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Digital Multiband DP-*M*-QAM System Using Dual-phase-conjugated Code in Long-haul Fiber Transmission with Polarization-dependent Loss

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Abstract: A digital multiband DP-*M*-QAM transmission with a polarization-domain dual phase-conjugated code has been demonstrated for simultaneously mitigating fiber nonlinear effects on straight forward SMF transmission when the PDL is occurred in the optical transmitter. However, the linear and nonlinear crosstalk are occurred in the multiband DP-16QAM signal that satisfy the Nyquist criterion subband spacing, so it deteriorates more than single carrier transmission. We observed that the crosstalk is not affected by setting the ratio of subband spacing and subband bandwidth to 1.02 or more when a roll-off of the Nyquist filter is set to 0.01. The Q-factors of 10000 km 4SB-DP-4QAM and 2400 km 4SB-DP-16QAM transmission using dual-phase-conjugated code show 0.9 dB and 0.3 dB improvement. While the optimum fiber input power varies between two polarizations in the case of single-band and multiband transmission without dual phase-conjugated code, the phase-conjugate code can equalize the optimum fiber input power between two polarizations for all subbands.

Keywords: Multiband, Dual-polarization multiplexing, Modulation, Coherent detection, Long-haul transmission, Fiber nonlinearlity, Polarization dependent loss.

1. Introduction

Dual-polarized four-level quadrature amplitude modulation (DP-4QAM)-based 100 Gb/s optical transport system is standardized and commercialized for long-reach optical fiber transmission systems [1]. Various digital signal processing (DSP) scheme has drawn much attention for compensating chromatic dispersion (CD), polarization dependent loss (PDL) [2], and fiber nonlinear distortion.

To mitigate nonlinear effects at CD unmanaged link, multiband transmission having multiple subband signals leads to better performance [3-4]. The subband signals with narrow-bandwidth and lower baud rate are positioned at a frequency spacing close to the Nyquist limit, e.g. by DSP-based root raised cosine (RRC) shaped lowpass filtering [5]. A pair-wise wavelength domain coding approach for multiband transmission has been demonstrated for suppressing crosstalk between subbands [6]. However, the wavelength domain coding method is not effective for the PDL in transmitter.

As a polarization domain coding/decoding for the standard DP-*M*-QAM, a phase-conjugated code with simple implementation by DSP has been proposed for compensating unwanted PDL and nonlinear distortions, simultaneously [7-8]. The DP-*M*-QAM signal with a phase-conjugated code involves time domain phase conjugate on orthogonal polarizations. However, the spectral efficiency halves of standard

DP-*M*-QAM because the phase-conjugated coding approach is set to original signal in one polarization and its phase conjugate in another polarization. Although the amount of performance improvement is degraded by the phase-conjugated code, a dual phase-conjugated (DPC) code can maintain the same spectral efficiency as standard DP-*M*-QAM [9-11].

In this paper, we demonstrate multiband DP-*M*-QAM signals with DPC coding that simultaneously mitigate the performance degradation due to PDL and nonlinear distortion. Through the performance comparison of 28 Gbaud, 42 Gbaud and 56 Gbaud of DP-4QAM and DP-16QAM signals, e.g. single-band, single-band with DPC code, multiband, and multiband with DPC code, we observed that four-subband DP-4QAM and DP-16QAM signals with DPC code is maximized the performance improving the nonlinear tolerance under the condition that PDL is over 6 dB.

2. Principle and Setup of Multiband DP-*M*-QAM with DPC Code

Fig. 1 shows a conceptual diagram of four different signals, e.g. standard single-band, single-band with DPC code, standard multiband, and multiband with DPC code. In the standard DP-*M*-QAM, an original data is independently for each polarization, while the data is shared between two polarizations by employing DPC code. The total signal bandwidth is similar in four cases. Here, the multiband number was set to four. A guard interval between the adjacent subbands is set to equal or wider than baud rate of the each subband. When the PDL occurs on the transmitter-side for one-side polarization, the power difference occurs between two polarizations at the input of the optical fiber and the influence of the fiber nonlinear effects are different, so the optimum fiber launched power that can obtain the maximum signal performance of each polarization is also different.

Fig. 2 shows a setup of multiband transmission with DPC code. At the transmitter, an original data stream *D*(*t*) is parallelized to bit block by serial-to-parallel (S/P) converter. At the bit to symbol mapper, parallelized data $D_{i\ j}$ are converted to symbol signal $E_{i\ j}$, where i is the subband index $(\boldsymbol{i} \in \{\mathbf{1},\mathbf{2},\mathbf{3},\mathbf{4}\})$ and j is the polarization index $(\boldsymbol{j} \in \{\boldsymbol{X},\boldsymbol{Y}\})$. At the DPC coding, the each subband is coded at the polarization domain. The encoded signal $E'_{i\ j}$ has $\left(\mathbf{2}\sqrt{\boldsymbol{M}}-\mathbf{1}\right)^{\mathbf{2}}$-point constellation with different occurrence rates like $\left(\mathbf{2}\sqrt{\boldsymbol{M}}-\mathbf{1}\right)^{\mathbf{2}}$-QAM signal. In the case of *M* = 4 and 16, the total numbers of signal point are 9 and 49. However, the probability of occurrence at each signal point is different from the standard

M-QAM format. To avoid a crosstalk from the adjacent subband, a Nyquist spectral shaped subband signal is generated and multiplexed. Each subband DP-*M*-QAM signal was RRC filtered with a roll-off factor of 0.01. The subband multiplexed signal is converted to the sampled analog signal by digital to analog converter (DAC). Here, we emulated the lumped the worst PDL (0° between the signal polarizations and the PDL lossy axis) [2]. Polarization mode dispersion (PMD) was not considered.

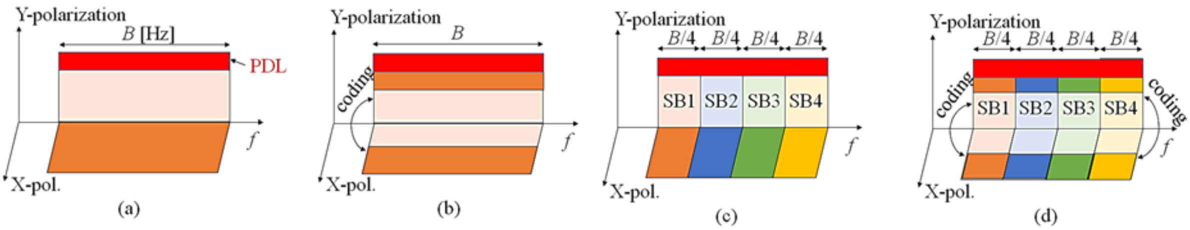

Fig. 1. Conceptual diagram of four DP-*M*-QAM signals; (a) Single-band, (b) single-band with DPC coding, (c) Four-subband, (d) Four-subband with DPC coding.

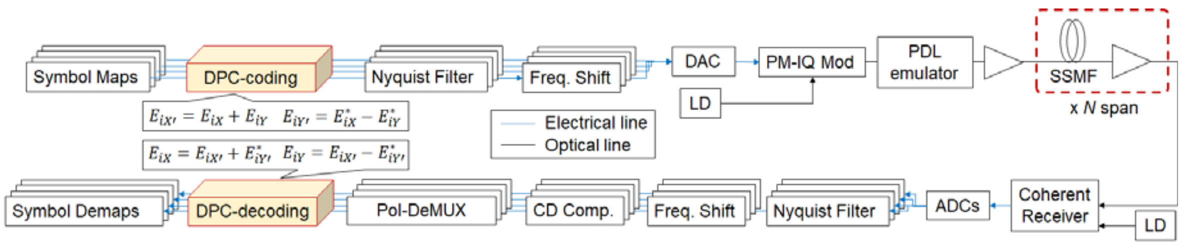

Fig. 2. System configuration of multiband DP-*M*-QAM transmission with DPC code.

The all tested signals were inserted to the transmission fiber consisting of *N* spans of 80 km standard single mode fiber (SSMF) having cumulative a loss of 0.2 dB/km, a chromatic dispersion of 17 ps/nm/km and nonlinear index of 1.3 $W^{-1}km^{-1}$. In the case of M = 4 and 16, the span numbers N are set to 125 and 30, respectively.

CD compensation was perfectly applied at the receiver. Erbium-doped fiber amplifiers (EDFA) were used for loss compensation with a noise figure of 5 dB.

The transmitted signal is filtered by the optical bandpass filter at the transmitter.

At the receiver, the detected signals can be expressed as

$$\boldsymbol{E'}_{iX} = (\boldsymbol{E}_{iX} + \boldsymbol{\delta}_{iX}) + (\boldsymbol{E}_{iY} + \boldsymbol{\delta}_{iY})$$
$$\boldsymbol{E'}_{iY} = (\boldsymbol{E}^{*}_{iX} - \boldsymbol{\delta}^{*}_{iX}) + (-\boldsymbol{E}^{*}_{iY} + \boldsymbol{\delta}^{*}_{iY}),$$

where $\boldsymbol{\delta}_{iX}$ and $\boldsymbol{\delta}_{iY}$ are perturbation terms related to fiber nonlinearity. A detected signal is sampled and quantized by analog to digital converter (ADC). After CD compensation, the multiple subband signals are separated by the passband filtering with different center frequency. After filtering, the each subband signal with DPC code is decoded at the polarization domain. In the linear transmission system, the original data pattern is perfectly recovered from decoded signals. Under the condition that PDL is zero, quadrature pulse shaping method has been demonstrated for reducing the perturbation term value. On the other hand, the our proposed DPC coding for multiband signal can mitigate the perturbation term for suppressing a fiber nonlinearity between two polarizations under the certain PDL.

3. Simulation Results

To verify the fiber nonlinearity and PDL tolerance of the proposed multiband DPC coded DP-M-QAM signal, we conducted the cases of three-type baud rate, two-type modulation format, and two-type subband number under the following setup. The total baud rate was set to 28, 42, and 56 Gbaud. In the case of four subband, the baud rate per subband was set to 7, 10.5, and 14 Gbaud. The total signal bandwidth is similar in four cases. Here, the multiband number was set to four. The data patterns were 100000-bit binary sequences. The tested signal types were standard single-band, single-band with DPC code, standard four-subband, and four-subband with DPC code. The pre-forward error correction bit error ratio was calculated and converted into Q-factors.

3.1. DP-4QAM Transmission

Fig. 3 (a-c) show the average Q-factors of single or four subband DP-4QAM transmission changing the fiber launched power for evaluating the power tolerance. Fig. 4 (a,b) show the Q-factors for each subband in the case of standard and DPC coded 56 Gbaud DP-4QAM. It can be confirmed that the characteristics between two polarization become the same by employing DPC code.

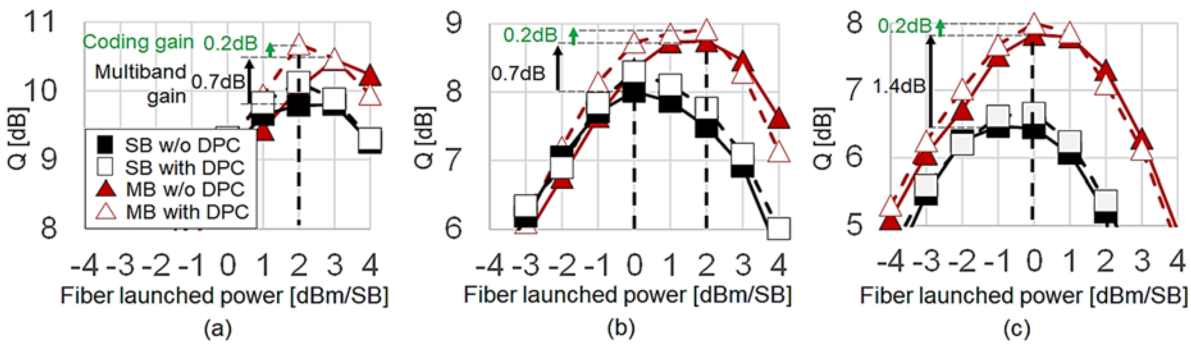

Fig. 3. Q-factors for nonlinear tolerance of DP-4QAM signal (a) 28 Gbaud, (b) 42 Gbaud, (c) 56 Gbaud.

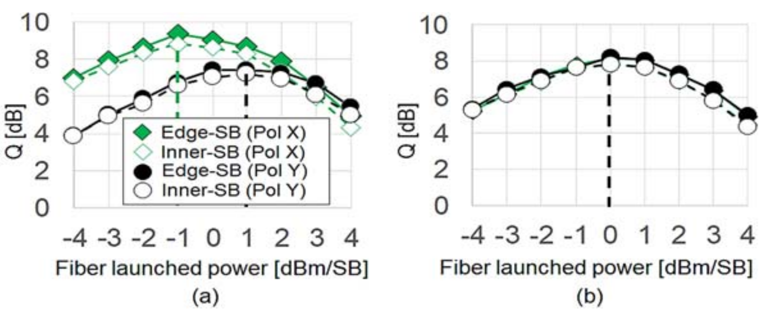

Fig. 4. Q-factors of each SB (a) multiband standard DP-4QAM signal, (b) multiband DPC coded DP-4QAM signal.

No-guard interval between the adjacent subbands is positioned since the DP-4QAM signal has tolerance for linear and nonlinear crosstalk. The Q-factors of four signals after 10000 km (N=125) transmission were measured in the case of 6 dB PDL. A multiband gain that is the performance difference between single- and multiband-case were different according to the baud rate. In the case of 56 Gbaud system with large degradation due to nonlinear effect, the performance of standard four subband signal was 1.4 dB higher than the performance of standard single-band signal. On the other hand, a coding gains that is the performance difference between standard multiband- and multiband DPC coding case were almost 0.2 dB regardless of the baud rate. Noteworthy, we can confirm that overall improvement was over 0.9 dB by employing multiband and DPC coding in the case of 6 dB PDL.

Fig. 5 show the constellation diagrams of the equalized edge and inner subband DP-4QAM signals of four-subband with DPC code in the case of 6 dB PDL. The signal point variations of Pol-Y are larger than Pol-X.

Fig. 6 and Fig. 7 show the constellation diagrams of the decoded four-subband signals in the case of 6 dB PDL. In the case of four-subband with DPC code, we can confirm the similar signal point variations between all subbands and polarizations.

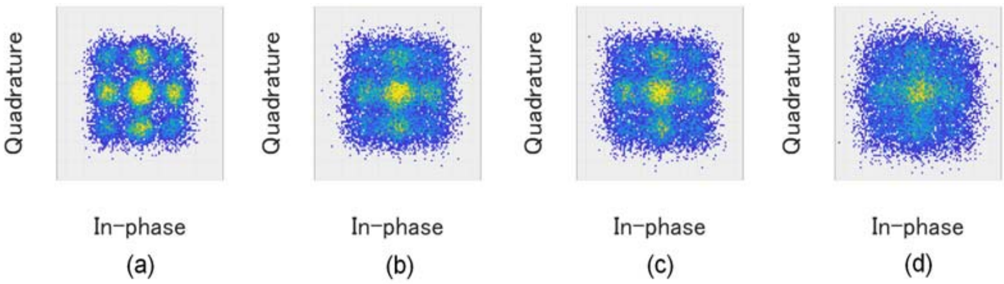

Fig. 5. Constellation diagrams of multiband DPC coded DP-4QAM signal before decoding; (a) SB1-Pol X, (b) SB2-Pol X, (c) SB1-Pol Y, (d) SB2-Pol Y.

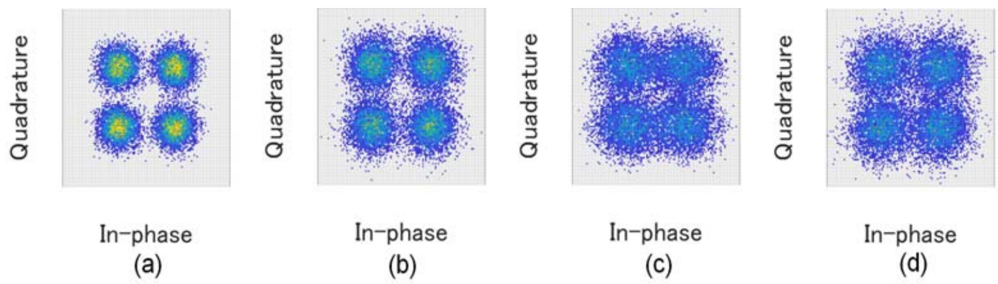

Fig. 6. Constellation diagrams of multiband standard DP-4QAM signal; (a) SB1-Pol X, (b) SB2-Pol X, (c) SB1-Pol Y, (d) SB2-Pol Y.

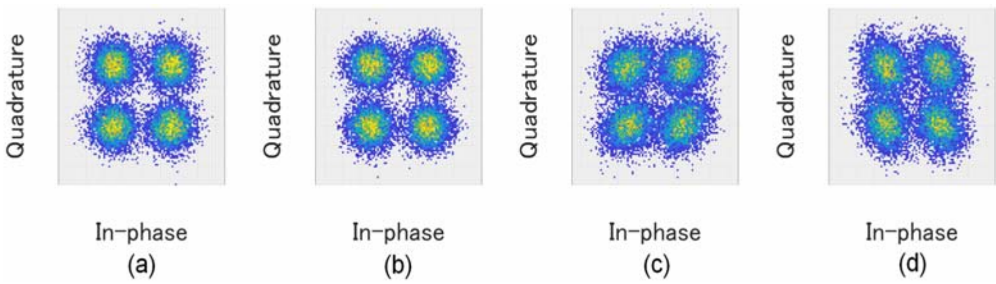

Fig. 7. Constellation diagrams of multiband DPC coded DP-4QAM signal after decoding; (a) SB1-Pol X, (b) SB2-Pol X, (c) SB1-Pol Y, (d) SB2-Pol Y.

Fig. 8 shows average Q-factors of four-subband for evaluating PDL tolerance. The Q-factors of three different baud rate signals after 10000 km transmission were measured in the condition that the fiber launched powers of single and four subbands are set to 0 dBm/SB or 2 dBm/SB where are the case of maximum Q-factor. When PDL was less than 3 dB, the coding gain was ineffective. When the PDL is 6 dB, the fiber launched power of respective polarizations with the highest Q-factors are different, respectively, so that coding gain can be obtained by balancing two polarized signal performances.

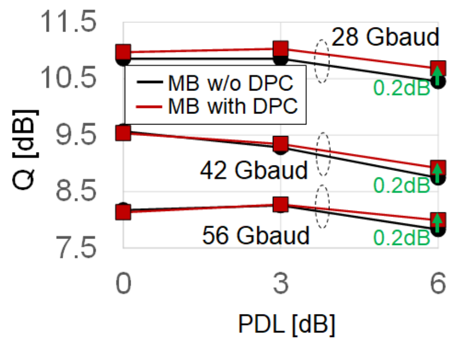

Fig. 8. Q-factors for PDL tolerance of DP-4QAM.

3.2. DP-16QAM Transmission

In the case of multiband DP-16QAM transmission, the characteristics are degraded over single-band DP-16QAM unless considering the subband spacing since the influence of linear and nonlinear crosstalk is larger than DP-4QAM. Fig. 9 shows the average Q-factors of four subband DP-16QAM transmission for evaluating inter-subband crosstalk tolerance. The Q-factors of four signals after 2400 km (N=30) transmission were measured in the condition that PDL = 6 dB, and the fiber launched powers of four subband are set to 0 dBm where is the case of maximum Q-factor. When the ratio of the subband spacing and the baud rate per subband is over 1.02, we can confirm the Q-factor was almost constant.

Fig. 10 show the constellation diagrams of the equalized edge and inner subband signals of four-subband without DPC code in the case of 6 dB PDL and no-guard interval between the adjacent subbands. The inner subband signal point variations are larger than the edge subband due to inter-subband crosstalk. Therefore, the ratio of the subband spacing and the baud rate per subband was set to 1.02 in the subsequent simulation evaluation.

Fig. 11(a-c) show average Q-factors of single or four subband DP-16QAM transmission changing the fiber launched power for evaluating the power tolerance. Fig. 12(a, b) show the Q-factors for each subband in the case of standard and DPC coded DP-16QAM. It can be confirmed that the characteristics between two polarization become the same by employing DPC code.

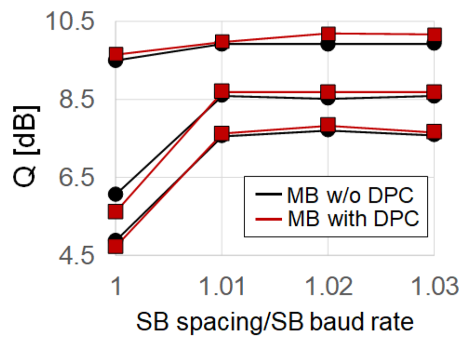

Fig. 9. Q-factors for crosstalk tolerance of DP-16QAM.

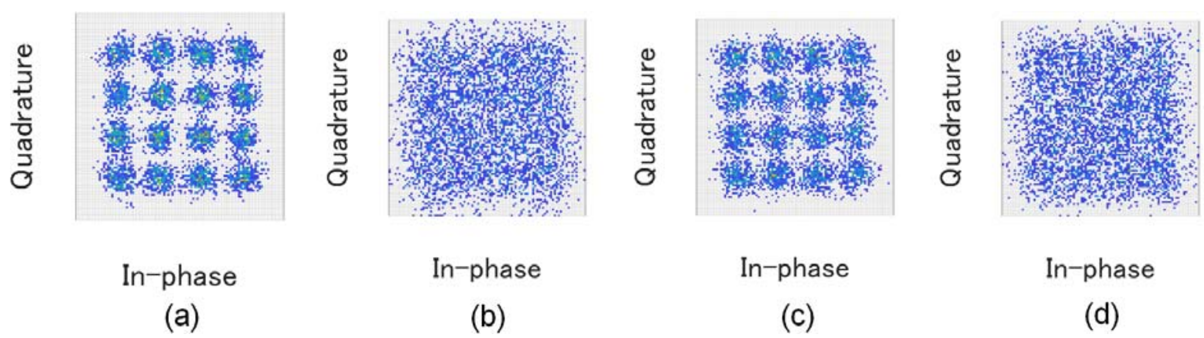

Fig. 10. Constellation diagrams of multiband standard DP-16QAM signal without guard interval between SBs; (a) SB1-Pol X, (b) SB2-Pol X, (c) SB1-Pol Y, (d) SB2-Pol Y.

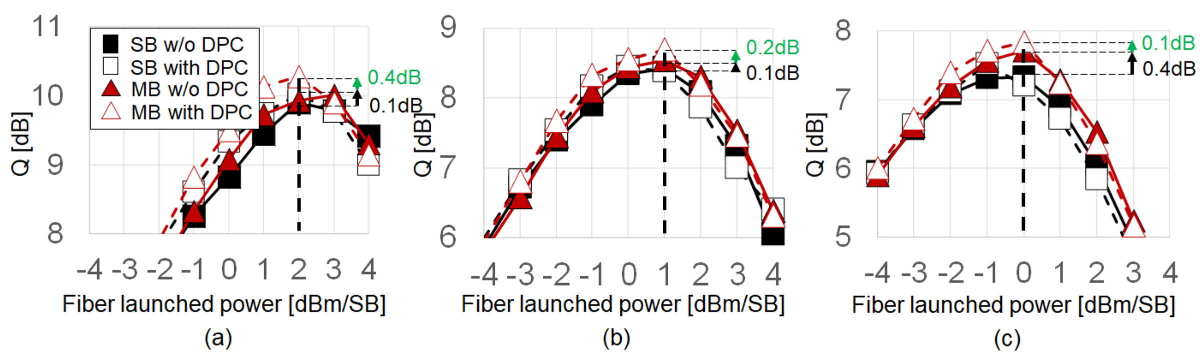

Fig. 11. Q-factors for nonlinear tolerance of DP-16QAM signal (a) 28 Gbaud, (b) 42 Gbaud, (c) 56 Gbaud.

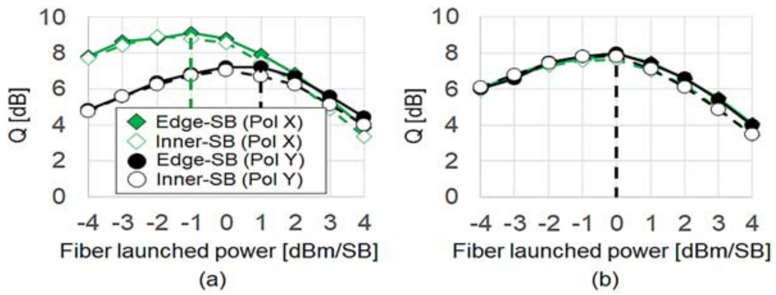

Fig. 12. Q-factors of each SB (a) multiband standard DP-16QAM, (b) multiband DPC coded DP-16QAM.

In the case of 56 Gbaud system with large degradation due to nonlinear effects, the performance of standard four subband signal was 0.4 dB higher than the performance of standard single-band signal. On the other hand, a coding gains that is the performance difference between standard multiband- and multiband DPC coding case were almost 0.1 dB regardless of the baud rate. Noteworthy, we can confirm that overall improvement was over 0.3 dB by employing multiband and DPC coding in the case of 6 dB PDL.

Fig. 13 show the constellation diagrams of the equalized edge and inner subband DP-16QAM signals of four-subband with DPC code in the case of 6 dB PDL. The signal point variations of Pol-Y are larger than Pol-X. Fig. 14 and Fig. 15 show the constellation diagrams of the decoded four-subband signals in the case of 6 dB PDL.

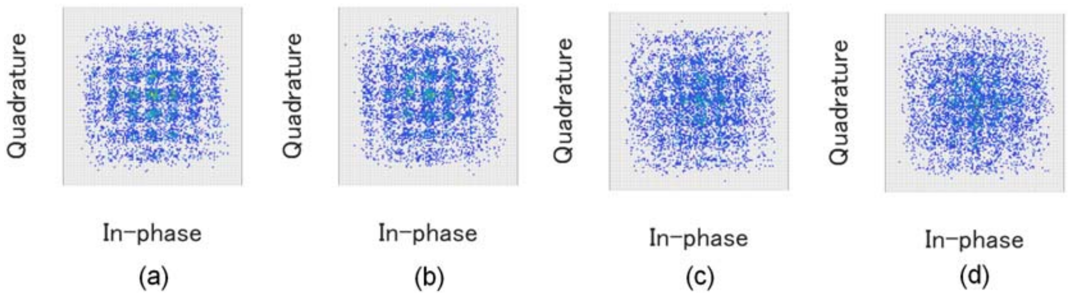

Fig. 13. Constellation diagrams of multiband DPC coded DP-16QAM signal before decoding; (a) SB1-Pol X, (b) SB2-Pol X, (c) SB1-Pol Y, (d) SB2-Pol Y.

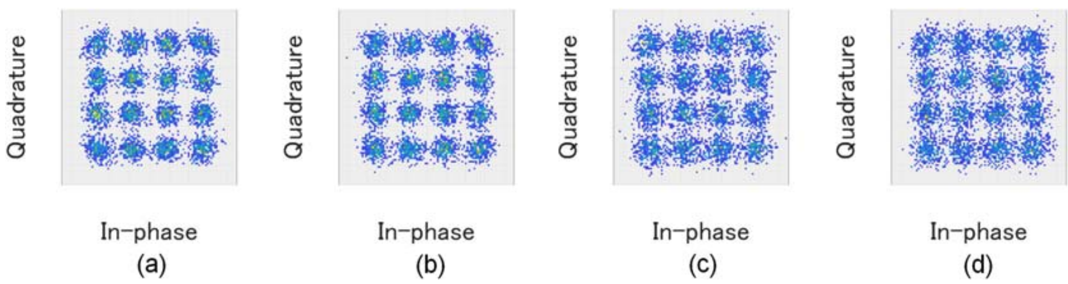

Fig. 14. Constellation diagrams of multiband standard DP-16QAM signal; (a) SB1-Pol X, (b) SB2-Pol X, (c) SB1-Pol Y, (d) SB2-Pol Y.

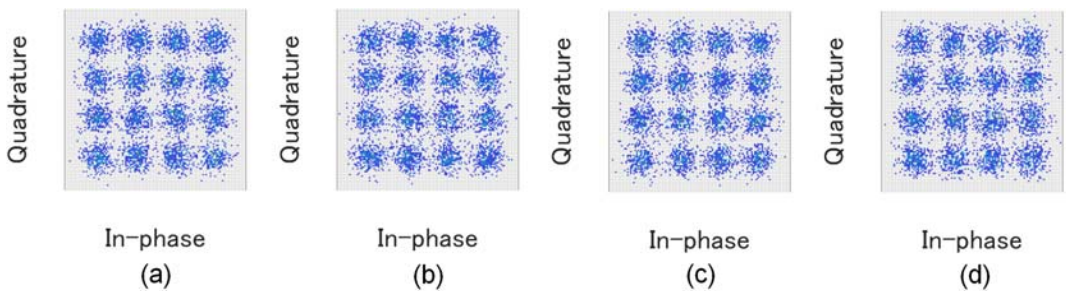

Fig. 15. Constellation diagrams of multiband DPC coded DP-16QAM signal after decoding; (a) SB1-Pol X, (b) SB2-Pol X, (c) SB1-Pol Y, (d) SB2-Pol Y.

In the case of four-subband with DPC code, we can confirm the similar signal point variations between all subbands and polarizations.

Fig. 16 shows average Q-factors of four-subband DP-16QAM signals for evaluating PDL tolerance. The Q-factors of three different baud rate signals after 2400 km transmission were measured in the condition that the fiber launched powers of single and four subbands are set to the optimum launched power. When PDL was less than 3 dB as same as DP-4QAM, the coding gain was ineffective. When the PDL is 6dB, the fiber launched power of respective polarizations with the highest Q-factors are different, respectively, so that coding gain can be obtained by balancing two polarized signal performances.

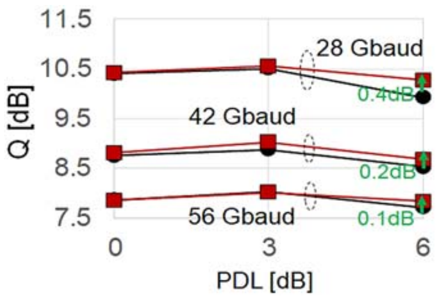

Fig. 16. Q-factors for PDL tolerance of DP-16QAM.

4. Conclusion

We proposed a multiband DP-*M*-QAM transmission using DPC code under the condition of the certain PDL The PDL and nonlinear tolerant multiband DP-4QAM and DP-16QAM signals with DPC code show effectiveness compared to standard multiband and DPC coded single-band transmission under the condition of a certain PDL.

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