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Dispersion-Managed Link Configured with Repetitively Shaped Dispersion Maps and Embedded with Mid-span Spectral Inversion

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Abstract

A dispersion map was proposed to improve the compensation effect of a distorted WDM (wavelength division multiplexed) channel in a dispersion-managed link coupled with optical phase conjugation. The dispersion map is an origin-symmetric structure around the optical phase conjugator in the middle of the transmission path. In addition, the dispersion map has a form in which a constant dispersion accumulation pattern is repeated regularly. Through simulation, we confirmed that the application of the origin-symmetric dispersion map with a repetitively shaped configuration was more effective in compensating for the distorted WDM channel than in the dispersion-managed link with a conventional dispersion map. In addition, we confirmed that the compensation effect could be increased when the cumulative dispersion distribution of the origin-symmetric distribution map had a positive value in the first half section and a negative value in the second half section. Further, we observed that as the number of repeated dispersion accumulation patterns increased, the residual dispersion per span should also be increased.

Index Terms: Chromatic dispersion, Dispersion management, Mid-span spectral inversion, Nonlinear Kerr effect, Origin-symmetric dispersion map

I. INTRODUCTION

In an intensity modulation/direct detection system, a semiconductor laser that is modulated directly by a signal produces a frequency chirp, in which the instantaneous frequency of the light pulse varies with time owing to the intrinsic nature of the modulator [1]. In other words, the signal frequencies constituting the optical pulse envelope are not constant throughout the duration of the optical pulse, and the frequencies gradually decrease (defined as down-chirp) or increase (defined as up-chirp) as the duration increases.

The phase perturbation owing to this frequency chirp is added to the phase change owing to the nonlinear Kerr effect inherent in the optical fiber, such as the standard single-mode fiber (SSMF), further exacerbating the distortion of the optical signal. The distortion becomes more severe as the bit rate of the light pulse increases.

Optical pulses are also distorted by the chromatic dispersion inherent in the SSMF. As the distance of the transmission path made of the SSMF increases, the distortion of the optical pulses owing to chromatic dispersion also increases. In particular, in wavelength division multiplexed (WDM) transmission, because the wavelength allocated to each channel is different, the degree of distortion owing to chromatic dispersion is different for each channel [2].

Optical phase conjugation is a technique for compensating for the optical signal distortion resulting from phase perturbations [3,4]. An optical phase conjugator (OPC) positioned

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in the middle of the transmission span is called a mid-span spectral inversion (MSSI) [5]. Meanwhile, when constructing long-distance transmission links, dispersion management (DM) is applied to eliminate or reduce the effect of chromatic dispersion on optical signals [6-8]. The DM involves applying a dispersion map that specifies the distribution of the cumulative dispersion amount for each fiber span that constitutes the entire transmission line. That is, the distribution map allows us to clearly observe the distribution of the accumulated dispersion in each fiber span.

When MSSI is applied to the dispersion-managed link, the compensation of optical signal distortion in the time and frequency domains is simultaneously possible, allowing ultra-wide-capacity WDM signals to be transmitted over long distances. However, the combination of MSSI and DM can complement each other's shortcomings [9,10].

To effectively compensate for WDM channels propagated through the dispersion-managed link combined with MSSI, the dispersion map shape must be symmetric with respect to the OPC because of the theoretical nature of MSSI. Many methods exist to symmetrize the dispersion map with respect to the OPC. The best compensation effect can be achieved by creating an origin-symmetric dispersion map.

To create an origin-symmetric dispersion map, the dispersion characteristics of each fiber span with respect to the OPC should be opposite to each other. A repetitively shaped dispersion map can be variously applied to an optical link by controlling the number of consecutive pairs of fiber spans with opposite dispersion features.

In this study, we investigated the compensation characteristics of distorted WDM channels in a DM link combined with MSSI, to which repetitively shaped dispersion maps are applied. The WDM considered in this study is a 24-channel transmission with a channel bit rate of 40 Gb/s. Each channel is assumed to be transmitted using return-to-zero (RZ) pulses with a frequency chirp.

II. WDM SYSTEM AND MIDWAY OPC

As shown on the left side of Fig. 1, each transmitter in the 24 WDM channels assumed in this study follows the intensity modulation (IM) scheme. Each transmitter consists of a pseudorandom bit sequence (PRBS), distributed feedback laser diode (DFB-LD), and external intensity modulator (MOD). First, a 40 Gb/s 127(= $2^7 - 1$)-bit sequence is generated in the PRBS, and then, the DFB-LD is externally intensity-modulated by an independent PRBS. The modulation format from the external optical modulator is assumed to be in the RZ format that is shaped as the second-order super-Gaussian pulse. The output electric field of the RZ format has an extinction ratio of 10 dB, a duty cycle of 0.5, and frequency chirp. According to ITU-T recommendation G.694.1, the center wavelength of the DFB-LD is assumed to be 1,550 nm-1,568.4 nm with a spacing of 0.8 nm [11].

The receiver for each WDM 24 channel is modeled as a direct detection (DD) scheme with a bandwidth of 0.65× bit rate, as shown on the right side of Fig. 1. In this study, the preamplifier is modeled as an erbium-doped fiber amplifier (EDFA) with a noise figure of 5 dB, the optical filter has a bandwidth of 1 nm, a PIN diode is used for the photodetector (PD), and a Butterworth filter acts as the pulse shaping filter.

The midway OPC depicted in Fig. 1 is modeled as a configuration with a highly nonlinear dispersion-shifted fiber (HNL-DSF) as a nonlinear medium. The propagated WDM channel signals combine with the optical signal generated by the pump laser to create a conjugated wave through the four-wave mixing (FWM) phenomenon in the nonlinear medium in the midway OPC. The HNL-DSF acts as a nonlinear medium for the OPC. The features of the HNL-DSF are as follows: loss = 0.61 dB/km, nonlinear coefficient = 20.4 W^{-1} km^{-1}, length = 0.75 km, zero dispersion wavelength = 1,550 nm, and dispersion slope = 0.032 $ps/nm^2/km$.

If the wavelength of pump LD of OPC is 1,549.5 nm for the signal wavelengths of 1,550 nm-1,568.4 (0.8 nm interval), the corresponding wavelengths of the conjugated wave are obtained as 1549.5 nm-1531.1 nm (−0.8 nm interval). The 3-dB bandwidth of the conversion efficiency in the OPC designed with the aforementioned parameters is 48 nm (1,526-1,574 nm). Therefore, both the signal and conjugate wavelengths of the 24 WDM channels belong to this 3-dB bandwidth.

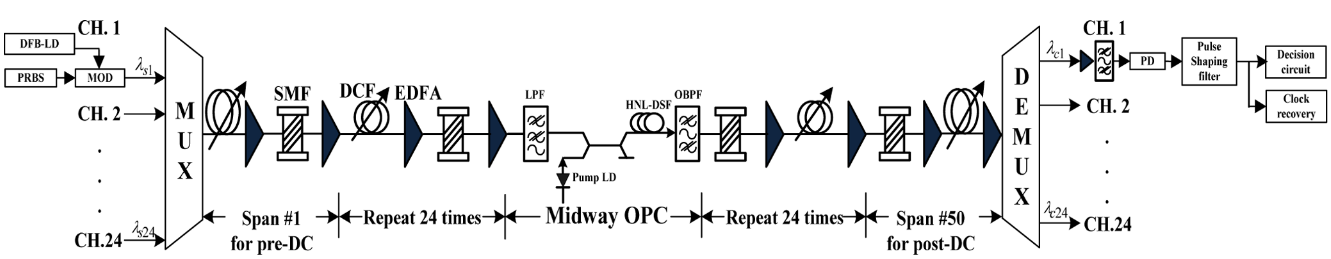


Fig. 1. Configuration of an optical link for transmitting 24-channel wavelength division multiplexing (WDM). DFB-LD: distributed feedback laser diode, PRBS: pseudo random bit sequence, MOD: modulator, SMF: single-mode fiber, DCF: dispersion compensating fiber, EDFA: erbium-doped fiber amplifier, OPC: optical phase conjugator, DC: dispersion calibrator, HNL-DSF: highly nonlinear dispersion-shifted fiber, OBPF: optical band pass filter, PD: photo detector.

III. TRANSMISSION LINK MODELLING

Fig. 1 shows the dispersion-managed link configuration for the 960 Gb/s WDM transmission considered in this study. The entire transmission path has 50 fiber spans. One fiber span consists of an SSMF and a dispersion-compensating fiber (DCF) for the DM. For near-perfect local dispersion symmetry, the deployment order of the fibers in the first and second half sections is reversed, as shown in Fig. 1. The fiber parameters are assumed as listed in Table 1.

Table 1. Fiber parameters

	SSMF	DCF
Length	lSMF = 80 km	lDCF = variable
Loss	αSMF = 0.2 dB/km	αDCF = 0.6 dB/km
Dispersion coefficient	DSMF = 17 ps/nm/km	DDCF = -100 ps/nm/km
Nonlinear coefficient	γSMF = 1.41 W-1km-1	γDCF = 5.06 W-1km-1

The residual dispersion per span (RDPS) is defined as the dispersion amount accumulated in each fiber span and is expressed as follows: $(l_{SMF} \times D_{SMF}) - (l_{DCF} \times D_{DCF})$. In this study, because l_{SMF}, D_{SMF}, and D_{DCF} are fixed, the RDPS is varied by the length of the DCF, that is, l_{DCF}.

The origin-symmetric dispersion maps vary depending on the way the RDPS of each fiber span is allocated. Several dispersion maps, as illustrated in Fig. 2, are considered in this study. The origin-symmetric dispersion map to be investigated has a form that is repeated in each half-section. For example, the "4-times" shown in Fig. 2 implies that "basic accumulation pattern (BAP)" of dispersion repeats four times in each half-section. This dispersion map can be obtained by inverting the signs of the RDPSs of the same magnitude with three pairs of fiber span spacing.

In this way, various repetitively shaped dispersion maps can be created according to the number of fiber span pairs having the same sign and magnitude as those of the RDPS. In this study, we consider six schemes: 1-time, 2-times, 3-times, 4-times, 6-times, and 12-times.

For the dispersion map to be origin-symmetric with respect to the midway OPC, the profile of the accumulated dispersion must also be opposite for each half-section. That is, the signs of the cumulative dispersion in the first and second half sections must be opposite. The "P:N" marked in Fig. 2 implies that the signs of the accumulated dispersion are positive and negative in the first and second half sections, respectively, although the magnitude varies according to the transmission distance. Thus, considering the sign of the cumulative dispersion, the repetitively shaped dispersion maps of the 12 schemes should be investigated.

As can be observed from Fig. 2, the net residual dispersion (NRD) in the remaining link, except for fiber spans #1 and #50, becomes 0 ps/nm owing to the repetitively shaped scheme. Reportedly, the optimal NRD in pseudo-linear systems is not 0 ps/nm but near 0 ps/nm [12]. This implies that an arbitrary fiber span should play a role in adjusting the NRD to achieve the best compensation performance in the dispersion-managed link, as shown in Fig. 1.

In this study, the DCFs of the first (#1) and last (#50) fiber spans performed this role. Determining the NRD by adjusting the DCF length of fiber spans #1 and #50 are called pre-DC (dispersion calibration) and post-DC, respectively. In this study, the NRD of the entire transmission link is adjusted only by the pre-DC. More specifically, first, the NRD in the second half section by post-DC is always 0 ps/nm, irrespective of the RDPS setting value, and at the same time, the NRD of the entire transmission link is changed only by pre-DC.

IV. NUMERICAL ANALYSIS AND PERFORMANCE ASSESSMENT

Each WDM channel propagating through an optical transmission link under the influence of loss and nonlinear Kerr effects is expressed by the nonlinear Schrödiger equation (NLSE) [1]. In this study, a numerical analysis of NLSE for 40 Gb/s × 24-channel WDM transmission is implemented in MATLAB according to the split-step Fourier (SSF) technique [1].

The eye-opening penalty (EOP) and Q-factor can most intuitively evaluate the reception performance based on the eye diagram in the optical domain. EOP is used to assess the compensated WDM signals in this study. The system perfor-

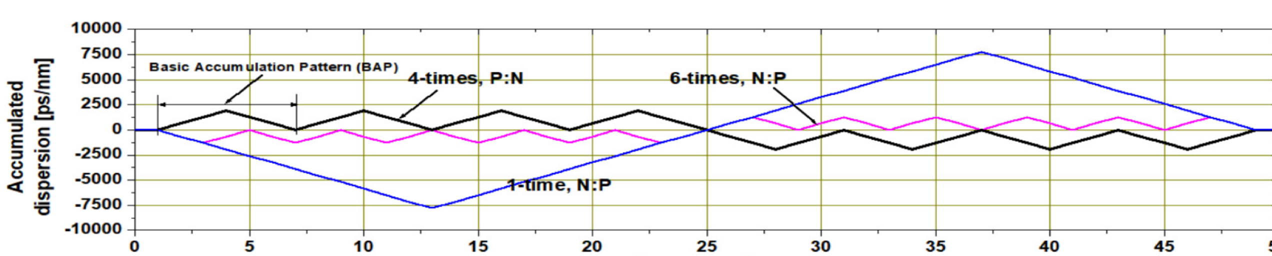


Fig. 2. Origin-symmetric dispersion maps with respect to the midway OPC.

mance criterion is a 1-dB EOP that is equivalent to a pulse broadening (the ratio of the received to the initial pulse RMS width) of 1.25 and corresponds to a bit error rate (BER) of 10^{-12} [13].

V. SIMULATION RESULTS AND DISCUSSION

Because the dispersion map examined in this study must have an origin-symmetric shape with respect to the midway OPC, the RDPS magnitude of each fiber span in the first and second half sections must be the same. However, in the case where the RDPS magnitude of each fiber span in the first and second half sections are different, the compensation characteristics of the distorted channels may be superior to those the authors believe. Therefore, the EOP of the received signal is assessed in all cases where the RDPS magnitude of each fiber span in both half sections was made with the same combinations and different combinations.

As a result of the analysis of the different combination case, when the cumulative dispersion form was P:N, the best compensation could be obtained in the “12-times” configuration in which the RDPS of each fiber span in the first and second half sections was set to ±650 ps/nm and ±20 ps/nm, respectively. Furthermore, the best compensation in the case of N:P could be obtained from the “12-times” configuration in which the RDPS value of each fiber span in the first and second half sections was set opposite to that in the case of P:N.

However, in the dispersion map comprising combinations with the same RDPS magnitude, we searched for the configuration in which the worst compensation could be obtained. First, in the case of P:N, the worst compensation was achieved in the “6-times” configuration where the RDPS in the fiber span of the two half sections were all set to ±200 ps/nm. Notably, the worst compensation was achieved in the “12-times” configuration where the RDPS in the fiber span of the two half sections were all set to ±1,300 ps/nm in the case of N:P.

Fig. 3 shows the compensation characteristics of the aforementioned four dispersion maps in terms of the channel launch power versus the EOP. The results in Fig. 3 show the EOP of the channel with the worst reception performance among the 24 channels. Further, Fig. 3 shows the results obtained from the dispersion-managed link with the NRD set to 10 ps/nm for all four cases.

The most important fact observed from Fig. 3 is that compensation through the repetitively shaped dispersion map designed with the same RDPS magnitude is better than that of the dispersion map with different RDPS magnitudes. The RDPS allocated to each fiber span of the first and second half sections must be the same to form a complete origin-symmetric dispersion map. Therefore, the results of Fig. 3 confirmed that the complete origin-symmetric dispersion map is more advantageous for compensating the distortion of the WDM channel.

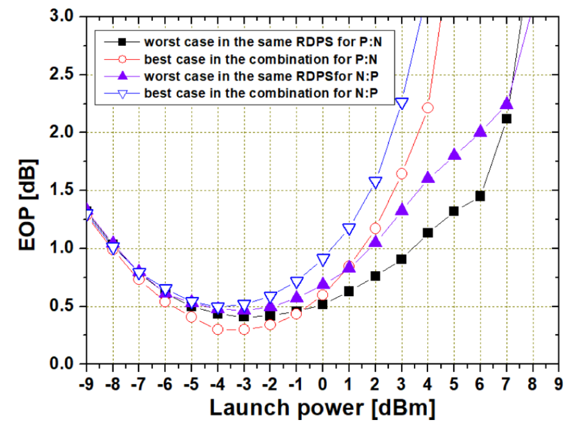
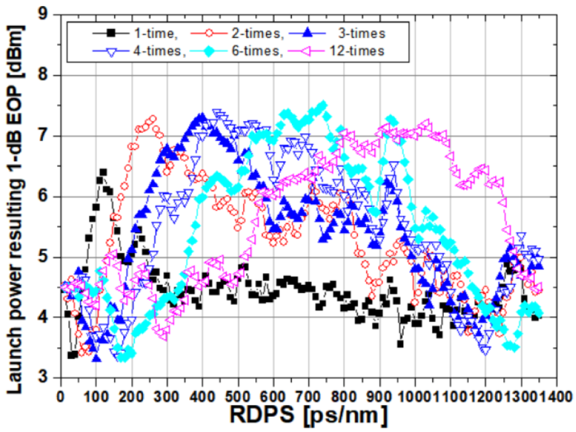


Fig. 3. Launch power versus EOP in several dispersion maps.

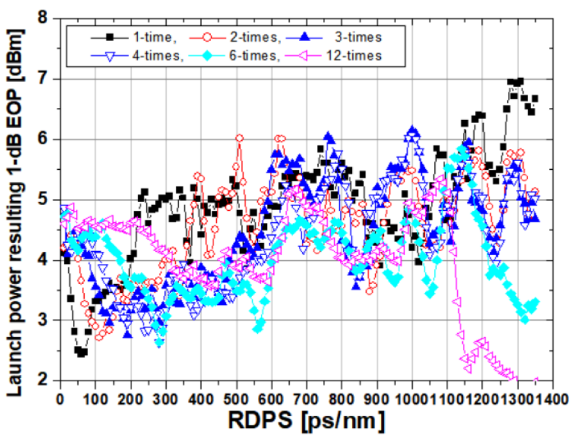
Fig. 4 illustrates the launch power resulting in a 1-dB EOP according to the RDPS magnitude of each fiber span when WDM channels are transmitted on a dispersion-managed link designed with each complete origin-symmetric dispersion maps. The larger the launch power that can achieve an EOP of 1 dB or less, the more effective is the WDM channel compensation. Comparing Figs. 4(a) and 4(b), notably, P:N is more advantageous for compensation than N:P. This can be proven by the fact that the magnitude of the launch power for the same RDPS magnitude is larger in the dispersion map of the same type, although the graph is considerably confusing to understand.

As observed in Fig. 4, the maximum launch power to obtain a 1-dB EOP is approximately 7 dBm. To facilitate the analysis of Fig. 4, Fig. 5 shows only the case in which the launch power to obtain a 1-dB EOP is 7 dBm or more. However, the results obtained for the N:P configuration cannot be included in Fig. 5. An important aspect observed from Fig. 5 is that, as the iteration number of the BAP forming the origin-symmetric dispersion map increases, the RDPS magnitude should increase for the best compensation.

As noted thus far, the fact that the origin-symmetric dispersion map of the repetitively shaped configuration is not advantageous for distortion compensation in all cases should not be ignored. Importantly, the RDPS should be appropriately selected according to the repetitively shaped dispersion map proposed herein. Table 2 summarizes the RDPS magnitude that provides the best and worst compensation in all the considered dispersion maps. The conventional dispersion-managed link is configured by applying an RDPS of 0 ps/nm to all fiber spans. We call this configuration the conventional scheme. A power margin of approximately 3 dB compared with the conventional scheme could be secured according to the repeating number of the BAP of the distribution map,



(a) "P:N" scheme



(b) "N:P" scheme

Fig. 4. Launch power resulting in a 1-dB EOP as a function of the RDPS magnitude.

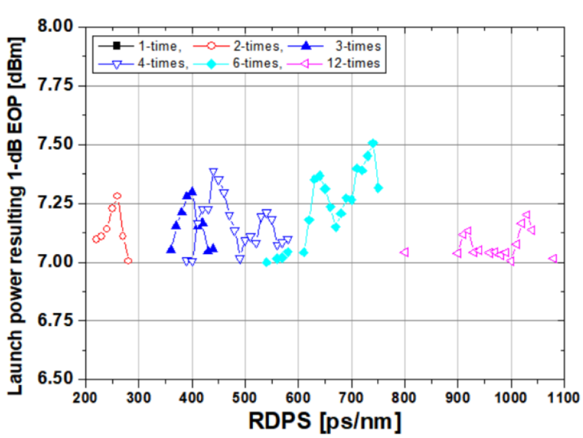


Fig. 5. Launch power of 7 dBm or more resulting in a 1-dB EOP as a function of the RDPS magnitude.

profile of the accumulated distribution, and most importantly, RDPS.

The authors used the effective NRD range to evaluate the flexibility of the dispersion-managed link. In the analysis thus far, the NRD was fixed at 10 ps/nm and then analyzed. This value can obtain the best compensation, but previous studies have confirmed that NRD can obtain a valid compensation even if it has a value larger or smaller than 10 ps/nm. That is, an NRD range exists in which a 1-dB EOP can be obtained, and the NRD range may vary depending on the DM configuration and link design conditions.

Table 2. RDPS providing the best and the worst compensation for each repetitively shaped dispersion map

		1-time	2-times	3-times	4-times	6-times	12-times
P:N	Best	120	260	400	440	740	1030
	Worst	30	60	100	160	180	290
N:P	Best	1310	510	1000	1000	1140	1080
	Worst	60	110	190	280	280	1320

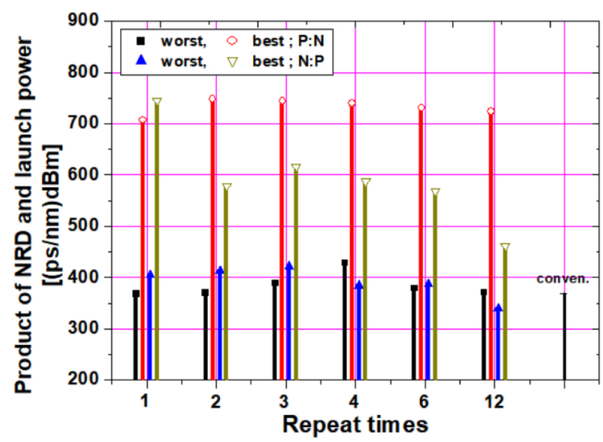


Fig. 6. Product of the NRD and launch power.

The effective NRD range, depending on the launch power, generally has the form of a closed curve. The area of the closed curve can be obtained, and consequently, from the viewpoint of performance, this area corresponds to the product of the NRD and launch power. As this product increases in an arbitrary distribution map, the NRD and launch power margins of the DM link increase.

Fig. 6 shows the result of the product of the NRD and launch power in each origin-symmetric dispersion map with each RDPS listed in Table 2. As shown in Fig. 6, the products of the NRD and launch power were overall better in the case of P:N than in the case of N:P, as in the previous result. However, if the origin-symmetric distribution map is applied with the N:P distribution, the product of the NRD and launch power is better than that of the conventional scheme; thus, a more flexible link design is possible. Notably, in terms of the product of NRD and launch power, both P:N and N:P had good flexibility in the structure in which the repeating number of BAP is one, that is, 1-time configuration.

The biggest difference between P:N and N:P is whether the sign of RDPS is positive or negative at the beginning of the first half section. As the transmission distance of the optical signal passing through the fiber span with a positive RDPS increases, the width of the optical pulse gradually spreads. As the width of the optical pulse gradually spreads, the light intensity gradually decreases, and consequently, and as a result, the optical pulses are less affected by the intensity-dependent nonlinear Kerr effect. However, the width of the optical pulse in fiber spans with a negative RDPS is gradually compressed to increase the instantaneous light intensity, and consequently, the optical pulses are strongly affected by the nonlinear effect.

The result that the structure capable of providing an excellent compensation is P:N suggests that the compensation for distortion owing to the nonlinear Kerr effect should focus more on the distortion owing to chromatic dispersion in the early stage of transmission. However, repetitively having as many negative RDPS as the number of fiber spans with positive RDPS is important because distortion owing to chromatic dispersion is further aggravated when all RDPS are positive in the entire half section to broaden the optical pulse width. In addition, the iteration number of the BAP, which determines the shape of the origin-symmetric dispersion map, and the RDPS magnitude applied to each fiber span affect the compensation of the distorted WDM channels. Under the condition of the P:N profile, as the iteration number of the BAP increases, the RDPS magnitude should increase for the best compensation.

VI. CONCLUSIONS

Thus far, we numerically investigated the compensation effect of distorted WDM channels in a dispersion-managed link comprising an origin-symmetric dispersion map with a repetitively shaped pattern. The proposed link also included an OPC in the middle of the total transmission length. First, the dispersion map, which is origin-symmetric with the repetitively shaped pattern proposed in this paper, was confirmed to be more effective in compensating for the distorted WDM channel compared with the dispersion map with the conventional configuration.

Notably, although this is a repetitively shaped configuration, the specific dispersion distributions in which the cumulative dispersion is positive in the first half section and negative in the second half section, is advantageous for compensation. Furthermore, the enhancement of the distortion compensation effect through the repetitively shaped origin-symmetric dispersion map with this design is possible by the appropriate selection of the RDPS of each fiber span depending on the number of iterations of the basic accumulated pattern, that is, the basic piece of the dispersion map.

Notably, the iterative origin-symmetric dispersion map proposed in this study can overcome the essential limitations of the midway OPC system. In addition, the compensation effect in the P:N configurations can be observed up to three times more than in the conventional dispersion-managed link, irrespective of the iteration number of the basic piece of the dispersion map.

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