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Control Position of Net Residual Dispersion in Dispersion-managed Link Configured with the Artificially Distribution of Lengths of SMF and Magnitudes of RDPS

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We propose the design methods for flexible dispersion-managed link configured by the artificial distribution of the lengths of single-mode fibers and the magnitude of residual dispersion per spans, in which the mid-span spectral inversion is combined. For this purpose, we investigate the optimal artificial distributions among 16 link configurations and the optimal control position of net residual dispersion in the entire transmission link among 4 control positions. Applying the optimal distribution patterns and the optimal positions controlling the net residual dispersion, which are induced in this study, the dispersion-managed link configured by these are capable to increase the transmitted power and the effective net residual dispersion range than the conventional dispersion-managed link.

Keywords: dispersion management; mids-pan spectral inversion; residual dispersion per span; net residual dispersion; dispersion calibrator

I. INTRODUCTION

Signal distortion owing to the interaction of optical Kerr nonlinearity and fiber chromatic dispersion is a fundamental barrier to increasing the transmission distance and ultra-high bit rate in fiber optic communications (Desurvire, 2006; Nadeem & Choi, 2016). Promising techniques for its compensation include dispersion management (DM) and mid-span spectral inversion (MSSI). Generally, in DM link, the path average dispersion (PAD) of the dispersion-managed link is made close to zero (Chen *et al.*, 2004). This link consists of a periodic chain of standard single-mode fiber (SMF) and dispersion-compensating fiber (DCF). Namely, zero/near zero of PAD is obtained by inserting DCF span with anomalous group velocity dispersion (GVD) into SMF span with normal GVD in which the length of DCF is decided by the length and dispersion coefficient of the selected SMF, the dispersion coefficient of DCF, and the desired value of residual dispersion.

The DM can simultaneously compensate of the signal deterioration from the dispersion and third order dispersion (i.e., dispersion slope) of the transmission fiber (Wei & Plant, 2004). Unfortunately, the DM link is less effective to compensate for the Kerr nonlinear effects, such as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM) (Wei & Plant, 2004). In addition, it is ill able to recover all of the channels completely for fiber chromatic dispersion in a dense wavelength-division multiplexing (DWDM) system. This drawback is caused by that the amounts of cumulative dispersion through optical link are different for each channels. Generally, in DWDM, total accumulated dispersion of wavelength channels is proportional to the transmitted distance and wavelength separations from the zero-dispersion wavelength (ZDW) of optical fiber (Talukder & Islam, 2005).

In contrast, optical phase conjugation including MSSI is capable of compensating the signal impairments owing to the chromatic dispersion and Kerr nonlinearity

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simultaneously using by an optical phase conjugator (OPC). In optical transmission link adopting the optical phase conjugation, the OPC should be placed at anywhere in the entire transmission link. By the OPC, impairments of the first half transmission link (before the OPC module) can be cancelled or mitigated by those phase-conjugated waves in the second half section (after the OPC module) (Yariv *et al*., 1979; Jansen *et al*., 2006). Theoretically, for the elimination and mitigation of Kerr nonlinearity by optical phase conjugation, it is required to symmetrically distribute the optical power and local dispersion with respect to OPC position (Watanabe & Shirasaki, 1996). Therefore, the OPC is commonly placed midway along the entire transmission link in order to satisfy the above mentioned condition. The system with the OPC placed at the middle of total transmission link is referred to as MSSI. MSSI can compensate impairments caused by nonlinear phase noise as well as impairments resulting from chromatic dispersion and Kerr nonlinearity. In addition, the significant advantages of MSSI are that it is effective for multiple channel transmission such as WDM transmission, that it is transparent to modulation formats (Jansen *et al*., 2006), and that it is available for coherent optical transmission such as coherent optical orthogonal frequency division multiplexing (CO-OFDM) (Morshed *et al*., 2013).

However, in MSSI, it is difficult to practically setup the perfectly symmetrical distribution of power and local dispersion, since the effects of fiber's intrinsic loss and the lumped amplification in long-haul system. Recently, the OPC position optimization (Xiao *et al*., 2006; Minzioni *et al*., 2004) and the combining appropriate dispersion map with the OPC (Xiao *et al*., 2006; Minzioni *et al*., 2004; Chowdhury & Essiambre, 2004; Minzioni & Schiffini, 2005), were proposed in order to overcome this drawback.

In a dispersion-managed optical fiber system, the deployment of the DCF and SMF in each fiber spans (Rothnie & Midwinter, 1996), residual dispersion per span (RDPS), the control position and the amounts of net residual dispersion (NRD) (Bellotti *et al*., 1999; Nuyts *et al*., 1996; Peucheret *et al*., 2000) affect the system performance. Based on the deployment of fibers, the inline DM scheme is specified into pre- or post-compensated DM. In pre-compensated inline DM, the DCF precedes the SMF in every fiber spans, on the other hand, the SMF is in front of the DCF in post-compensated inline DM. In inline DM scheme, the RDPS is defined as total dispersion amounts of one fiber span consisted of the SMF and the DCF, and NRD is defined as the cumulative dispersion amounts in the entire transmission link, i.e., the sum of the RDPSs (Xiao *et al*., 2006).

In a DM link combined with MSSI, a simple configuration can be obtained by uniformly deploying the SMF's lengths and RDPSs over all of the fiber spans. However, it is required for implementing the flexible optical link topology that the SMF's lengths and RDPSs are not fixed. One possible way to set up the flexible DM link configuration is to distribute the random SMF's length and RDPSs for every fiber spans. However, there are so many cases for investigating the system performance depending on the random pattern, therefore, it is difficult to decide the best random pattern for the excellent compensation.

Other possible way to implement the flexible DM link configuration is to use the artificial distributions of the SMF's lengths and the magnitude of RDPSs, such as the ascending/descending distribution, as the position of fiber span move away from the transmitter and the OPC. This configuration is more attractive to find out the best distribution pattern since the case numbers are finite (Chung, & Lee, 2016).

It is also important for the best compensation to select the position for controlling the NRD as well as pre- or post-compensation scheme of a fiber span when the RDPS exists in every fiber span. To the best of the authors' knowledge, the compensation effects of the control position of the NRD (which depends upon the pre- or post-compensation of the fiber spans) on the system performance in a long-haul transmission system, especially in which the optical link consists of artificially distributed SMF lengths and RDPSs, are yet to be reported.

Therefore, in this work, the interactive compensation effects of the artificial distributions of the SMF lengths, RDPSs, and the control position of the NRD on the DM link with MSSI for transmitting 24 channels × 40-Gbps WDM signals are assessed and analyzed. It is possible to obtain 16 combinations of the artificial distributions, and the NRD control positions have 4 cases, such as the start point of the link, end point of the link, front point of OPC, and rear point of OPC. That is, the system performances in each of the 16 DM links having one NRD control position are assessed. In turn, the system performances are assessed in other NRD control positions, and then the induced results in all of the considered link configurations are compared in this research.

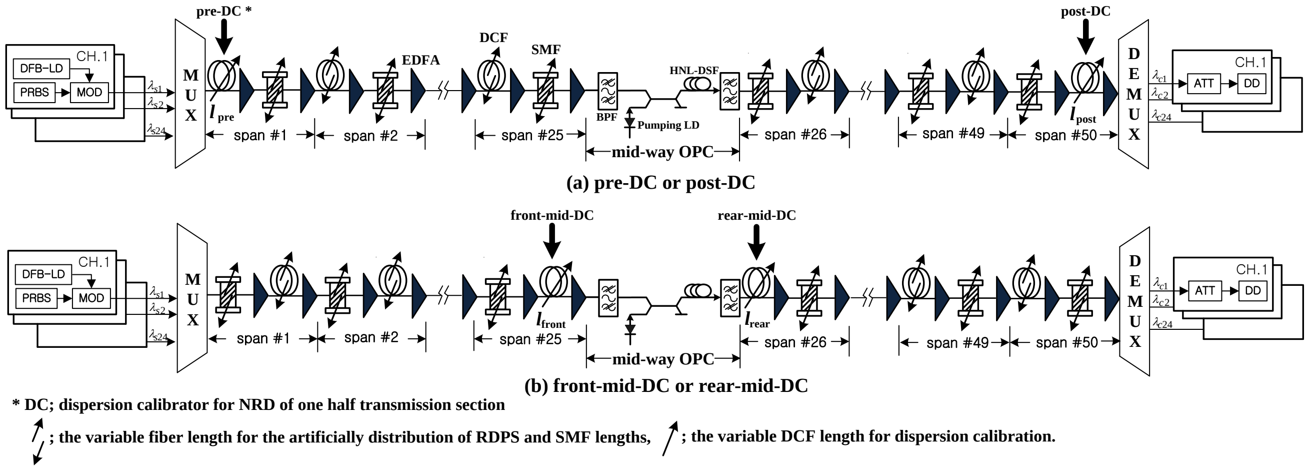


Figure 1. The proposed configuration of 24-channel DWDM system and the dispersion-managed link

II. MODELLING OF DISPERSION-MANAGED LINK

Table 1. Fiber parameters

	SMF	DCF
Attenuation coefficient	0.2 dB/km	0.6 dB/km
Dispersion coefficient	17 ps/nm/km	-100 ps/nm/km
Nonlinear coefficient	1.35 $W^{-1}km^{-1}$	5.06 $W^{-1}km^{-1}$

Figure 1 shows the proposed DM optical transmission link combining with the MSSI. The considered link is comprised of 50 fiber spans. Each fiber span includes the SMF and the DCF; however, the deploy order of fibers varies depending upon the inline dispersion compensation scheme (in other words, the control of RDPS). As shown in Figure 1, two link configurations are considered in this research: one [see Figure 1(a)] is pre-compensation and post-compensation in front and rear of the mid-way OPC, respectively, and the other [see Figure 1(b)] is post-compensation and pre-compensation in front and rear of the mid-way OPC, respectively.

The SMF lengths of every fiber spans are varied to artificially distribute the SMF lengths. And simultaneously the DCF lengths from span #2 to span #49 are varied to artificially distribute the RDPSs. However, the rest of the fiber parameters are fixed in all of the spans as summarized in Table 1.

The SMF lengths in both half sections, i.e., the first half section (we called this as "FHS") before the mid-way OPC and the second half section ((we called this as "SHS") after the mid-way OPC, are ranged by ascending order or descending order from 44 to 116 km (at 3-km intervals) for the artificial distribution as the position of fiber span move away from the transmitter and the mid-way OPC. There are four cases related with the combination of each half section's distributions: i) ascending distribution in FHS and simultaneously ascending distribution in SHS (this distribution is abbreviated as "A-A"), ii) descending distribution in FHS and simultaneously descending distribution in SHS (abbreviated as "D-D"), iii) ascending distribution in FHS and simultaneously descending distribution in SHS (abbreviated as "A-D"), and iv) descending distribution in FHS and simultaneously ascending distribution in SHS (abbreviated as "D-A").

It is assumed that the averaged RDPS of 24 fiber spans is equal to each both half sections at 200 ps/nm. However, the exact RDPSs in both half sections are also ranged by ascending order or descending order from 9 ps/nm to 392 ps/nm (11 or 21 ps/nm intervals) as the position of fiber span move away from the transmitter and the mid-way OPC. There are also four cases related with the combination of each half section's RDPS distributions: these are abbreviated as A-A, D-D, A-D, and D-A. The each RDPS of every fiber span is determined by calculating the DCF length l_{DCF} according to $(l_{SMF} \cdot D_{SMF} - \text{RDPS}) / |D_{DCF}|$, where l_{SMF} is the length of the SMF, D_{SMF} is the dispersion coefficient of the SMF, D_{DCF} is the dispersion coefficient of the DCF.

Therefore, there are 16 cases according to the combination of the artificial distributions the SMF length and exact RDPS. These cases are expressed by the abbreviations of the artificially distributed SMF lengths in both fiber sections: the abbreviations of the artificially distributed RDPSs in both fiber sections, such as A-A:A-A, A-D:D-A, D-A:A-D, D-D:A-A, and D-D:D-D, etc. For example, D-A:A-D means the optical link with descending distribution of the SMF lengths and ascending distribution of the exact RDPSs in FHS, and simultaneously ascending distribution of SMF lengths and descending distribution of the exact RDPSs in SHS.

Total cumulated dispersion amounts in each half section, except for the first and last fiber spans, are 4,800 ps/nm since the assumed mean RDPS of each fiber spans is 200 ps/nm. This value is not suitable to good compensate for the distorted DWDM signals, because this is very large. Therefore, it is required to suppress the cumulated dispersion amounts (i.e., NRD) in each half section for desirable compensation by using the arbitrary fiber span. For controlling of NRD by a particular span, it is also important to select an appropriate span because the position of the NRD control in the optical link should influence the compensation. We consider the NRD controlling methods as following. First, in the pre-compensation-&-post-compensation scheme plotted in Figure 1(a), the DCF length of the first fiber span and the last fiber span, i.e., l_{pre} and l_{post}, play roles as the NRD controllers (i.e., dispersion calibrator (DC)) of FHS and SHS, respectively. On the other hand, in the post-compensation-&-pre-compensation scheme plotted in Figure 1(b), the DCF length of #25 first fiber span and #26 fiber span, i.e., l_{front} and l_{rear}, play roles as the DC of FHS and SHS, respectively.

We consider four methods to control the NRD in the entire transmission link depending on the inline DM configurations. Two methods among these are concern with Figure 1(a) as follows: the dispersion amounts accumulated through the entire link is calibrated by the NRD of FHS using only l_{pre}, and simultaneously the perfect dispersion elimination in SHS. The perfect dispersion elimination of SHS is obtained by fixing l_{post} to be 61.6 km, which is induced from $[\sum \mathrm{RDPS}+(l_{\#25,SMF} \cdot D_{SMF})] / |D_{DCF}|$. This NRD control method is called pre-dispersion calibration (pre-DC). The other method is called to post-DC as following: the dispersion amounts accumulated in the entire link is calibrated by using only l_{post}, and by simultaneously the perfect dispersion elimination through l_{pre} = 61.6 km.

On the other hand, the rest two methods are concern with Figure 1(b). One of these is called to front-DC: the dispersion amounts accumulated through the entire length is calibrated by the NRD of FHS using only l_{front}, and by simultaneously the perfect dispersion elimination of SHS. The other is called to rear-DC: the dispersion amounts accumulated in the entire link is calibrated by using only l_{rear}, and by simultaneously the perfect dispersion elimination of FHS.

III. MODELLING OF TRANSMITTER, RECEIVER AND OPC

Figure 1 also shows the configuration of the mid-way OPC. We select highly nonlinear dispersion-shifted fiber (HNL-DSF) OPC as a phase conjugator for MSSI. The feature of HNL-DSF as the nonlinear medium of the OPC is listed in Table 2. The power and wavelength of the pump light for generating the phase conjugated waves is assumed to be 18.5 dBm and 1,549.75 nm, respectively.

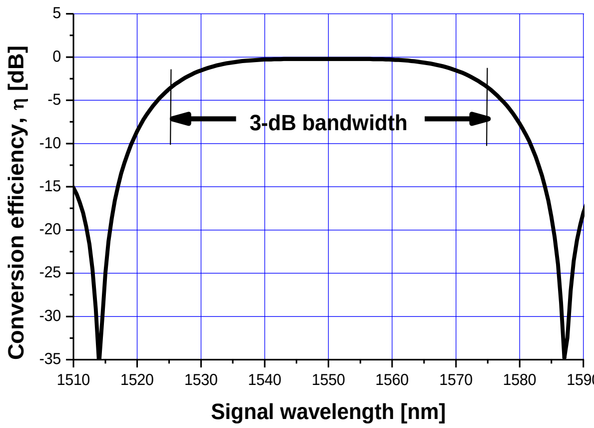


Figure 2. Conversion efficiency of HNL-DSF OPC

Table 2. The features of HNL-DSF

Parameter	Value
Loss	0.61 dB/km
Nonlinear coefficient	20.4 $W^{-1}km^{-1}$
Length	0.75 km
Zero dispersion wavelength	1,550 nm
Dispersion slope	0.032 $ps/nm^2/km$

The distributed feedback laser diodes (DFB-LDs) are used for the 24-channel DWDM transmitters (Tx). The center wavelengths of each Tx are selected from 1,550 nm to 1,568.4 nm. These are allocated at an interval of 0.8 nm (100 GHz) according to ITU-T recommendation G.694.1 (ITU, 2003). Each Tx generate an independent 40-Gbps 127(=2^7-1) pseudorandom bit sequence (PRBS). The continuous light waves from each DFB-LDs are injected into the external optical modulator (MOD). Finally, return-to-zero (RZ) pulses are generated as the modulated format from the external optical modulator. We assume the output electric field of the RZ format as a second-order super-Gaussian pulse with a 10-dB extinction ratio (ER), duty cycle of 0.5, and chirp-free. The DWDM RZ signals of 24 channels are multiplexed in AWG MUX and then transmitted into the first half section.

The distorted optical signals owing to the chromatic dispersion and Kerr nonlinearities of the first half section reach the mid-way OPC. Through FWM process of the input waves and the pump light, the conjugated waves with wavelengths of 1549.5–1528.5 nm are generated in in the mid-way OPC. The ratio of the FWM product power to the input signal power is defined to conversion efficiency (Inoue, 1992). The result of Figure 2 shows the calculated conversion efficiency from the parameters of Table 2. It is confirmed that the original and the conjugated wavelengths are belong to the 3-dB bandwidth (from 1,526 nm to 1,547 nm).

The 24 conjugated multiplexed channels are propagated through the second half of link, demultiplexed, and sent into each receiver (Rx), for direct detection. Each Rx in Figure 1 consists of EDFA as a pre-amplification stage, an optical filter, a photodetector, a pulse shaping Butterworth filter, and a decision circuit. The noise figure of EDFA is 5 dB, and bandwidth of optical filter is 1 nm in this study. Modeling of the photodetector is based on the PIN diode. We assume the receiver bandwidth to be 0.65 times of 40 Gbps (Agrawal, 2002).

IV. METHOD OF NUMERICAL ASSESSMENT

The silica optical fibers including the SMF and the DCF are the lossy, dispersive, and intensity-dependent nonlinear medium. Only one expression for the propagation of the optical signal in the silica fiber having these feature is the nonlinear SchrÖdinger equation (NLSE) (Agrawal, 2001):

$$\frac{\partial A_j}{\partial z} = -\frac{\alpha}{2}A_j - \frac{i}{2}\beta_{2j}\frac{\partial^2 A_j}{\partial T^2} + \frac{1}{6}\beta_{3j}\frac{\partial^3 A_j}{\partial T^3} + i\gamma_j\left|A_j\right|^2 A_j + 2i\gamma_j\left|A_k\right|^2 A_j, \quad (1)$$

where j,k = 1,2,...,24 ($j \neq k$), A_j represents the complex amplitude of the optical signal of the j-th channel, z is the propagation distance, β_{2j} is the GVD, β_{3j} is dispersion slope, γ_j is nonlinear coefficient, and $T = t - z/v_j$ is the time measured in a retarded frame. The last two terms of (1) express the effect of nonlinearity including SPM and XPM. The last term of (1), i.e., XPM influence on the optical signals is neglected in case of the high dispersive circumstance (Minzioni *et al.*, 2004). In this research, since we use the SMF and the DCF, which have the large coefficients, The XPM effect on DWDM signals is also omitted. The most common approach for solving (1) is the split-step Fourier method (Agrawal, 2001).

An easy way to assess the optical pulses deteriorated by the distortions is the calculation of the eye opening penalty (EOP). The EOP of decibel unit is defined as the common logarithm of the value of non-distorted reference signal's eye opening (EO) divided by the distorted signal's EO as shown in the following equation:

$$EOP\ [dB] = 10\ log_{10}\frac{EO_{rec}}{EO_{btb}}, \quad (2)$$

where EO_{rec} is the EO of receiving optical signals and EO_{btb} is the EO of the back-to-back optical signals (i.e., the reference signals). The EO is defined as twice the averaged power of all of the received signals divided by the smallest power level of the 'one' optical signal minus the largest power level of the 'zero' optical signal.

From the previous research, we have recognized that the optimal NRD is 10 ps/nm in the DM link, in which the accumulated dispersion amounts in the entire transmission link controlled by pre-DC (Lee, 2016). Also, this optimal value independent with the lengths of the SMF, RDPS, the transmitted power of each channels, and fiber's dispersion coefficient (Lee, 2016). This fact is concordant with the result of Killey *et al.*, (2000) of R. I. Killey's research dealing with "pseudo-linear" systems. In this paper, we confirmed that most of the optimal NRDs of the proposed 16-cases artificial distributions are also obtained to be 10 ps/nm. Therefore, we will assess and analyze the compensation quality of the distorted DWDM signals under the circumstance of NRD = 10 ps/nm for all of the artificial distributions and for all dispersion calibrators.

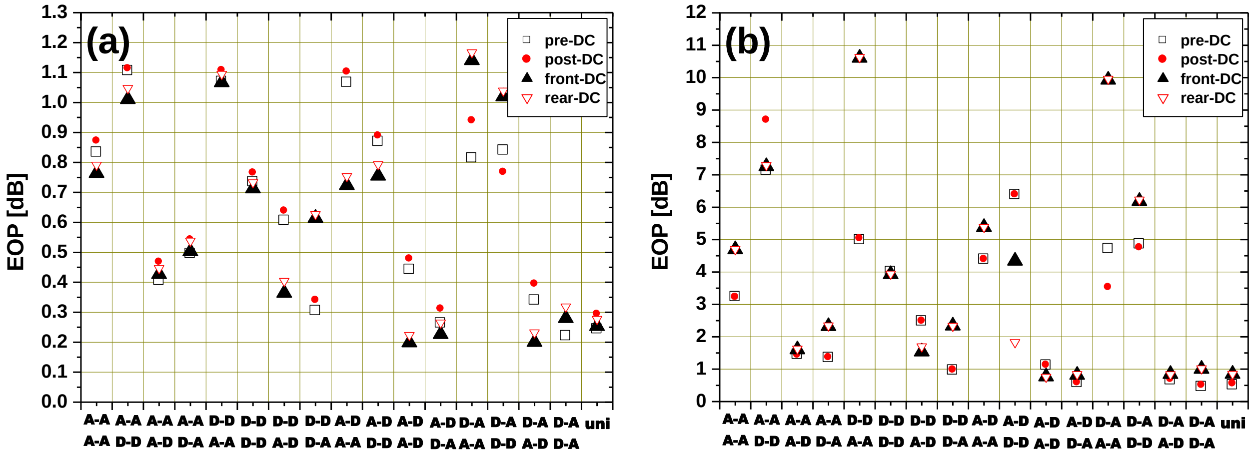


Figure 3. EOPs of worst channel depending on the artificial distribution patterns and dispersion calibrators in transmissions of (a) −3 dBm and (b) 2 dBm of launch power (Yim & Lee, 2018)

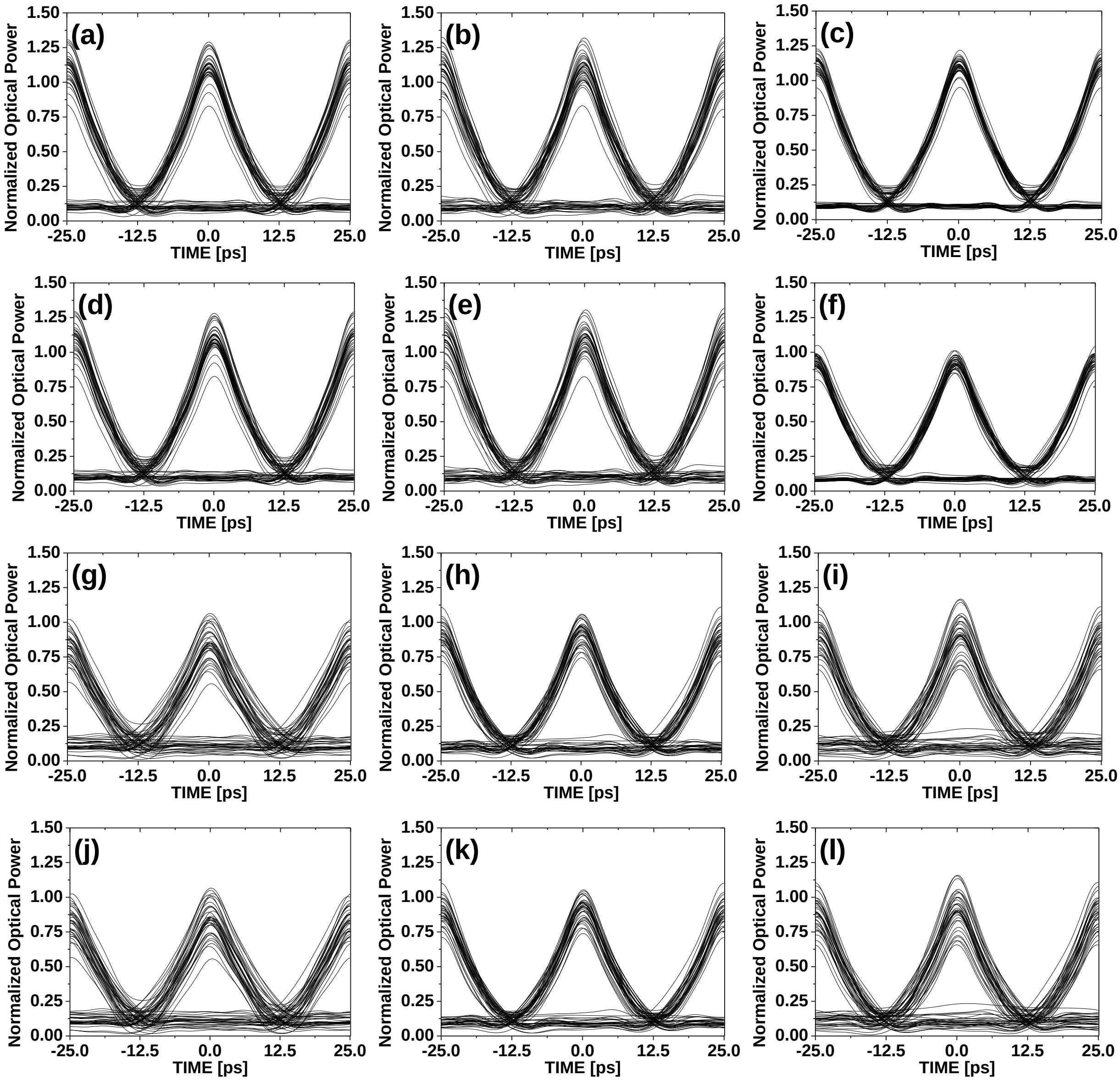


Figure 4. Eye diagrams of 4 dBm: (a) uniform distribution, (b) A-D:A-D pattern, and (c) D-A:D-A pattern in pre-DC scheme; (d) uniform distribution, (e) A-D:A-D pattern, and (f) D-A:D-A pattern in post-DC scheme; (g) uniform distribution, (h) A-D:D-A pattern, and (i) D-A:D-A pattern in front-DC scheme; and (j) uniform distribution, (k) A-D:D-A pattern, and (l) D-A:D-A pattern in rear-DC scheme

V. SIMULATION RESULTS AND ANALYSIS

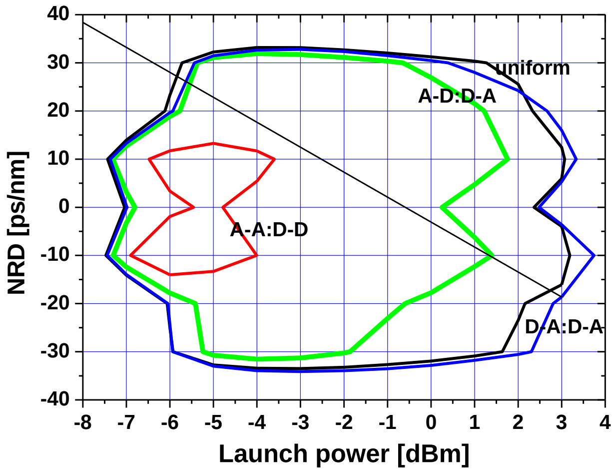
Figure 3 shows the EOPs of the worst DWDM channel depending on the proposed dispersion calibrators, which all make the NRD as 10 ps/nm, and on the combinations of artificial distribution patterns when each DWDM channels are transmitted with a launch power of -3 dBm [Figure 3(a)] and 2 dBm [Figure 3(b)] (Yim & Lee, 2018). For performance comparison, the right most values of the *x*-axis (marked as "uni") in Figure 3 (a) and (b) refer to the NRD values obtained in the optical links configured the uniform distribution. We investigate that the EOPs are more affected by the aspect of the artificial distribution of the SMF lengths and RDPSs than the NRD control position (i.e., the position of dispersion calibration). Furthermore, the quality of the compensated DWDM signal in DM link configured with the particular distribution patterns correspond or are superior to the uniform distribution, irrelevant of the NRD control position.

When launching at -3 dBm on all channels, the optical link configurations arranged by A-D:D-A and D-A:D-A represent this property. On the other hand, when launching at 2 dBm, the A-D:A-D and D-A:A-D patterns as well as the abovementioned two patterns are also included in the particular patterns. That is, by using the artificially distributed SMF's lengths and RDPSs, it is confirmed that the performance in the high-power transmission of the WDM channels is improved further than in the low-power system.

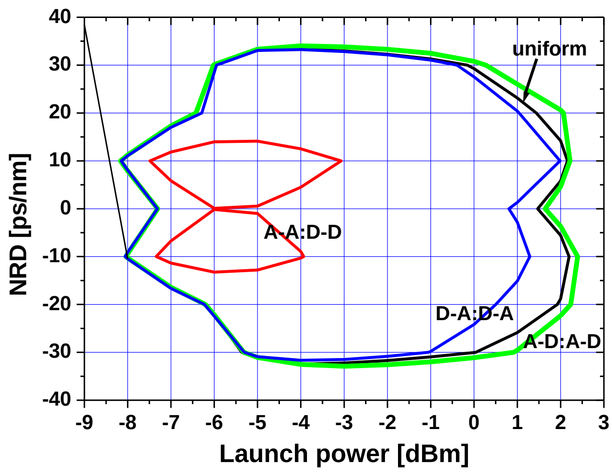
Figure 4 shows eye diagrams of the worst channels launched at 4 dBm into the optical links with three artificial patterns (i.e., A-D:A-D, A-D:D-A, and D-A:D-A). These result in good performance with uniform distribution in which the NRD is controlled by pre-DC, post-DC, front-DC, or rear-DC. It is shown that the signal compensation through the DA-DA pattern is slightly better than the others when NRD = 10 ps/nm as determined by pre-DC and post-DC. On the other hand, the signal compensation through the A-D:D-A pattern is slightly better than the others when NRD = 10 ps/nm as determined by front-DC and rear-DC. It should be considered that the difference in compensation between A-D:D-A and D-A:D-A is negligible.

The similarity between A-D:D-A and D-A:D-A is the distribution pattern of the RDPSs, i.e., X-X:D-A. This pattern is identical with the RDPSs are gradually decreased in the first half section, in contrast, the RDPSs are gradually increased in the second half section. This result means that it is desirable to temporally broaden the DWDM pulse widths at the start point of transmission, and then to gradually compress the DWDM pulse widths when they get closer to the mid-way OPC. In addition, the temporally compressed and spectrally inverted optical pulses after the mid-way OPC are more inversely broadened as the transmission distance is closer to Rx for the best compensation of overall DDM channels.

Two patterns (AA-DA and DD-DA) are also included in xx-DA. However, it is shown from the results in Figure 3 that the signal compensation through two patterns of AA-DA and



(a) Post-DC



(b) Front-DC

Figure 5. Effective NRD contours for various artificial distribution patterns as function of launch power

DD-DA is deteriorated more than the uniform distribution. That is, the results of Figure 3 and Figure 4 show that, for the best compensation through the artificial distribution, it is necessary to gradually increase the RDPSs with respect to OPCs closer to Tx and Rx. Simultaneously, the artificial distribution of the SMF's lengths must be symmetrical with respect to the OPC, such as gradually ascending and gradually descending or gradually descending and gradually ascending.

In ultra-high speed transmission systems upper than 10-Gbps, the criterion of EOP is commonly 1-dB. This criterion is corresponds to error-free transmission (Kikuchi & Sasaki, 1995). Also, this criterion is analytically equivalent to a pulse broadening of 1.25 (Kikuchi & Sasaki, 1995). Through an analysis of our previous studies, it is recognized that EOP below 1 dB are obtained in various NRD values beside 10 ps/nm at an arbitrary launch power. The range from the minimum NRD to the maximum NRD, which result in an EOP below 1 dB, is defined as the effective NRD range.

Figure 5(a) and 5(b) illustrate the effective NRD contours of the worst channel, i.e., the effective NRD ranges versus the launch power of DWDM, in the optical links of the uniform distribution and the characteristic patterns of the artificial distribution, in which the NRD is controlled by post-DC and front-DC, respectively. It is shown that for a relatively high launch power, the NRD margin controlled by post-DC and front-DC is more expanded than others in the optical link that are artificially configured with the DA-DA pattern and the AD-AD pattern, respectively.

The effective NRD contours for pre-DC and rear-DC are not shown in this paper since the results are similar to those in Figure 5. However, for the easy comparative analysis of the effective NRD contours of all cases (4 cases of the NRD control positions and 16 cases of the artificial distribution), it should be required to use the quantitative factor. For this, we evaluate the area of the contour as a quantitative factor. For the simplicity of numerical process, the area of contour is obtained through calculating the sum of the product of the NRD and (launch) power.

Figure 6(a) and 6(b) illustrate the areas of the effective NRD contours for X-X:A-D and X-X:D-A distribution patterns and the uniform distribution in the DM link controlled by pre-DC/post-DC and front-DC/rear-DC, respectively. We confirm that the artificial distribution pattern capable of resulting in an excellent the area of contour than the uniform distribution is only the D-A:D-A pattern in the pre-DC and post-DC schemes. On the other hand, in front-DC and rear-DC schemes, the area of contours of A-D:A-D and D-A:A-D patterns are larger than the uniform distribution, and the area of contour of A-D:D-A corresponds to that in the uniform distribution.

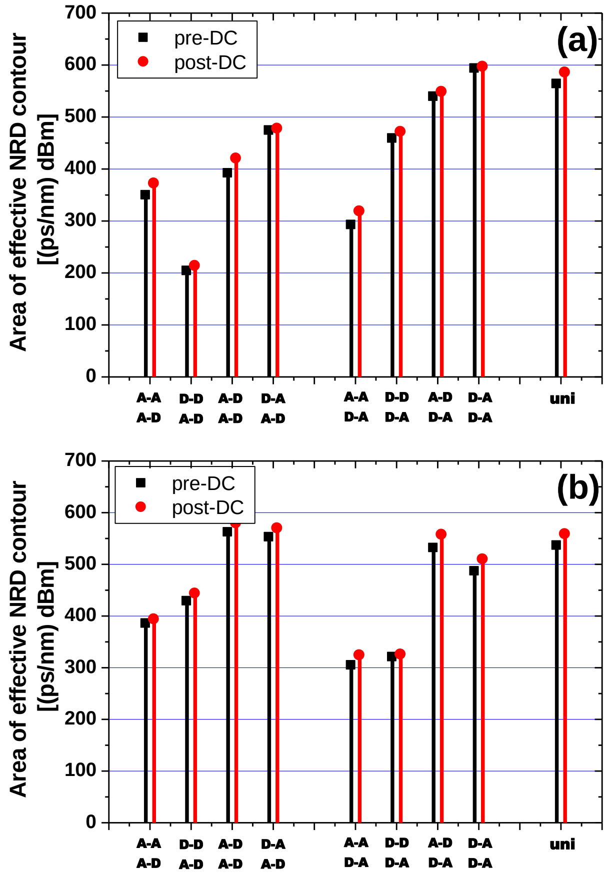


Figure 6. The areas of effective NRD contours of X-X:A-D and X-X:D-A distributed DM link controlled by (a) pre-DC and post-DC, and by (b) front-DC and rear-DC

VI. CONCLUSION

The purpose of this research was aimed at examining the implementation and the performance improvement of a flexible long-haul DM link configured with the artificial distribution of the SMF lengths and RDPS in which the midway OPC combined. In addition, in order to verify this aim, we assessed the interactive compensation effects of 16 cases of the artificial distributions and 4 cases of the control position of NRD on the proposed DM link. We first confirmed that the best distribution pattern depends on the

NRD control position in the link and the launching power of the distorted DWDM channels in the particular patterns (i.e., A-D:D-A and D-A:A-D) are less affected by the NRD position, and this property is greater in high-power rather than low-power transmission. That is, the flexible long-haul DWDM system is quite possible as long as the artificial distribution pattern of the DM link is properly selected.

We used the area of the effective NRD contour as the design rule of the flexibility of the proposed DM links. From this viewpoint, it was confirmed that the area of the effective DWDM channel. However, the compensation of NRD contour depends on the NRD control position. We confirmed that the area of the effective NRD contour in the artificial distribution patterns based on X-X:D-A is more expanded than the uniform distribution for pre-DC and post-DC schemes. On the other hand, in case of front-DC and rear-DC schemes, the area of the effective NRD contour in the artificial distribution patterns based on X-X:A-D is superior to the uniform distribution.

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