Chapter 1
Dispersion Managed Optical Links with Randomly Distributed Residual Dispersion Per Span for 960 Gbps WDM Transmission

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Abstract The possibility of implementing the randomly distributed residual dispersion per span (RDPS) in optical links with optical phase conjugator (OPC) for 960 Gbps WDM transmissions is studied and discussed. It is confirmed that RDPS of each fiber spans should be randomly selected to ensure that the deviation of the accumulated dispersion between two transmission sections with respect to OPC was set to be small, for example, RDPS of each fiber spans are randomly selected to ensure that the accumulated dispersion at each transmission sections are to $-10 \sim 20$ ps/nm for optical link with net residual dispersion (NRD) of 10 ps/nm. It is also confirmed that the best NRD in optical link with the randomly distributed RDPS is ±10 ps/nm rather than 0 ps/nm. Consequently, the randomly distributed RDPS is possible by applying the best NRD into optical link specified with the optimal combination condition of random RDPS.

Keywords: Dispersion management · Optical phase conjugator · Random distribution of residual dispersion per span (RDPS) · Net residual dispersion (NRD) · Effective launch power · Group velocity dispersion (GVD) · Kerr nonlinearity · WDM transmission

1.1 Introduction

Optical signal distortions due to group velocity dispersion (GVD) and Kerr nonlinear effects, such as self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM), provide the limitation of transmission capacity and transmission distance [1]. In long haul communication systems,

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dispersion management (DM) is used for eliminating or mitigating the impact of distortion due to GVD [2, 3]. Pre- and postcompensation, residual dispersion per span (RDPS) and net residual dispersion (NRD) are key parameters for improving system performance in dispersion managed optical transmission links [4]. Pre- and postcompensation are defined as the compensated dispersion using dispersion compensating fiber (DCF) after transmitter and before receiver, respectively. In case of DM applied into every fiber spans, RDPS is defined as dispersion accumulated in each fiber spans. And, NRD is defined as total dispersion accumulated at the end of the transmission link. Generally, NRD is determined by controlling pre- or postcompensation and RDPS. The most advanced DCFs are even capable of slope-matching compensation, namely, compensating the dispersion and the dispersion slope of the transmission fiber simultaneously [5]. But, DM technique using DCF is used only in optical links without nonlinear effects on optical signals.

On the other hand, optical phase conjugation is a promising technique to compensate for the nonlinear impairments as well as GVD impairments [6–8]. The key subsystem of this technique is an optical phase conjugator (OPC) usually placed at the middle of optical link. Namely, a complete compensation of nonlinear effects and GVD effects is possible, if OPC is placed in the middle of a system exhibiting a perfectly symmetrical distribution along the link of dispersive and nonlinear effects. 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.

In optical phase conjugation technique, compensation for nonlinearity by OPC is limited by the asymmetry of the strength of the Kerr effect along the fiber with respect to the OPC position, due to the presence of fiber attenuation and fiber amplification by erbium-doped fiber amplifier (EDFA) [6]. However, there are a lot of techniques to overcome this drawback. For example, optimizing OPC position [9, 10] or combining appropriate dispersion mapping [11, 12], has been proposed recently. 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 to be optimized.

Author also had shown 960 Gbps (40 Gbps × 24 channels) WDM transmission system with good receive performance could be implemented by applying the combined DM and OPC into optical links through the previous work [13]. In that research, the basic scheme of DM is that system NRD is controlled by precompensation using DCF of first span, postcompensation using DCF of last span, and RDPS of the same value in rest fiber spans. Single-mode fiber (SMF) lengths and RDPS are assumed to be equal in every fiber spans for simplicity of optical link configuration. However, SMF length and RDPS need to be unlimited for the flexible implementation of optical network topology. As far as author knows, the analysis and assessment of WDM transmission link, where OPC and DM are applied, with the random distribution of RDPS in each fiber span, 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 is investigated, and the condition of RDPS random distribution for improving system performance is induced. 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 RZ, and transmission fiber of every fiber spans are assumed to be SMF of 80 km length.

1.2 Optical Links and WDM System for 960 Gbps Transmission

WDM system and optical transmission link configuration investigated in this research is shown in Fig. 1.1. Optical transmission link consists of 14 fiber spans, in which including SMF with 80 km length, i.e., $l_{SMF,n} = 80$ km (where, n is span number) and DCF with variable length depending on the randomly distributed RDPS. SMF of all fiber spans is characterized by the attenuation coefficient $\alpha_{SMF} = 0.2$ dB/km, dispersion coefficient $D_{SMF} = 17$ ps/nm/km, and the nonlinear coefficient $\gamma_{SMF} = 1.35\ \mathrm{W}^{-1}\mathrm{km}^{-1}$ at 1,550 nm. On the other hand, DCF of all fiber spans is characterized by the attenuation coefficient $\alpha_{DCF} = 0.6$ dB/km, dispersion coefficient of DCF $D_{\mathrm{DCF}} = -100$ ps/nm/km, and the nonlinear coefficient $\gamma_{DCF} = 5.06\ \mathrm{W}^{-1}\mathrm{km}^{-1}$ at 1,550 nm.

The accumulated dispersion at SMF of each fiber spans is 1,360 ps/nm. Thus, in order to fix RDPS of each fiber spans to 0 ps/nm, DCF length of each fiber spans, i.e., $l_{DCF,n}$ have to be set to 13.6 km. But, each DCF's length of 13 fiber spans is randomly selected to be one value between from 12.9 to 14.3 km (interval of 0.1 km), excepting one fiber span, because the assumed every RDPS of optical link are randomly distributed between from −70 to 70 ps/nm (interval of 10 ps/nm) in this research.

RDPS of one fiber span excluded from 14 fiber spans is used to determine NRD of optical link. Of course, number of this fiber span is also randomly selected and

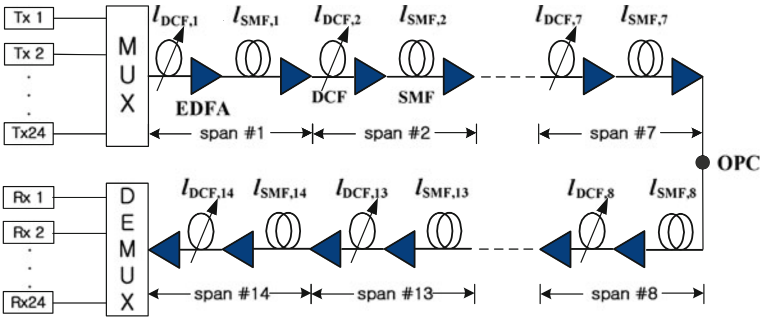


Fig. 1.1 Configuration of optical links and WDM transmission system

the exact RDPS value of this fiber span may be deviated from the range of −70 to 70 ps/nm. For example, if RDPS of 13 fiber spans were selected to be −70, −60, −50, −40, −30, −20, −10, 0, 10, 20, 30, 40, 50, and 60 ps/nm, RDPS of the excluded fiber span has to be 80 and 110 ps/nm for NRD of 10 and 40 ps/nm, respectively.

Tx illustrated in Fig. 1.1 is assumed to be distributed feedback laser diode (DFB-LD). The center wavelength of DFB-LD is assumed to be 1,550–1,568.4 nm by spacing 100 GHz (0.8 nm) based on ITU-T recommendation G.694.1. DFB-LD is externally modulated by an independent 40 Gbps 128(=2^7) pseudo random bit sequence (PRBS). The modulation format from external optical modulator is assumed to be RZ. And output electric field of RZ format is assumed to be second-order super-Gaussian pulse with 10 dB extinction ratio (ER), duty cycle of 0.5 and chirp-free.

The nonlinear medium of OPC around mid-way of total transmission length is highly nonlinearity-dispersion shifted fiber (HNL-DSF). The parameters of OPC are as follows; loss of HNL-DSF $\alpha_0 = 0.61$ dB/km, nonlinear coefficient of HNL-DSF $\gamma_0 = 20.4\ \mathrm{W}^{-1}\ \mathrm{km}^{-1}$, length of HNL-DSF $z_0 = 0.75$ km, zero dispersion wavelength of HNL-DSF $\lambda_0 = 1{,}550$ nm, dispersion slope $dD_0/d\lambda = 0.032$ ps/nm^2/km, pump light power $P_p = 18.5$ dBm, and pump light wavelength $\lambda_\mathrm{p} = 1549.75$ nm.

And, Rx consists of the pre-amplifier of 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 0.65 × bit-rate [14].

1.3 Simulation Results and Discussion

Figure 1.2 illustrates EOPs of worst channel among 24 WDM channels with 1 dBm launch power as a function of NRD. There is large number of the randomly distributed RDPS, but 60 cases of random distribution are considered for satisfying the accurately and simply numerical analysis in this research. EOPs plotted in Fig. 1.1 are the best 10 values among 60 times random distribution of RDPS. It is confirmed that the optimal NRDs, which are resulting the relative low EOP for the considered random distribution, are obtained to ±10 ps/nm.

Figure 1.3 shows EOPs of worst channel as a function of launch power at NRD of 10 ps/nm. The random RDPS patterns can be sorted into three classes, depending on the system performance. First class is defined as “good performance” corresponding EOP below 2 dB. Second class is defined as “not bad performance”, corresponding EOP upper 2 dB. And, third class is defined as “worst performance”, corresponding the ineffectively compensated EOP, which cannot be plotted in Fig. 1.3 due to the imaginary EOP values, because the maximum optical peak of ‘1’ is lower than the minimum optical peak of ‘0’.

For the high performance WDM transmission, the optimal combination condition of the randomly distributed RDPS should be induced by analyzing the patterns of the random RDPS used in the results of Fig. 1.3. Figure 1.4 shows the accumulated

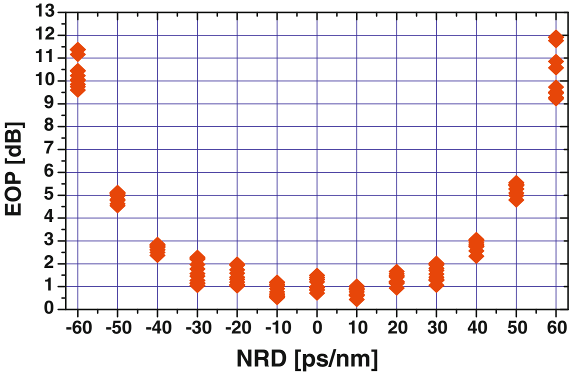


Fig. 1.2 EOP of worst channel with launch power of 1 dBm depends on NRD

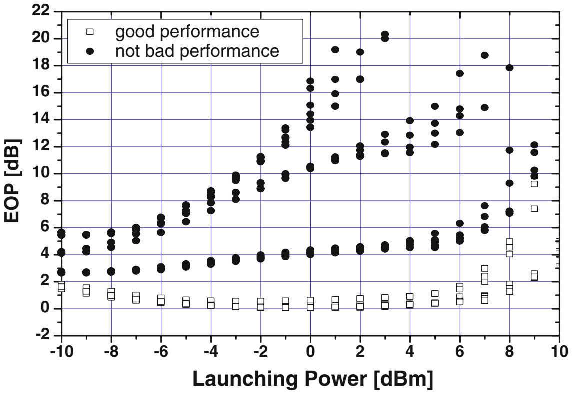


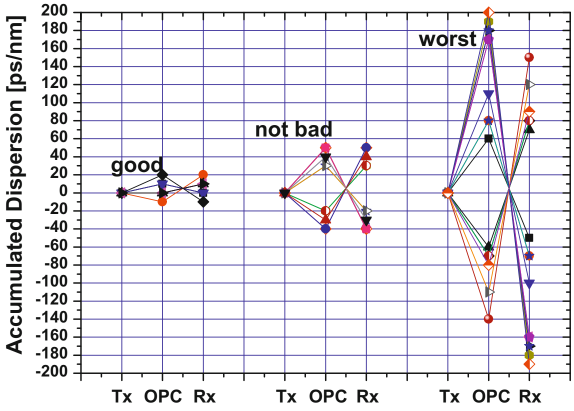
Fig. 1.3 EOP of worst channel as a function of launch power at NRD = 10 ps/nm

dispersions at transmitter(Tx), OPC and receiver(Rx) calculating from the random RDPS patterns of "good performance", "not bad performance" and "worst performance" in optical link with NRD = 10 ps/nm, respectively. In Fig. 1.4, the accumulated dispersion at Tx and Rx correspond to those at the input and output of optical link, respectively. The exact RDPS of each fiber spans dose not effect on system performance, but the effect of accumulated dispersion at each transmission sections (Tx-OPC and OPC-Rx sections) on the compensation for the distorted WDM signals is significant in optical link with the randomly distributed RDPS.

It is confirmed that the deviation of the accumulated dispersion between two transmission sections is set to be small for "good performance", i.e., RDPS of each fiber spans are randomly selected to ensure that the accumulated dispersion at each transmission sections are to $-10 \sim 20$ ps/nm for optical link with NRD = 10 ps/nm. For example, if the accumulated dispersion at the front of OPC was 10 ps/nm by the randomly selected RDPS in each fiber spans of former transmission section, RDPS of each fiber spans in latter transmission section should be randomly selected to ensure that the accumulated dispersion at the front of Rx is to be 0 ps/nm.

Figure 1.5 illustrates EOPs of worst channel in optical link with NRD = 10 ps/nm determined by 60 cases of the randomly distributed RDPS satisfying the optimal

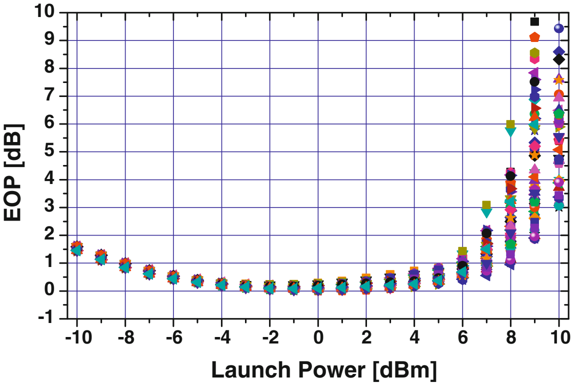
Fig. 1.4 Accumulated dispersion at transmitter, OPC and receiver



combination condition of "good performance". It is shown that EOP variation depending on the randomly distributed RDPS pattern is more widened as launch power of WDM channel is more increased.

Figure 1.6 shows the maximum EOP of worst channel in optical link with the randomly distributed RDPS satisfying the optimal combination condition, which corresponds to EOP obtained from the worst pattern among 60 cases of the random RDPS patterns, as a function of launch power for NRD = −10, 0, and 10 ps/nm. If the criterion value of EOP for the excellent reception performance is selected to be 1 dB EOP, then launch power resulting below 1 dB EOP is defined as the allowable launch power. In optical link with NRD = ±10 ps/nm, the allowable launch power are obtained to be $-8 \sim 5$ dBm, on the other hand $-7 \sim 3.5$ dBm in optical link with NRD = 0 ps/nm. Namely, the effective launch power in optical link with NRD = ±10 ps/nm determined by the randomly distributed RDPS is more improved than that in optical link with NRD = 0 ps/nm. Therefore, NRD of ±10 ps/nm can be regarded as the best NRD in optical link with the randomly distributed RDPS.

Fig. 1.5 EOP of worst channel as a function of launch power under the optimal combination condition of the randomly distributed RDPS



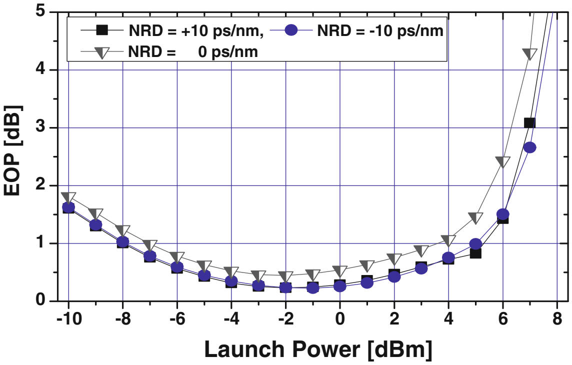


Fig. 1.6 Maximum EOP of worst channel as a function of launch power in optical link with NRD = −10, 0 and 10 ps/nm determined by the randomly distributed RDPS

1.4 Conclusion

This research discussed the possibility of implementing optical transmission link with the randomly distributed RDPS of fiber spans in optical links for 960 Gbps WDM transmissions. It was first confirmed that system performance was intensely dependent of the random pattern of RDPS. Namely, it was confirmed that RDPS of each fiber spans should be randomly selected to ensure that the deviation of the accumulated dispersion between two transmission sections with respect to OPC was set to be smaller than 20 ps/nm for the good compensating for the distorted WDM signals.

It was also confirmed that the best NRD in optical link with the randomly distributed RDPS was ±10 ps/nm rather than 0 ps/nm, because the effective launch power at NRD = ±10 ps/nm was improved by 2.5 dB than at NRD = 0 ps/nm in optical link specified by the optimal combination condition of random RDPS.

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