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Dispersion Managed Optical Links with Optical Phase Conjugator Placed at the Various Positions

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Abstract

The needs of ultra-high optical backbone systems are currently increased to transmit the high-quality multimedia services. For transmitting the ultra-high speed optical signals with better performance, the techniques to suppress or mitigate the optical signal distortion due to group velocity dispersion and optical Kerr effects are required. Dispersion management (DM), optical phase conjugation, and the combination of these two are promising techniques to compensate for the signal distortion. The goal of this paper is to investigate the possibility of the flexible configurations of the ultra-high and long-haul optical backbone systems using optical links with the random distribution of residual dispersion per span (RDPS) and optical phase conjugator (OPC) placed at the various positions. We confirm that the proposed link configurations should be one of the methods suitable for implementing the flexible optical backbone systems, also, the possibility is more available to longer backbone.

Keywords: *Random distribution of Residual Dispersion per Span, non-midway Optical Phase Conjugator, Dispersion-Managed Optical Links, Net Residual Dispersion, Optical backbone system, High-quality multimedia transmission*

1. Introduction

The demands on the ultra-high optical fiber backbone systems are drastically increasing by the growth of the high-speed internet and new multimedia services like video on demand (VOD), high-definition television (HDTV), and internet protocol television (IPTV). Digital subsciber lines are unable to offer such capacity, and therefore carriers are adding passive optical networks (PONs) in the local loop. In turn this will increase the bandwidth demand further and require high-capacity, longer backbone optical links that have better performance and lower costs [1].

A technological challenge in the long-haul optical transmission systems is severely limited in standard single-mode fiber (SSMF) due to nonlinear distortion and group velocity dispersion (GVD) [2–4]. It is well known that dispersion management (DM) and optical phase conjugation are the available mitigation techniques, which compensate for the optical signal distortion due to GVD and nonlinear effects [5, 6].

To minimize the impact of the signal distortion due to GVD, a dispersion map involving optical pre(post)compensation, residual dispersion per span (RDPS), net

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residual dispersion (NRD) in DM technique must be used. Pre- and postcompensation are defined as dispersion compensation using dispersion compensation fiber (DCF) after transmitter and before receiver, respectively. In case of dispersion map applied to every fiber spans, RDPS is defined as dispersion accumulated in each fiber spans consisted of optical transmission links. And, NRD is defined as total dispersion accumulated at the end of the transmission link [7]. These quantities are key parameters for designing a transmission system with high performance. Generally, NRD is decided by controlling pre(post)compensation and RDPS. DM technique is even capable of slope-matching compensation, namely, compensating the dispersion and the dispersion slope of the transmission fiber simultaneously [8]. However this is not the case when nonlinear effects cannot be neglected.

Optical phase conjugation is another effective technique to simultaneously reduce GVD and nonlinear impairment mainly due to self-phase modulation (SPM). The compensation for signal impairment in this technique is theoretically possible through the use of optical phase conjugator (OPC) in the middle of total transmission length, i.e., the midway OPC. This technique offers unique advantages over other competitive methods such as data rate and modulation format transparency, ultra-fast responses, and simultaneous multi-channel compensation. It is independent of the transmission fiber's dispersion property as long as the same type of fiber is used for both halves of the transmission link with respect to OPC [6].

But, the effective suppression of nonlinear impairment is not practically obtained in the exact transmission systems, because nonlinearity cancellation requires a perfectly symmetrical distribution of power and local dispersion with respect to OPC position. Due to the presence of fiber attenuation, this condition cannot be satisfied in real links [9]. Fortunately, the various techniques, such as optimizing OPC position [10, 11] or combining appropriate dispersion mapping [10, 12, 13] has been recently proposed for overcoming this problem. In order to suppress the nonlinearity impairments to a large extent, the system parameters of an OPC link, such as the location of OPC or the dispersion map, need be optimized.

The optical transmission link as the backbone systems for providing the high quality and ultra-high data rate multimedia services has not to be affected by the link configurations and the optical network topology. However, in the optical link with only OPC, the variety of link configurations had been restricted, because OPC has to be placed at the middle of total transmission length for the effective mitigation of the optical distortion.

Authors also had shown 960 Gbps (40 Gbps × 24 channels) wavelength division multiplexing (WDM) transmission system with better receive performance could be implemented by applying the combined DM and the midway OPC into optical links through the previous work [14]. In that research, the basic scheme of DM is that NRD is controlled by precompensation using DCF of first span, by postcompensation using DCF of last span, and by the uniform RDPS for the rest fiber spans. The uniform RDPS is obtained by deploying the equal lengths of SMF and DCF for every fiber spans. This uniform RDPS makes the optical link configurations simple. However, OPC position, SMF length and RDPS need to be unlimited for the flexible implementation of optical network topology. As far as authors know, the analysis and assessment of WDM transmission link with the random distribution of RDPS in each fiber span and OPC placed at the various positions have not been reported yet.

Therefore, in this paper, the implementation possibility of dispersion managed optical links with the randomly distributed RDPS of fiber spans and OPC placed at the various positions is investigated for the flexible optical backbone configurations. Also, we investigate the optimal parameters of DM, such as the optimal NRD, the effective NRD range and the effective power range, for improving system performance in these optical links. Optical link considered in this paper is specified for 24 channels × 40 Gbps WDM transmission. The modulation format of each WDM channels is assumed to be return-to-zero (RZ), and transmission fiber of every fiber spans are assumed to be SMF of 80 km length.

The rest of the paper is organized as follows. In Section 2, the modeling and specifications of the proposed optical transmission links and WDM systems for 960 Gbps are presented. Numerical assessment method and the system performance are described in Section 3. In Section 4, the simulation results and our analysis are presented. And, the conclusion is addressed in Section 5.

2. Modeling of Optical Links and 960 Gbps WDM Transmission Systems

2.1. Modeling of optical links

The optical transmission link configuration investigated in this research is shown in Figure 1. The total transmission links consist of 14 fiber spans, which include SMF and DCF. The SMF length, l_{SMF} of the every fiber spans is equally designed to be 80 km in both optical links of the uniformly distributed RDPS and the randomly distributed RDPS. And, SMF is characterized by attenuation coefficient α_{SMF} = 0.2 dB/km, dispersion coefficient D_{SMF} = 17 ps/nm/km, and nonlinear coefficient γ_{SMF} = 1.35 $W^{-1}km^{-1}$ at 1,550 nm. On the other hand, the DCF of the every fiber spans is characterized by dispersion coefficient D_{DCF} = -100 ps/nm/km, attenuation coefficient α_{DCF} = 0.6 dB/km, and nonlinear coefficient γ_{DCF} = 5.06 $W^{-1}km^{-1}$ at 1,550 nm.

The accumulated dispersion at the end of SMF of each fiber spans is 1,360 ps/nm. Thus, in order to fix RDPS of each fiber spans to 150 ps/nm, DCF length of each fiber spans, *i.e.*, $l_{DCF,n}$ have to be set to 12.1 km. But, each DCF's length of 13 fiber spans is randomly selected for the random distribution of RDPS in the all cases of OPC position. DCF length of the first fiber span or the last fiber span, excluded from 14 fiber spans, *i.e.*, l_{pre} or l_{post} is used to determine NRD of the optical link.

We consider 7 cases of the OPC position as shown in Figure 1. We present the OPC position in the optical links as "number of fiber spans before OPC: number of fiber spans after OPC". For example, 2:12 means OPC placed between the first 2 fiber spans and the rest 12 fiber spans. In 2:12 configuration, RDPS of the second fiber span is fixed to 150 ps/nm, on the other hand, RDPSs of the fiber spans after OPC, *i.e.*, from 3th to 13th fiber spans, is assumed to be selected to be one value among -100, -50, 0, 50, 100, 150, 200, 250, 300, 350 or 400 ps/nm, except the first and the last fiber spans. In 4:10 configuration, RDPSs of three fiber spans before OPC is selected to be one value among 100, 150, or 200 ps/nm, on the other hand, RDPSs of 9 fiber spans after OPC is assumed to be selected to be one value among -50, 0, 50, 100, 150, 200, 250, 300, or 350 ps/nm. In 6:8 configuration, RDPSs of 5 fiber spans before OPC is selected to be one value among 50, 100, 150, 200, or 250 ps/nm, on the other hand, RDPSs of 7 fiber spans after OPC is assumed to be selected to be one value among 0, 50, 100, 150, 200, 250, or 300 ps/nm. In 7:7 configuration, *i.e.*, the midway OPC configuration, RDPSs of 6 fiber spans before and after OPC is selected to be one value among 0, 50, 100, 150, 200 or 400 ps/nm.

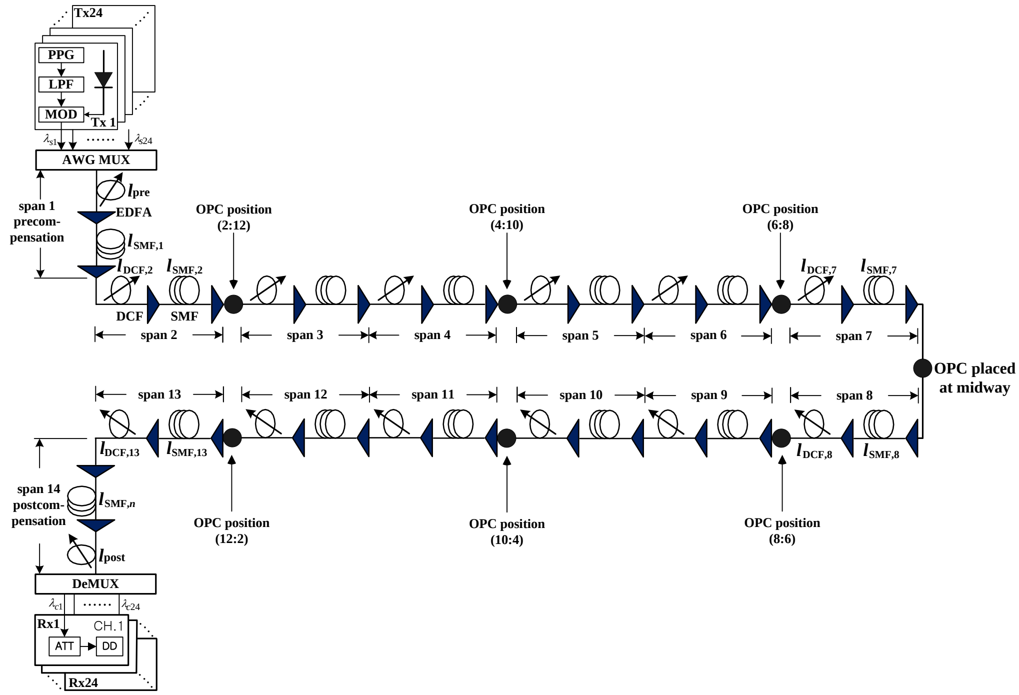


Figure 1. The optical link configurations and WDM transmission system

In 8:6, 10:4, 12:2 configurations, the fiber spans before and after OPC randomly select one value among the previously mentioned RDPSs after and before OPC in 6:8, 4:10, 2:12 configurations, respectively. The averaged RDPS of the fiber spans with the randomly selected RDPS is 150 ps/nm in the all configurations. Therefore, in the optical links with the uniform distribution of RDPS, which is compared with the random distribution, RDPS of the every fiber spans is assumed to be 150 ps/nm.

The NRD is controlled by pre- or postcompensation in both cases of the uniform distribution and the random distribution of RDPS, as plotted in Figure 1. In case of determining the NRD by only precompensation, the NRD depends on the variable length of the first DCF, *i.e.*, l_{pre}, the accumulated dispersion in the first SMF, and the total RDPSs before OPC, when the total accumulated dispersion in the optical links after OPC has been fixed to be 0 ps/nm by the variable l_{post}. On the other hand, when the NRD is determined by only postcompensation, it depends on the variable length of the last DCF, *i.e.*, l_{post}, the accumulated dispersion in the last SMF, and the total RDPSs before OPC when the total accumulated dispersion in the optical links before OPC has been fixed to be 0 ps/nm by the variable l_{pre}.

2.2. Modeling of WDM transmission system

In Figure 1, the transmitters (Tx) for WDM transmission is assumed to be a distributed feedback laser diode (DFB-LD). The center wavelengths of the DFB-LD are allocated from 1550.0 nm to 1568.4 nm by spacing of 100 GHz (0.8 nm) based on ITU-T recommendation G.694.1. The DFB-LD is externally modulated by an independent 40 Gbps 127 (= 2^7 -1) pseudo random bit sequence (PRBS). The modulation format from the external optical modulator is assumed to be return-to-zero (RZ), and the output electric field of the RZ format was assumed to be a second-order super-Gaussian pulse with a 10 dB extinction ratio, duty cycle of 0.5, and chirp-free.

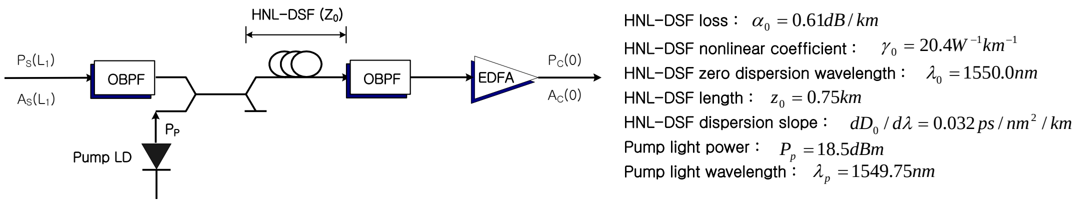


Figure 2. OPC configuration and parameters

The configuration of OPC in the optical links is illustrated in Figure 2. The nonlinear medium of OPC is assumed to be the highly nonlinear dispersion-shifted fiber (HNL-DSF). The parameters of HNL-DSF and pump light for generating the conjugated wave are also summarized in Figure 2. The transmitted signals are converted to the conjugated signals with wavelengths of 1549.5–1528.5 nm through OPC. The 3-dB bandwidth of conversion efficiency η of the OPC is set at 48 nm (1526–1574 nm). Thus, the all signal wavelengths and these conjugated wavelengths belonged within the 3-dB bandwidth of η.

The conjugated wavelengths are sent into the receivers (Rx) of direct detection. The Rx consists of the pre-amplifier of erbium-doped fiber amplifier (EDFA) with 5 dB noise figure, the optical filter of 1 nm bandwidth, PIN diode, pulse shaping filter (Butterworth filter), and the decision circuit. The receiver bandwidth is assumed to be at 0.65 × bit-rate [15].

3. Numerical Assessment Method

The propagation of the signal in a lossy, dispersive, and nonlinear medium can be expressed by the nonlinear SchrÖdinger equation (NLSE), assuming a slowly varying envelope approximation [16]. The numerical approach of NLSE is completed by using the split-step Fourier method [16].

The eye opening penalty (EOP) is used to assess the system performance of the receiving WDM signals in this work, as shown in the following equation:

$$EOP\ [dB] = 10\ log_{10} \frac{EO_{rec}}{EO_{btb}}, \tag{1}$$

where EO_{rec} and EO_{btb} are the eye opening (EO) of the receiving optical pulse and EO of the input optical pulse, respectively. EO is defined as the following equation:

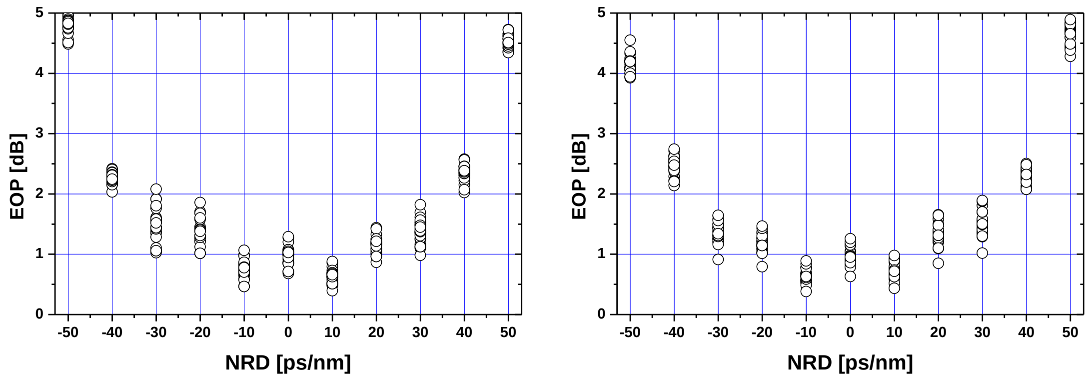
$$2P_{av}/(P_{1,min} - P_{0,max}), \tag{2}$$

where P_{av} is the averaged power of the optical signals, and $P_{1,min}$ and $P_{0,max}$ are the minimum power of the '1' optical pulse and the maximum power of the '0' optical pulse, respectively.

There are many random distribution patterns of RDPS. It is difficult to assess the system performance of the overall cases because it is a time consuming process. Therefore, in this work, 30 patterns of random distribution are considered for an accurate and simple assessment.

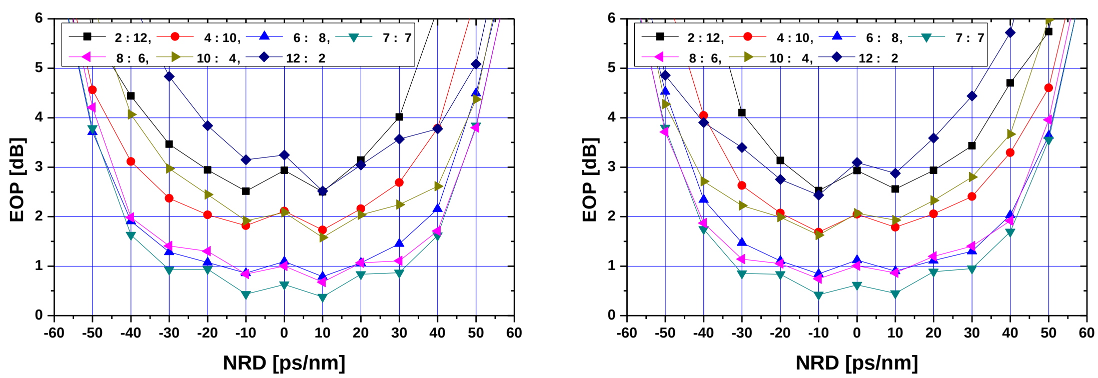
4. Simulation Results and Discussion

Figure 3 illustrates EOPs of the worst channel among the 24 WDM channels with the launch power of 0 dBm as a function of the NRD controlled by pre- and postcompensation, respectively, in the optical transmission links of the midway OPC and the randomly distributed RDPS. And, Figure 4 shows the worst EOPs among 30 random RDPS patterns in the optical transmission links with OPC placed at the various positions. Through analysis of the results of Figures 3 and 4, it is confirmed that the EOP depends upon the pattern of RDPS random distribution. However, the optimal NRDs, which are result the relative low EOP for the considered random distribution, are obtained to 10 ps/nm by precompensation and -10 ps/nm by postcompensation in the all cases of OPC positions. These results are remarkably consistent with the result of Reference [7] by Xiao's research dealing with "pseudolinear" system.



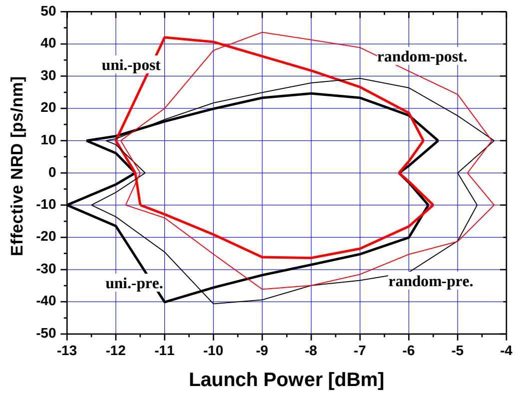
(a) precompensation (b) postcompensation

Figure 3. EOP versus NRD in the optical links with the midway OPC

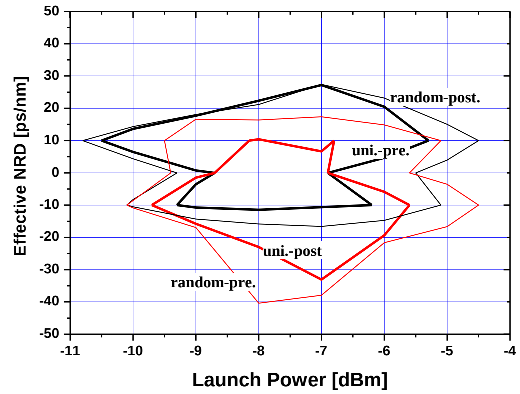


(a) precompensation (b) postcompensation

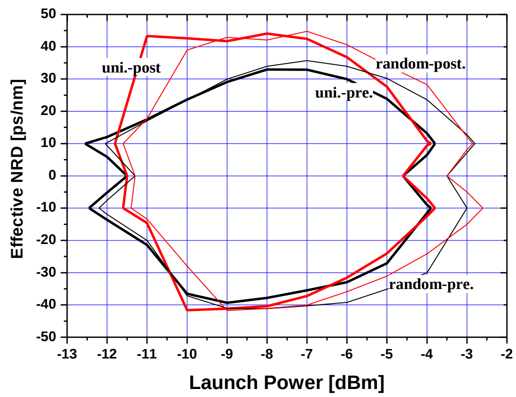
Figure 4. The worst EOP versus NRD



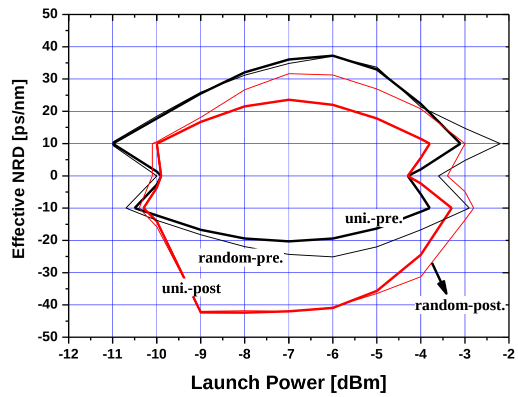
(a) 2:12 configuration



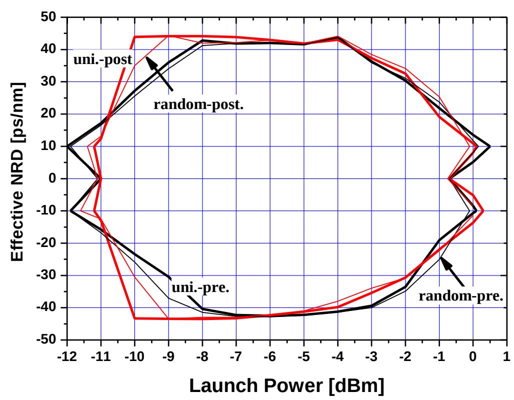
(b) 12:2 configuration



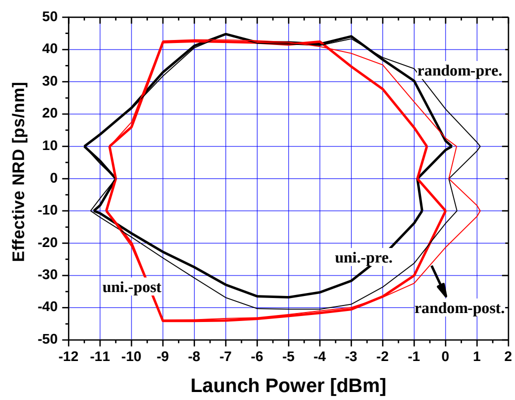
(c) 4:10 configuration



(d) 10:4 configuration



(e) 6:8 configuration



(f) 8:6 configuration

Figure 5. The effective NRD as a function of the launch power in the optical links with OPC placed at the various positions (*i.e.*, the non-midway OPC)

In fiber communication systems, 1 dB EOP is used for the system performance criterion, which is equivalent to the pulse broadening (the ratio of the received pulse RMS width to the initial pulse RMS width) of 1.25 and corresponds to 10^{-12} bit error rate (BER) [17]. From the criterion of 1 dB EOP, there is the wide NRD range, which is dependence of the launch power and the OPC positions. We define the NRD values result the EOP below 1 dB as the effective NRD range. Figures 5 and 6 illustrate the effective NRD ranges of the worst channel as a function of the launch power in the optical links with OPC placed at the non-midway positions and the midway, respectively. In figures, "uni" and "random" mean the uniform distribution and the random distribution of RDPS, respectively, and "pre' and "post" mean precompensation and post compensation, respectively.

It is shown that the effective NRD ranges are not largely dependent on the RDPS distribution in case of the midway OPC, from Figure 6. However, the effective NRD ranges in the uniform RDPS distribution and the random distribution are more different from one another, as OPC moves away from the midway. That is, it is confirmed that in 2:12 and 12:2 configurations the difference of the effective NRD ranges is particularly noticeable in comparison with others, from Figures 5(a) and 5(b).

From the results of Figures 5 and 6, the important points to be additionally confirmed. First, when OPC is closer to transmitter, *i.e.*, 2:12, 4:10, and 6:8 configurations, the characteristics of the effective NRD ranges are more improved than those in 12:2, 10:4, and 8:6 configurations, because the effective NRD ranges are relatively wider and the launch power having the effective NRD ranges upper ±30 ps/nm are relatively larger in those configurations. Second, in several non-midway OPC systems with the randomly distributed RDPS, especially 2:12, 4:10, 10:4, and 12:2 configurations, the characteristics of the effective NRD ranges depending on the launch power are more improved than those obtained in the uniform distributed RDPS systems. That is, it is confirmed that the system performance impairments due to the non-midway OPC should be mitigated by randomly distributing RDPS of the fiber spans. This effect by the random distribution of RDPS is more intensive, as the deviation of OPC position from the midway is larger.

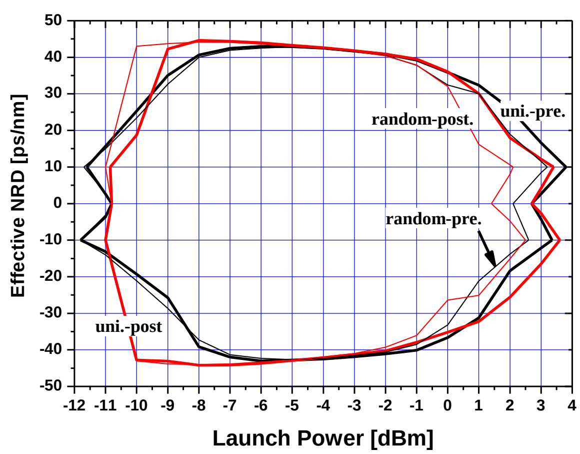
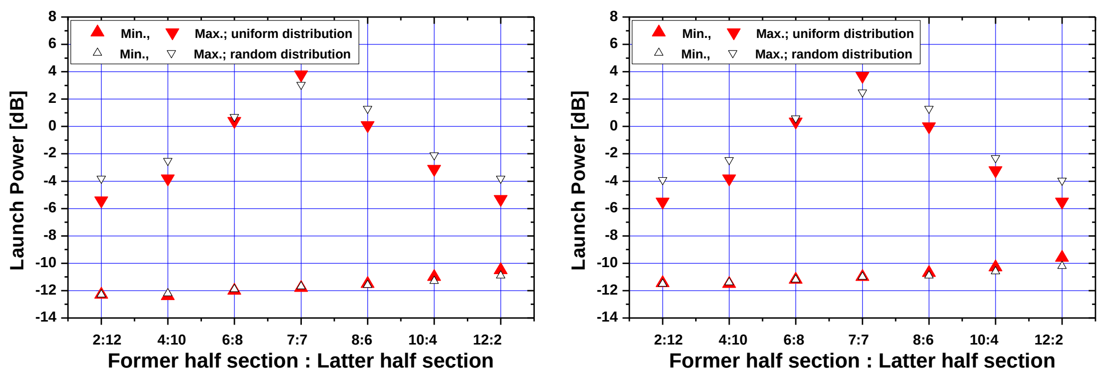


Figure 6. The effective NRD as a function of the launch power in the optical links with the midway OPC

Figure 7 shows the launch power resulting 1 dB EOP for the various OPC positions in cases of NRD = 10 ps/nm by precompensation and NRD = -10 ps/nm by postcompensation. In Figure 7, "former half section" and "latter half section" indicate the transmission sections form Tx to OPC and from OPC to Rx, respectively. In both cases of precompensation and postcompensation, the effective launch power ranges between the maximum and minimum powers in the optical links with the uniformly distributed RDPS are slightly larger than those in the randomly distributed RDPS in the midway OPC systems. However, the effective launch power ranges obtained in the randomly distributed RDPS are gradually improved than those in the uniformly distributed RDPS, as OPC moves away from the midway. This result is similar with the results from Figures 5 and 6. Thus, we conclude that the random distribution of RDPS becomes one successful methods mitigate the impairment of WDM signals due to OPC displacement from the midway.



(a) at NRD = 10 ps/nm by precompensation (b) at NRD = -10 ps/nm by postcompensation

Figure 7. The effective launch power for OPC positions

5. Conclusions

This paper discussed the implementation possibility of dispersion managed optical links with the randomly distributed RDPS of fiber spans and OPC placed at the various positions for the flexible optical backbone configurations. It was shown that the impairments of system performance due to the non-midway OPC should be mitigated by distributing RDPS of the fiber spans to random. Furthermore, it was confirmed that the compensation extents by the random distribution of RDPS is more intensive, as OPC moved away from the midway.

Consequently, it is expected that the implementation of the flexible configurations of the ultra-high speed optical backbone is possible by applying the randomly distributed RDPS into the optical links with the non-mid OPC used for suppressing the optical distortion due to GVD and SPM. Furthermore, this possibility should be more available to the long-haul backbone systems, because the more the fiber spans increase, the more the effectiveness of compensation by the randomly distributed RDPS is extended.

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