerically and experimentally the effect of the cross phase modulation (XPM) from narrow-band unpolarized idlers on neighboring 100 Gbps PM-QPSK signals in submarine cable systems. We investigated the effect of XPM from an ASE idler whose bandwidth was set from 25 to 75 GHz. Experimental results showed a maximum XPM penalty of 1.0 dB at 25 GHz bandwidth, which agreed with the simulation. The narrower the ASE idler bandwidth, the more severe the nonlinear penalty was. Also, a modulated idler reduced the nonlinear penalty by 0.9 dB compared to the ASE idler.

1 INTRODUCTION

Submarine cable systems have been upgraded to 100 Gbps per signal channel by combining coherent detection with polarization multiplexing [1]. In legacy submarine cable systems, intensity modulation (On/Off Keying: OOK) has been widely applied, whereas phase modulation is used for coherent transmission. With nonlinear effects such as self-phase modulation affecting the phase component of phase-modulated signals, it is important to adjust the optical power level because the coherent signals are more sensitive to the nonlinear effect than OOK signals. Since the output power of the repeaters in a submarine cable is held constant, idler signals are inserted in vacant channel slots as a simple way of adjusting the power in the coherent signals.
Continuous wave (CW) lights and amplified spontaneous emission (ASE) noise have been used as idlers. Being polarized, the optical power in CW idlers can vary along the transmission line due to polarization-dependent gain (PDG) and polarization-dependent loss (PDL) in the repeaters. Also, PDG and PDL are increased by polarization hole burning (PHB), which degrades the coherent signals [2]. To reduce these effects, the state of polarization of CW idlers is randomized by a polarization scrambler, but this destabilizes the transmission performance of polarization-multiplexed signals due to cross polarization modulation (XPolM) from the CW idlers [3].
On the other hand, with ASE idlers being unpolarized, they cause no such problems. ASE idlers usually have a wide bandwidth, but narrow-band idlers are essential to maximize the system capacity. There are reports of cross-phase modulation from ASE idlers (idler-XPM) degrading the performance of neighboring signals [4]. However, this has not been investigated sufficiently to quantify the XPM from narrow-band ASE idlers or to find an alternative approach.
In this paper, we evaluate numerically and experimentally the effect of the XPM from narrow-band ASE idlers on neighboring 100 Gbps polarization-multiplexed quadrature phase-shift keyed (PM-QPSK) signals spaced at 75 GHz in a 3,000 km transmission line.

2 SIMULATION

We have examined numerically the transmission performance of 100 Gbps PM-QPSK signals in order to evaluate the effect of the XPM from unpolarized narrow-band idlers in a submarine cable system.

2.1 Simulation model

Figure 1 shows the simulation model. At the transmit side, four 100 Gbps PM-QPSK signals were generated by four transmitters (TX1~4), and these were multiplexed with either an ASE idler or a modulated PM-QPSK idler. The test channel was at 1550 nm, and the other wavelengths were distributed above and below it, spaced at 75 GHz. The idler was inserted at the shorter wavelength side, spaced at 75 GHz from the test wavelength. The transmission distance was 3,000 km, and the transmission line consisted of non-zero dispersion-shifted fiber (NZ-DSF) and standard single-mode fiber (SMF), in-line dispersion-managed.

At the receive side, the test wavelength was extracted using an optical band pass filter (OBPF) and fed to the receiver. The PM-QPSK signal to be measured was demodulated and the bit-error ratio (BER) was calculated and converted to the corresponding Q-factor.

Figure 2 shows the dispersion map for this simulation. The chromatic dispersions (CD) of the NZ-DSF and SMF were respectively -4 and +17 ps/nm/km. The residual CD of the dispersion-managed transmission line was 400 ps/nm, which was compensated by digital signal processing at the receiver. The noise figure of the repeaters, the effective core area, the optical fiber loss and the span length were respectively 4.3 dB, 70 um^2, 0.2 dB/km and 70 km.

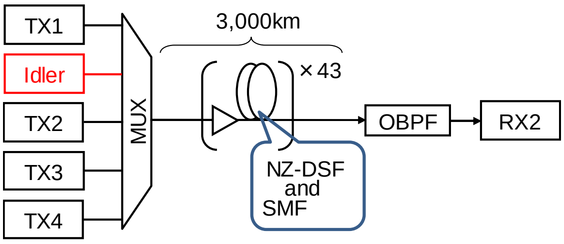

Figure 1: Simulation model

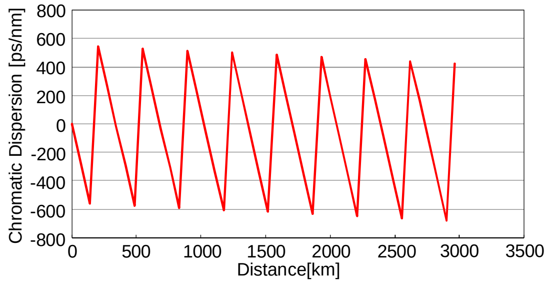

Figure 2: Dispersion map

In this paper, two simulations were performed to investigate the nonlinear effects:

(1) The effects of idler-XPM with varying ASE idler bandwidth.

(2) A comparison of ASE and modulated idlers.

For case (1), the ASE idler was given three bandwidths: 25, 50, and 75 GHz. We investigated the nonlinear impairment of the neighboring PM-QPSK signal caused by the idler-XPM with the above ASE idler bandwidths and with the optical signal-to-noise ratio (OSNR) of the test signal held constant. For case (2), we compared the effects of XPM from the ASE and modulated idlers using the same method as for case (1).

2.2 Simulation results

Figure 3 shows the optical spectrum at the transmit side. There are nominally five PM-QPSK signals with 75 GHz channel spacing, with the shorter neighboring wavelength replaced with an ASE idler. The total optical power of the ASE idler corresponded to that of a PM-QPSK signal for each of the bandwidths as shown in Figure 3. We measured the Q-factor of the middle signal after 3,000 km transmission to examine the nonlinear effect from the ASE idler.

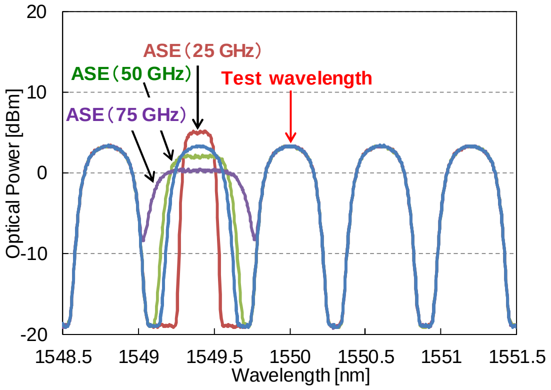

Figure 3: Optical spectrum at the transmit side

Figure 4 shows the simulation results for cases (1) and (2), which plots the nonlinear impairment of Q-factor after transmission as a function of the optical power of the idler relative to a PM-QPSK signal. The nonlinear impairments due to idler-XPM at 25, 50 and 75 GHz bandwidth were respectively 1.0 dB, 0.7 dB, and 0.4 dB at a relative idler optical power of 2.0 dB. The simulation indicates that the narrower the ASE idler bandwidth became, the more severe the penalty was, and a maximum idler-XPM penalty of 1.0 dB occurred at 25 GHz bandwidth.
On the other hand, a nonlinear penalty of only 0.2 dB occurred at a relative optical power of 2.0 dB in the case of the modulated idler. We have therefore shown that the modulated idler reduced the penalty by 0.8 dB compared to an ASE idler with 25 GHz bandwidth.
Since the ASE idler was generated in an optical amplifier and exhibited random amplitude variation, it caused a large amount of XPM, which degraded the performance of the neighboring signals. In contrast, the modulated idler caused less XPM penalty for the neighboring signals, since it was phase-modulated and its amplitude variation was smaller. In addition, the amplitude variation of an ASE signal is spread evenly across its full bandwidth. When the ASE idler bandwidth is narrow, the low-frequency component of the amplitude variations is relatively large. Low-frequency amplitude variations cause more severe nonlinear penalty in a dispersion-managed transmission line [5], [6]. This is why the simulation results in Figure 4 show that the idler-XPM becomes more severe as the ASE idler bandwidth is reduced.

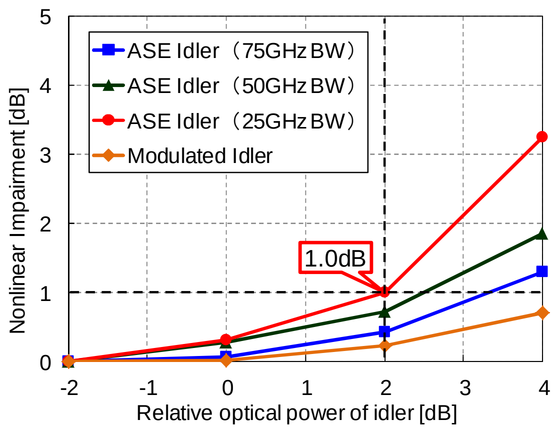

Figure 4: Results of the evaluation of nonlinear impairment from the narrow-band unpolarized idler

3 EXPERIMENT

We examined the nonlinear impairment of the idler-XPM experimentally in a 3,000 km dispersion-managed transmission line. First, we measured the optical power variation of the ASE and compared it to that of the modulated idler. Secondly, we examined the effect of the XPM from a narrow-band ASE idler on the neighboring 100 Gbps PM-QPSK signal compared to that from the modulated idler.

3.1 Optical power variation of the unpolarized idler

Figure 5 shows the setup for measuring the optical power variation. The idler bandwidth was controlled using an OBPF, and we measured the optical power variation using an oscilloscope after the optical power variation of the idler was converted to an electrical signal in the O/E converter. The bandwidth we could measure was limited by the 1.5 GHz bandwidth of the oscilloscope. Figure 6 shows the frequency distribution of the optical power of the ASE and modulated idlers, the horizontal axis being the normalized optical power. The time variation of the optical power is also shown in this figure. We confirmed that the variance of the modulated idler was less than that of the ASE idler, and that the time variation was also smaller. In addition, the variance of the ASE idler being greater, its peak power was 1.7 times higher than that of the modulated idler. We consider that it is this larger optical power variation that induces more severe XPM and degrades the performance of the neighboring signals.

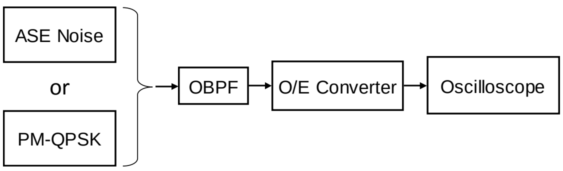

Figure 5: Setup for measuring optical power variation

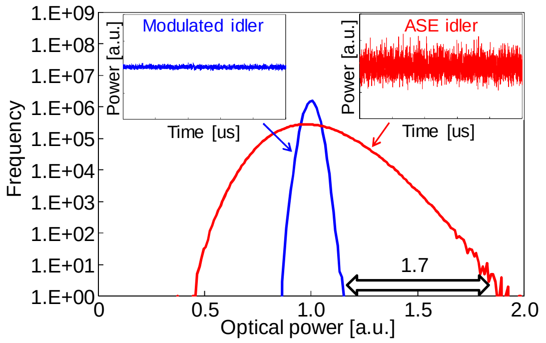

Figure 6: Frequency distribution of optical power

3.2 Evaluation of the nonlinear impairment caused by the narrow-band unpolarized idler

Figure 7 shows the experimental setup. At the transmit side, the five laser diodes (LD) were distributed from 1549.12 to 1551.52 nm with 75 GHz channel spacing. The odd and even carriers were multiplexed separately in arrayed waveguide gratings (AWG) and modulated to produce PM-QPSK signals. The odd and even carriers were then combined in a 3 dB coupler (CPL). The ASE idler was generated in an optical amplifier and its bandwidth was reduced using an OBPF. A further 52 PM-QPSK signals at 50 GHz channel spacing occupied the remaining bandwidth. The PM-QPSK signals and the ASE idler were multiplexed in the wavelength selective switch (WSS).

The straight fiber line consisted of 36 NZ-DSF spans and 9 SMF spans. The average span length was 68.4 km, the average span loss was 15.4 dB, the CD at 1550 nm was -0.239 ps/nm/km, and the CD slope of the NZ-DSF spans was 0.088 ps/nm^2/km. The cumulative CD was compensated by 9 spans of SMF. There were 45 erbium-doped fiber amplifier (EDFA) repeaters. The typical gain, output power and noise figure of the EDFAs were respectively 15.4 dB, 14 dBm and 4.6 dB.

At the receive side, the test wavelength was extracted using an OBPF and fed to the receiver. The PM-QPSK signal to be measured was demodulated and the BER calculated by counting the number of errors corrected by the forward error correction (FEC) decoder, the BER then being converted to Q-factor.

Figure 8 plots the nonlinear impairment of Q-factor after transmission as a function of the optical power of the idler relative to the PM-QPSK signal. The experimental results show that the maximum idler-XPM penalty was 1.1 dB at 25 GHz, which agrees with the simulation. The modulated idler caused only 0.2 dB nonlinear impairment, reducing the penalty by 0.9 dB compared to the ASE idler, which is also consistent with the simulation.

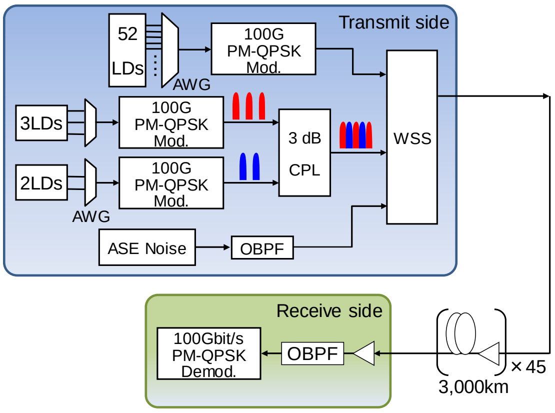

Figure 7: Experimental setup

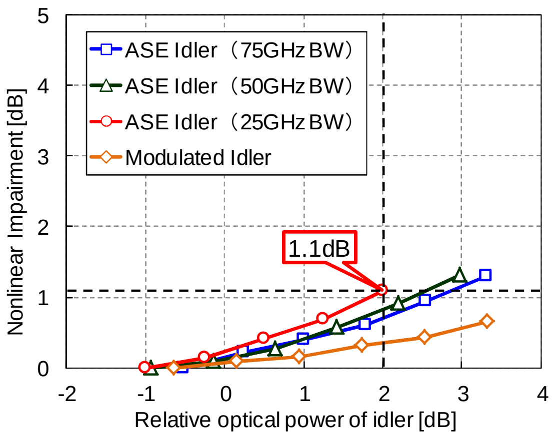

Figure 8: Experimental results

4 CONCLUSIONS

We have evaluated numerically and experimentally the nonlinear impairment of a neighboring 100 Gbps PM-QPSK signal to quantify the XPM from narrow-band unpolarized idlers in submarine cable systems. We have shown that an ASE idler with 25 GHz bandwidth caused severe XPM, resulting in up to 1.1 dB degradation of the neighboring signals. The narrower the ASE idler bandwidth became, the more severe the penalty was. A modulated idler reduced the penalty by 0.9 dB compared to an ASE idler. Not only being non-polarized, but also having less amplitude variation are the keys to reducing idler-induced nonlinear impairments.

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