Far East Journal of Electronics and Communications

http://www.pphmj.com
http://dx.doi.org/10.17654/EC018010029
Volume 18, Number 1, 2018, Pages 29-42 **ISSN: 0973-7006**

COMPENSATION FOR DISTORTED WDM SIGNALS IN DISPERSION-MANAGED OPTICAL LINKS WITH ALTERNATING POSITIVE AND NEGATIVE RESIDUAL DISPERSION PER SPAN

Hwang-Bin Yim and Seong-Real Lee*

Department of ICT and Drone Technology
Gangwon State University
270 Yeonju-ro, Jumunjin-eup
Gangneung-shi, Gangwon-do, 25425
Korea

Division of Navigation Information System
Mokpo National Maritime University
Haeyangdaehang-ro 91, Mokpo-si
Jeollanam-do, 58628, Korea

Abstract

In high-capacity and long-haul optical communication systems, signal distortion is induced by group velocity dispersion and the nonlinearity of optical fibers. Numerous techniques have been proposed to compensate for this distortion. These include dispersion management

Received: September 26, 2017; Accepted: October 30, 2017
Keywords and phrases: optical phase conjugation, dispersion management, residual dispersion per span, net residual dispersion, wavelength-division multiplexing.
Conference held during June 26-July 1, 2017 in Courtyard Irkutsk City Center Hotel (Marriott), Irkutsk (Near Baikal Lake), Russian Federation.
*Corresponding author

(DM), the use of an optical phase conjugator (OPC), and a combination of the two. Improvements in system performance have been reported for these combined systems, but the fixed residual dispersion per span (RDPS) often used in such optical links restricts the flexibility of the link configuration. In this study, we investigated the effect of alternating the positive and negative RDPS two fiber spans apart on the compensation of distorted 24 channel × 40Gbps WDM signals in a DM link with a midway OPC. We confirmed that a pattern of alternating positive and negative RDPS was superior to uniform distribution of RDPS across whole spans with a view of compensating the distorted WDM channels.

1. Introduction

In conventional fiber optic systems, the group velocity dispersion (GVD) of standard single-mode fibers (SMFs) induces intense temporal distortion of the wavelength-division multiplexing (WDM) pulses [1]. In systems comprising cascaded erbium-doped fiber amplifiers (EDFA), nonlinear deterioration is also greater because fiber nonlinearities depend upon signal intensity amplification. Therefore, optical signal distortion due to GVD and fiber nonlinearity must be compensated for in this technology.

Promising approaches include dispersion management (DM) and optical phase conjugation. ADM transmission link is built by inserting a dispersion-compensating fiber (DCF) with anomalous GVD into the SMF to mitigate or eliminate the impact of the distortion caused by GVD. This also allows for slope-matching compensation, in which the dispersion and the dispersion slope of the transmission fiber are compensated simultaneously [3]. However, the DM technique can only compensate for optical signal distortion produced by GVD.

In contrast, optical phase conjugation can compensate for both nonlinear impairment and GVD impairment [4-7]. An optical phase conjugator (OPC) placed at the midway of the link converts the signal waves propagating in the first half transmission section (before OPC) into phase-conjugated waves. The distortion generated in the first half can then be compensated for by propagating these phase-conjugated waves through the second half transmission section (after OPC). Optical phase conjugation can be effectively used in multiple-channel transmission systems such as WDM as it is in different to the modulation format [6]. It can also be applied to coherent optical transmission systems such as coherent optical orthogonal frequency division multiplexing [8]. However, nonlinear impairment in optical transmission systems is not fully suppressed when using only an OPC because nonlinearity cancellation by OPC requires a perfectly symmetrical distribution of power and local dispersion with respect to OPC position [5]. Fiber attenuation makes this impossible to achieve in real applications.

Systems combining DM and optical phase conjugation have been proposed to address these drawbacks [9-11]. Studies have demonstrated 960Gbps (40Gbps × 24 channels) WDM transmission with satisfactory system performance by applying both DM and a midpoint OPC [12-14].

In DM optical links, the system performance depends on tuning the dispersion to match the fiber span and total link. The parameters used are the residual dispersion per span (RDPS) and the net residual dispersion (NRD). RDPS is defined as the dispersion accumulated in each span of fiber, and NRD as the total accumulated dispersion at the endpoint of the link [15]. In general, NRD is determined by controlling RDPS. It has been reported [16] that in a “pseudolinear” system, the optimal NRD is close to zero. An NRD value of approximately zero is normally achieved by setting RDPS close to zero in each fiber span. In such DM links, the combined RDPS of all spans is uniformly fixed to a single value to simplify the configuration. However, a zero NRD can be achieved in a number of alternative ways. One approach alternates the positive and negative RDPS between two fiber spans with the same absolute magnitude. To the best of our knowledge, no previous study has proposed a configuration in which the positive and negative RDPS are separated by two fiber spans, and the compensation effect on the WDM signal of this configuration has not yet been reported.

In this study, we analyzed the effect of such a system configuration on the compensation of distortion in 24 channel × 40Gbps WDM signals. The modulation format of each WDM channel was assumed to be of the returnto-zero (RZ) type, and each span was assumed to comprise an SMF that is 80km in length.

2. Modeling of Optical Links and WDM System

2.1. Optical links

The DM optical transmission link comprised 50 fiber spans, with a midway OPC. The setup is shown in Figure 1. Each span included an SMF and DCF, but the order of the fibers in the two half-sections was reversed to achieve symmetrical local dispersion with respect to the OPC. In-line dispersion compensation is usually classified into precompensation and postcompensation. In precompensation, the DCF precedes the SMF; in postcompensation, they are reversed. As shown in Figure 1, precompensation and postcompensation were configured in all fiber spans before and after the OPC to allow predispersion calibration (pre-DC) and post-dispersion calibration (post-DC) for use in controlling the NRD.

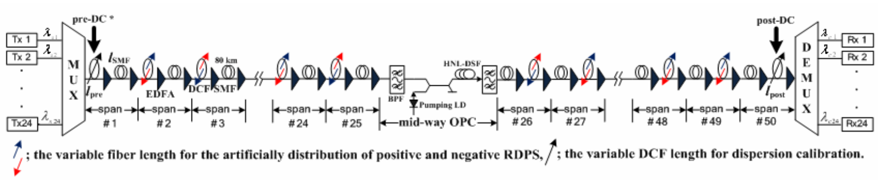


Figure 1. The configuration of the optical link for transmission of 24-channel WDM.

The goal of the research was to investigate the effect on system performance of deploying the alternating positive and negative RDPS two fiber spans apart. The optical pulses in the WDM channel were compressed in the fiber span with negative RDPS and expanded in the fiber span with positive RDPS. As shown in Figure 1, with the exception of the first and last spans, the sign of the RDPS was switched every two spans by controlling the length of each DCF. However, the averaged RDPS of each two spans was maintained at 0ps/nm by keeping the absolute magnitude the same. The sign of the RDPS within any two fiber spans was positive after negative (negative-positive) or negative after positive (positive-negative). To ensure local dispersion symmetry with respect to the midway OPC, if the positive-negative RDPS across two fiber spans was repeated in one transmission half-section, then the repeat pattern would be negative-positive in the second half-section. The research considered two repeat patterns: negative-positive in the first half-section and positive-negative in the second half-section (we refer to this pattern as “neg:pos-OPC-pos:neg”), and positive-negative in the first half-section and negative-negative in the second half-section (“pos:neg-OPC-neg:pos”).

The magnitude of the RDPS in each repeat period would be expected to affect the compensation of the distorted WDM signal. To investigate the relation between system performance and the magnitude of the RDPS, we used the deviation of RDPS between two fiber spans. This assumed that the magnitude of the RDPS would vary with the deviation of each two fiber spans. For example, the exact order of the RDPS defined by a deviation of 10ps/nm would be 10ps/nm, −10ps/nm, 20ps/nm, −20ps/nm, …, 120ps/nm −120ps/nm in a half-section with a repeating pattern of pos:neg.

When designing a DM link, the arrangement of the RDPS values in the two half-sections must compensate for the distorted WDM channels. We considered four arrangements for each RDPS, depending on the increment in the number of fiber spans: an ascending distribution of the absolute magnitudes of the RDPS both preceding and following the OPC (denoted as “AA”), an ascending distribution preceding the OPC and a descending distribution following it (“AD”), a descending distribution preceding the OPC and an ascending distribution following it (“DA”), and a descending distribution both preceding and following the OPC (“DD”).

To allow a comparative assessment of system performance, we also considered two alternative DM systems. The first was uniform system with an RDPS of 0ps/nm in each fiber span. The second was a flat distribution with an RDPS of 650ps/nm, in which the sign was alternated each two fiber spans, but the absolute magnitude of the RDPS was maintained at 650ps/nm so that there was no deviation. In total, therefore, 11 DM link configurations were investigated in this research. They are summarized in Table 1. A symbol is given for each configuration to clarify the discussion of the simulation results.

Table 1. The DM link configurations used in the simulation

Distribution	Repeat pattern	Symbol
AA	neg:pos-OPC-pos:neg	Anp-Apn
	pos:neg-OPC-neg:pos	Apn-Anp
AD	neg:pos-OPC-pos:neg	Anp-Dpn
	pos:neg-OPC-neg:pos	Apn-Dnp
DA	neg:pos-OPC-pos:neg	Dnp-Apn
	pos:neg-OPC-neg:pos	Dpn-Anp
DD	neg:pos-OPC-pos:neg	Dnp-Dpn
	pos:neg-OPC-neg:pos	Dpn-Dnp
Flat	neg:pos-OPC-pos:neg	Fnp-Fpn
	pos:neg-OPC-neg:pos	Fpn-Fnp
Uniform	none-OPC-none	Uniform

The SMF length (l_{SMF}) of each span was assumed to be 80km, but the DCF lengths (l_{DCF}) of spans two to 49 were varied to determine the RDPS as follows: $(l_{SMF} \cdot D_{SMF} - RDPS)/|D_{DCF}|$. The other parameters were set as follows: the attenuation coefficient of the SMF as α_{SMF} = 0.2dB/km, the dispersion coefficient of the SMF as D_{SMF} = 17ps/nm/km, the nonlinear coefficient of the SMF as γ_{SMF} = 1.35$\mathrm{W^{-1}km^{-1}}$ at 1550nm, the attenuation coefficient of the DCF as α_{DCF} = 0.6dB/km, the dispersion coefficient of the DCF as $D_{DCF} = -100$ps/nm/km, and the nonlinear coefficient of the DCF as γ_{DCF} = 5.06$\mathrm{W^{-1}km^{-1}}$ at 1550nm.

Because the averaged RDPS from the second to the 25th fiber span, and from the 26th to the 49th fiber spans, were both 0ps/nm, the averaged NRD of each half transmission section was also close to 0ps/nm. This was necessary to derive the optimal value for compensation by controlling the NRD of each half-section using an arbitrary span. The DCF length of the first and last fiber spans, l_{pre} and l_{post}, was used to determine the NRD of the two half-sections. However, to simplify the numerical simulations, we assumed a fixed l_{post} for setting the NRD of the second half-section to 0ps/nm, and only l_{pre} was varied to determine the NRD of the entire link. With l_{post} fixed, only the pre-DC shown in Figure 1 played a role in controlling the total NRD, as the second half-section had an NRD of zero.

2.2. WDM transmitter, receiver, and OPC

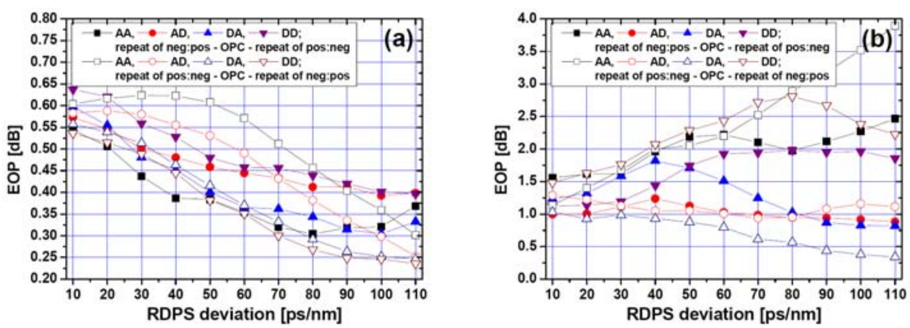
The WDM transmitters (Tx) shown in Figure 1 were assumed to be a distributed feedback laser diode (DFB-LD). The center wavelength of the DFB-LD was assumed to be 1,550-1,568.4nm, with spacing of 100GHz (0.8nm), following ITU-T recommendation G.694.1. As each wavelength was allocated one WDM channel, the total wavelength corresponded to that of a 24-channel WDM transmission. The DFB-LD was externally modulated by an independent 40-Gbps $127(=2^7-1)$ pseudorandom bit sequence (PRBS). The format of the modulation from the external optical modulator was assumed to be of the RZ type, and the output electric field of the RZ format was assumed to be a chirp-free second-order super-Gaussian pulse with a 10dB extinction ratio and a duty cycle of 0.5.

The configuration of the OPC at the middle of the optical links is shown in Figure 1. The nonlinear medium of the OPC was assumed to be highly nonlinear dispersion-shifted fiber (HNL-DSF). The OPC parameters were set as follows: the HNL-DSF loss as $\alpha_0 = 0.61$dB/km, the nonlinear coefficient of the HNL-DSF as $\gamma_0 = 20.4\text{W}^{-1}\text{km}^{-1}$, the length of the HNL-DSF as $z_0 = 0.75$km, the zero dispersion wavelength of the HNL-DSF as $\lambda_0 =$ 1,550nm, the dispersion slope as $dD_0/d\lambda = 0.032\text{ps/nm}^2\text{/km}$, the pump light power as $P_p = 18.5$dBm, and the pump light wavelength as $\lambda_p = 1{,}549.75$nm. The optical signals propagating through the first half-section were converted by the midway OPC to conjugated signals with wavelengths of 1549.5-1528.5nm. The 3dB bandwidth conversion efficiency was calculated to be close to 48nm (1526-1574nm), given by the OPC parameter settings. All the signal wavelengths and conjugated wavelengths, therefore, fell within the 3dB bandwidth of conversion efficiency.

The conjugated wavelengths were sent to the WDM receivers (Rx) for direct detection. The Rx shown in Figure 1 comprised a preamplifier of EDFA with a 5dB noise figure, an optical filter with a bandwidth of 1nm, a PIN diode, a Butterworth pulse shaping filter, and a decision circuit. The receiver was assumed to have a bandwidth of 0.65×bit-rate [1].

3. Simulation Results and Discussion

It had been confirmed that the optimal NRD of the overall configuration, at which the eye opening penalty (EOP) was smallest, was found to be 10ps/nm. This is remarkably close to the result reported in [16] dealing with "pseudolinear" system and with other results reported in [12-14]. Figure 2 shows the EOPs of the worst channel with a launch power of 0dBm (Figure 2(a)) and 5dBm (Figure 2(b)), as a function of the deviations in RDPS in each of the optical links. These were configured as shown in Table 1, with the exception of the "flat" distribution.



(a) (b)

Figure 2. The EOPs of the worst channel as a function of the deviations of RDPS at a launch power of (a) 0dBm and (b) 5dB.

It can be easily demonstrated that the deviation in the absolute magnitude of the RDPS for two fiber span intervals plays an important role in the compensation of a distorted WDM signal, as the compensation characteristics of each optical link vary according to the deviation in the repeat pattern of negative and positive RDPS. Overall, the transmission with low launch power (0dBm, Figure 2(a)) showed a greater improvement in EOP as the deviation of the RDPS increased. This was true for all optical link configurations. However, when the launch power was increased to 5dBm (Figure 2(b)), the compensation characteristics of several link configurations changed. For optical links in which the RDPS distribution was AA and DD (the Anp-Apn, Apn-Anp, Dnp-Dpn and Dpn-Dnp configurations in Table 1), the EOPs deteriorated more severely as the RDPS deviation increased. In contrast, for optical links in which the RDPS distribution was AD and DA, the EOP characteristics at the high launch power were the same as those at 0dBm.

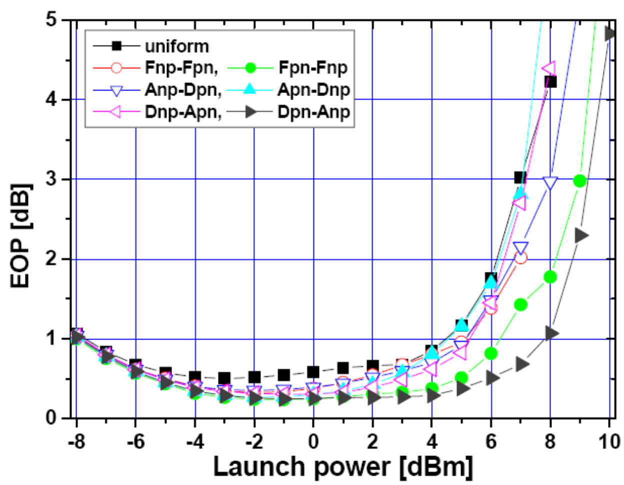


Figure 3. EOPs of the worst channel as a function of the launch power, in an optical link configured with an RDPS deviation of 100ps/nm.

The results shown in Figure 2 suggest that the large deviations achieved by locating the RDPS two fiber spans apart significantly improved compensation of the distorted WDM signal, through the repeating pattern of negative and positive RDPS. The results further suggest that using AD and DA distributions across the whole fiber span improved compensation by leveraging the large RDPS deviation.

Figure 3 shows the EOPs of the worst channel as a function of the launch power to allow comparison of the compensation achieved by the “AD” and “DA” distributions in the uniform and “flat” distributions, when the RDPS deviation was set to 100ps/nm. In fiber communication systems, 1dB EOP is used as the standard system performance criterion. This is equivalent to pulse broadening (the ratio of the received pulse root-mean-square (RMS) width to the initial pulse RMS width) of 1.25 and corresponds to a 10^{-12} bit error rate (BER) [17]. The highest maximum launch power producing a 1dB EOP was obtained in the optical link configured as Dpn-Anp. This was almost 4dB higher than the power of the uniform distribution and almost 1.6dB higher than the second-highest launch power, which was obtained by the Fpn-Fnp configuration. Figure 3 shows that the optimum repeat pattern and distribution was a descending distribution of positive-negative RDPS preceding the OPC and an ascending distribution of negative-positive RDPS after it.

Analyses made in our previous studies have confirmed that an EOP below 1dB can be obtained at arbitrary launch power for a range of NRD values, including 10ps/nm. These values constitute the effective NRD range. Figure 4 shows the effective NRD contours of the worst channels as a function of launch power for uniform distribution, flat distribution, and “DA” distribution. The results were consistent with those obtained from Figure 3. The Dpn-Anp link configuration gave the widest effective NRD range, followed by Fpn-Fnp, Dnp-Apn, Fnp-Fpn, and the uniform configuration.

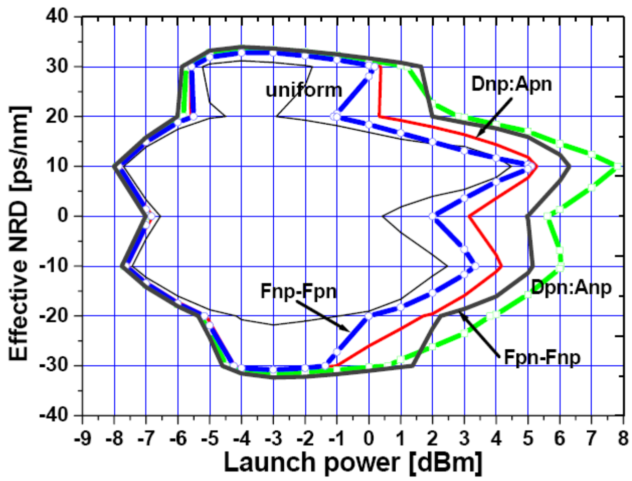


Figure 4. The effective NRD ranges as a function of launch power.

The results shown in Figure 4 can contribute to link design by allowing an NRD value to be selected that maintains the EOP at below 1dB for an arbitrary launch power, including 10ps/nm. For example, when a WDM channel was launched with a dBm power into a Dpn-Anp configured optical link, good performance was achieved, even when an NRD of 20ps/nm was selected.

Figures 5(a) and (b) show dispersion mapping of the optical links, with the absolute RDPS of the two fiber spans arranged as AD and DA, respectively, at an interval of 100ps/nm. In the proposed link configurations, the WDM pulses were compressed and then expanded (or vice versa) across two fiber spans. In each transmission half-section, the magnitude of compression and expansion more increased or decreased as the fiber spans more increased. However, as can be seen from Figure 5, the WDM pulses underwent compression or expansion across the whole half-section. The most significant result from this study is that compensation of the distorted WDM channels largely depends on the magnitude of the repetition pattern of compression and expansion, reflecting RDPS. The best compensation was achieved when using the Dpn-Anp pattern. In this configuration, the WDM pulses underwent expansion in the first half-section, but expansion and compression were greatest across the first two fiber spans and decreased as the spans increased. In contrast, the distribution in the second half-section was symmetrical.

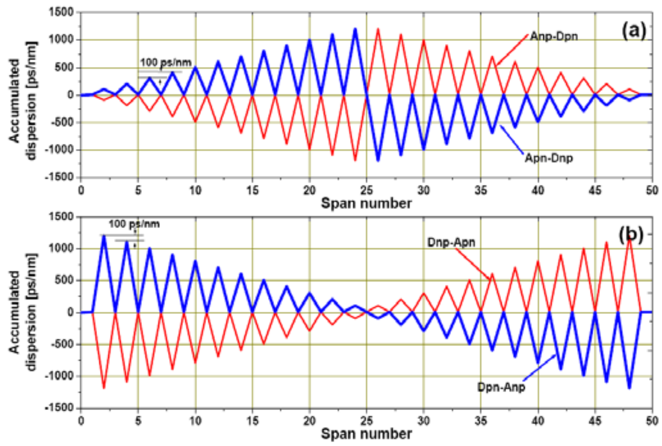


Figure 5. Dispersion map of optical links with (a) an AD distribution and (b) a DA distribution.

The superior performance in Dpn-Anp was attributed to the relatively high power of the WDM channels due to the EDFAs. For a DM link configured with alternating positive and negative RDPS two fiber spans apart, the optimal link conditions to compensate for a distorted WDM signal are as follows: (1) the WDM pulses must undergo expansion throughout the first transmission half-section to decrease the amplified optical intensity of the WDM pulses and reduce nonlinear impairment. (2) To mitigate the effect of GVD, the magnitude of residual dispersion between two fiber spans should reduce as the fiber span increases in the first transmission half-section because the WDM pulses are strongly distorted by the accumulated GVD when the magnitude of residual dispersion across two fiber spans is uniform. (3) The distribution of RDPS in the second half-section must be symmetric with the first half-section to increase the compensation produced by the OPC.

4. Conclusions

Simulations were conducted to investigate the effect of alternating positive and negative RDPS two fiber spans apart on the compensation of distorted 24 channel × 40Gbps WDM signals in a DM optical link with a midway OPC. We first confirmed the superiority of a pattern of alternating positive and negative RDPS to uniform distribution of RDPS across whole spans. The optimal pattern was shown to be Dpn-Anp. In this pattern, the sign of the RDPS within two fiber spans is negative after positive. The absolute magnitude of the RDPS of the two fiber spans decreased as the number of fiber spans increased in the first transmission half-section and was symmetrically distributed in the second half-section.

Although the optical link configuration proposed in this study is complex, it is necessary to artificially arrange the signs and magnitudes of the RDPS in DM links, rather than using uniform RDPS distribution across the whole link to improve the quality of the WDM signal. In real applications, the dispersion map of an artificially configured link must be designed to reflect the specific characteristics of the amplification of optical pulses by the EDFAs and the signal compensation from the OPC.

References

[1] G. P. Agrawal, Fiber Optic Communication Systems 3rd ed., John Wiley and Sons, New York, 2002.

[2] M. F. Uddin, A. B. M. N. Doulah, A. B. M. I. Hossain, M. Z. Alam and M. N. Islam, Reduction of four-wave mixing effect in an optical wavelength-division multiplexed system by utilizing different channel spacing and chromatic dispersion schemes, Opt. Eng. 42 (2003), 2761-2767.

[3] H. Wei and D. V. Plant, Simultaneous nonlinearity suppression and wide-band dispersion compensation using optical phase conjugation, Opt. Express. 12 (2004), 1938-1958.

[4] A. Yariv, D. Feketa and D. M. Pepper, Compensation for channel dispersion by nonlinear optical phase conjugation, Opt. Lett. 4 (1979), 52-54.

[5] S. Watanabe and M. Shirasaki, Exact compensation for both chromatic dispersion and Kerr effect in a transmission fiber using optical phase conjugation, J. Lightwave Technol. 14 (1996), 243-248.

[6] S. L. Jansen, D. van den Borne, B. Spinnler, S. Calabro, H. Suche, P. M. Krummrich, W. Sohler, G. D. Khoe and H. de Waardt, Optical phase conjugation for ultra long-haul phase-shift-keyed transmission, J. Lightwave. Technol. 24 (2006), 54-64.

[7] X. Tang and Z. Wu, Reduction of intrachannel nonlinearity using optical phase conjugation, IEEE Photon. Technol. Lett. 17 (2005), 1863-1865.

[8] M. Morshed, L. B. Du and A. J. Lowery, Mid-span spectral inversion for coherent optical OFDM systems: fundamental limits to performance, J. Lightwave Technol. 31 (2013), 58-66.

[9] X. Xiao, C. Yang, S. Gao and Y. Tian, Partial compensation of Kerr nonlinearities by optical phase conjugation in optical fiber transmission systems without power symmetry, Opt. Commun. 265 (2006), 326-330.

[10] A. Chowdhury and R. J. Essiambre, Optical phase conjugation and pseudolinear transmission, Opt. Lett. 29 (2004), 1105-1107.

[11] P. Minzioni and A. Schiffini, Unifying theory of compensation techniques for intrachannel nonlinear effects, Opt. Express. 13 (2005), 8460-8468.

[12] S. R. Lee, Pseudo-symmetrically dispersion-managed optical transmission links with the midway OPC for compensation for the distorted WDM signals, J. Inf. Commun. Converg. Eng. 13 (2015), 228-234.

[13] J. P. Chung and S. R. Lee, The compensation effects of the position of dispersion compensating fiber and the control position of net residual dispersion on the WDM signal distortions in the dispersion-managed optical links with optical phase conjugator, Inf. 19 (2016), 149-156.

[14] H. B. Yim and S. R. Lee, Compensation characteristics of optical signal distortions in dispersion-managed optical links with randomly distributed RDPS, Int. J. Inf. Commun. Technol. 8 (2016), 37-49.

[15] X. Xiao, S. Gao, Y. Tian and C. Yang, Analytical optimization of the net residual dispersion in SPM-limited dispersion-managed systems, J. Lightwave Technol. 24 (2006), 2038-2044.

[16] R. I. Killey, H. J. Thiele, V. Mikhailov and P. Bayvel, Reduction of intrachannel nonlinear distortion in 40-Gb/s-based WDM transmission over standard fiber, IEEE Photon. Technol. Lett. 12 (2000), 1624-1626.

[17] N. Kikuchi and S. Sasaki, Analytical evaluation technique of self-phase modulation effect on the performance of cascaded optical amplifier systems, J. Lightwave Technol. 13 (1995), 868-878.