40 Gbps RZ Transmission Using Dispersion Compensation of Single-Span in Optical Transmission Links with Multi-Span of Single Mode Fiber

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Abstract— **In dispersion management (DM) and optical phase conjugation applied into optical transmission links with multi fiber spans for minimizing the impact of nonlinearity and group velocity (GVD), implementation possibility of DM using only one fiber span for pre- or postcompensation was assessed as a function of duty cycle of RZ pulse and residual dispersion per span (RDPS). It is confirmed that DM with optimal net residual dispersion (NRD) controlled by only one fiber span could be sufficiently applied into optical transmission links, though optimal NRD is more increased than that in transmission links with the general DM scheme of pre- and postcompensation. Thus, it is expected that optical transmission system is simply designed and implemented by applying the proposed DM scheme into real optical transmission links. Also, it is confirmed that the advantageous duty cycle of RZ is 0.5 and RDPS is setting to be small value for the effective transmitting wide signal wavelength range in optical links with optimal NRD controlled by only one fiber span.**

Index Terms— **Dispersion management, Optical phase conjugator, Single-span dispersion compensation, Residual dispersion per span (RDPS), Net residual dispersion (NRD), Optimal NRD window**

I. INTRODUCTION

A technological challenge as the signal transmission at 40 Gb/s or above is severely limited in standard single-mode fiber (SSMF) due to nonlinear distortion and group velocity dispersion (GVD) [1]–[4]. To minimize the impact of such distortion, a dispersion map involving optical pre- and postcompensation in dispersion management (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, residual dispersion per span (RDPS) is defined as dispersion accumulated in each fiber span. And, net residual dispersion (NRD) is defined as total dispersion accumulated at the end of the transmission link. These quantities are key parameters for designing a transmission system with high performance. Generally, NRD is decided by controlling pre(post)compensation and RDPS.

In order to suppress the nonlinearities mostly by DM, the amounts of GVD compensations of the system should be optimized. This fact makes the design of optical transmission systems to more complicate, especially wavelength division multiplexing (WDM) transmission. In order to maximize the transmission distance, return-to-zero (RZ) pulses must be used instead of non-RZ (NRZ) pulses as the system-performance scales with the relation $P_p \times T_{FWHM}^2$, where P_p is the pulse peak power, and T_{FWHM} is the pulse full width at half maximum [5]. In RZ transmission systems NRD is typically very low (in the order of few ps/nm) to reduce the impact of the GVD[4].

Optical phase conjugation is another effective technique to 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. But, the effective suppression of nonlinear impairment is not practically obtained in WDM transmission systems using only OPC, 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 [6].

Author had shown the implementation possibility of WDM transmission system with good receive performance by applying DM and OPC into optical links in the studies presented in previous works [7]-[9]. In these researches, 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. However, this link configuration is more complicate for implementing optical transmission system, because both of pre- and postcompensation are simultaneously using for deciding NRD and DCF lengths of first and last span must be different with that of the rest spans for optimizing dispersion map.

If only one fiber span is used for pre- or postcompensation and the rest fiber spans are designed to have the same RDPS, then total optical transmission link becomes simpler configuration. Therefore, in this research, the receive performance of optical signal will be assessed using eye opening penalty (EOP) in optical links with multi-fiber spans, in which only one fiber span must be controlled for DM. Also, optimal NRD value will be induced as a function of duty cycle of RZ pulses and RDPS.

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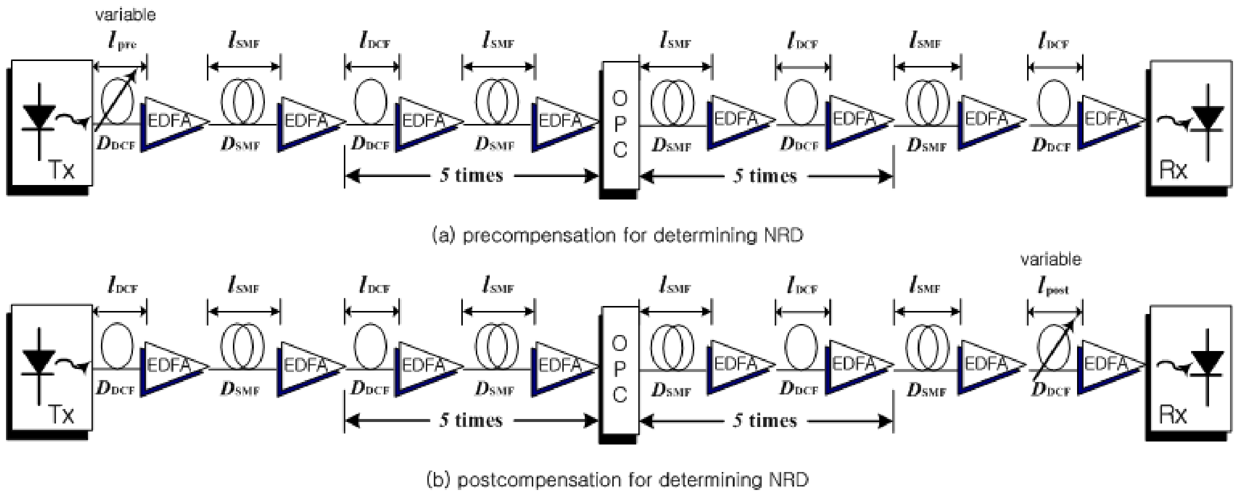


Fig. 1 Configuration of optical transmission links.

II. CONFIGURATIONS OF OPTICAL TRANSMISSION LINK

Optical transmission link configuration investigated in this research is shown in Fig. 1. Total transmission links consists of 12 spans, in which including SMF and DCF. SMF length of all spans is designed to l_{SMF} = 80 km, and SMF was characterized by the attenuation coefficient α_{SMF} = 0.2 dB/km, dispersion coefficient D_{SMF} = 17 ps/nm/km, and the nonlinear coefficient γ_{SMF} = 1.41 $W^{-1}km^{-1}$ at 1,550 nm. Thus, accumulated dispersion in each SMF is 1,360 ps/nm (= 17 ps/nm/km × 80 km).

In order to make symmetric distribution of dispersion with respect to OPC, DCFs are placed before each SMF in transmission section from transmitter (Tx) to OPC, on the other hand DCFs are placed after each SMF in transmission section from OPC to receiver (Rx), as illustrated in Fig. 1. Dispersion coefficient of DCF D_{DCF} is assumed to be -100 ps/nm/km in all spans. DCF was characterized by the attenuation coefficient α_{DCF} = 0.4 dB/km, and the nonlinear coefficient γ_{DCF} = 4.83 $W^{-1}km^{-1}$ at 1,550 nm.

In case of deciding NRD by only precompensation shown in Fig. 1(a), length of first DCF, i.e., l_{pre} is only changed, but lengths of the rest DCF including last DCF, i.e., l_{DCF} are fixed for RDPS of each spans. Other case of deciding NRD by only postcompensation shown in Fig. 1(b), length of last DCF, i.e., l_{post} is only changed. RDPS is assumed to be 50 ps/nm, 200 ps/nm and 400 ps/nm. Thus, for precompensation or postcompensation, l_{DCF} are setted to be 13.1 km for RDPS = 50 ps/nm, 11.6 km for RDPS = 200 ps/nm and 9.6 km for RDPS = 400 ps/nm, except l_{pre} or l_{pre}, respectively.

Tx illustrated in Fig. 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. Thus, if each wavelength is allocated for one WDM channel, the considered total wavelength corresponds to 24-channel WDM transmission.

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) and chirp-free. In this research, the duty cycle of RZ format is assumed to be 0.2, 0.3, 0.4, and 0.5, because optimal NRD depending on duty cycle of RZ format will be investigated in optical transmission links controlled only pre- or postcompensation.

The nonlinear medium of OPC around mid-way of total transmission length is highly nonlinearity-dispersion shifted fiber (HNL-DSF). The parameters of OPC using HNL-DSF are as follows; loss of HNL-DSF α_0=0.61 dB/km, nonlinear coefficient of HNL-DSF γ_0=20.4 $W^{-1}km^{-1}$, length of HNL-DSF z_0=0.75 km, zero dispersion wavelength of HNL-DSF λ_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 λ_p = 1549.75 nm. The 3-dB bandwidth of conversion efficiency η of the OPC is obtained to be 48 nm (1526～1574 nm). The signal wavelengths are converted to 1,549.5～1,528.5 nm (these are called to the conjugated wavelength) through OPC. Thus, allocated 24 signal wavelengths and these conjugated wavelengths are belongs within 3-dB bandwidth of η.

The conjugated wavelength is sent into Rx of direct detection. 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.

III. SIMULATION RESULTS AND DISCUSSION

Fig. 2 illustrates EOPs of RZ with duty cycle of 0.4 and with 0.8 nm wavelength spacing as a function of NRD controlled by precompensation in optical transmission links of RDPS = 50 ps/nm. It is shown that EOPs depend on signal wavelength, but the best NRD resulting minimum EOP for every signal wavelengths exist. In case of duty cycle of 0.4, RDPS = 50 ps/nm and NRD controlled by precompensation, that is, in Fig. 2, the best NRD appear around 600 ps/nm.

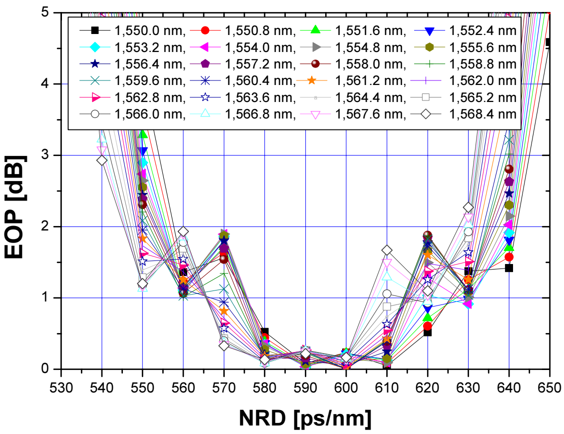


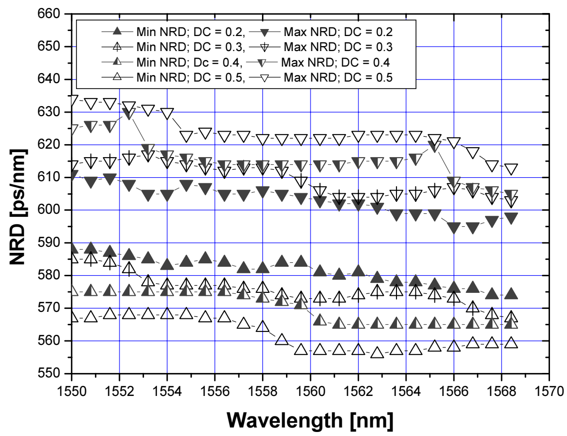
Fig. 2. EOP of RZ format with duty cycle of 0.4 as a function of NRD controlled by precompensation in optical transmission links of RDPS = 50 ps/nm.

Also, if optimal NRD is defined as NRD value resulting 1 dB EOP, in this case, optimal NRD is 576 ~ 605 ps/nm for total wavelength. The result of Fig. 2 means that DM with optimal NRD controlled by only one fiber span could be applied into optical transmission links, but optimal NRD range depends on duty cycle of RZ, RDPS and signal wavelengths.

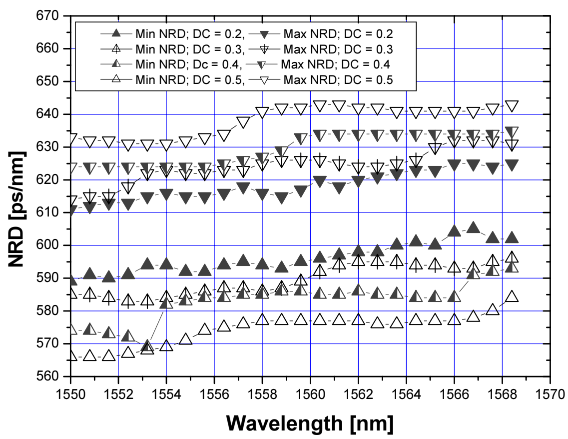
Fig. 3 shows optimal NRD, which consists of maximum NRD and minimum NRD resulting 1 dB EOP, as a function of signal wavelengths in case of various RDPS and pre- or postcompensation. It is shown that, in case of NRD controlled by precompensation, optimal NRD is more decreased as signal wavelengths are more increased, and the reverse phenomenon appears in case of NRD controlled by postcompensation.

If optimal NRD window is defined as the difference between maximum NRD and minimum NRD resulting 1 dB EOP, optimal NRD window is more decreased as duty cycle of RZ are more decreased in all cases. It is confirmed that, from a viewpoint of transmitting total wavelengths, optimal NRD window depends on RDPS as well as duty cycle of RZ.

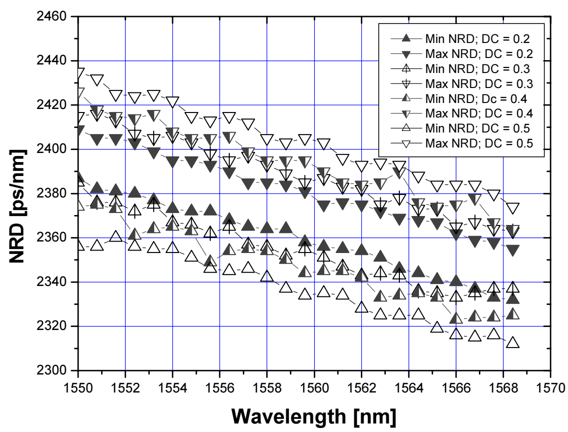
For example, in transmission of RZ with duty cycle of 0.3 through optical links designed with RDPS = 50 ps/nm and NRD controlled by precompensation plotted in Fig. 4(a), optimal NRD window is obtained to be 18 ps/nm from 585 ps/nm, which is minimum NRD at 1,550.0 nm, to 603 ps/nm, which is maximum NRD at 1568.4 nm. And, in equal transmission links except for NRD controlled by postcompensation, optimal NRD window is obtained to be 18 ps/nm, i.e., from 596 ps/nm at 1568.4 nm to 614 ps/nm at 1550.0 nm. But, if RDPS is increased to be 400 ps/nm although duty cycle of RZ is 0.5 in plotted in Fig. 4(b), optimal NRD window do not exist for total signal wavelengths, on the other hands, several wavelengths are simultaneously transmitted at arbitrarily NRD. For example in case of NRD controlled by precompensation, if NRD



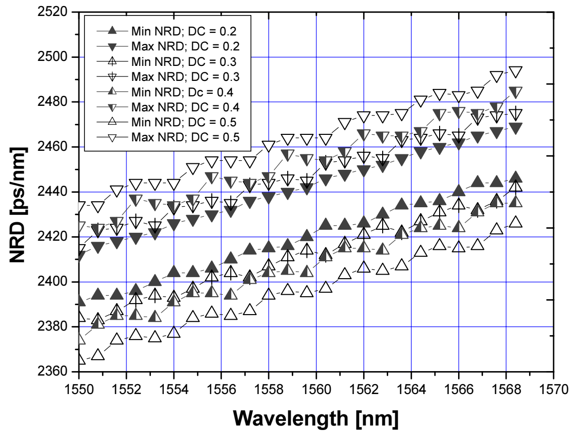
(a) RDPS = 50 ps/nm; precompensation



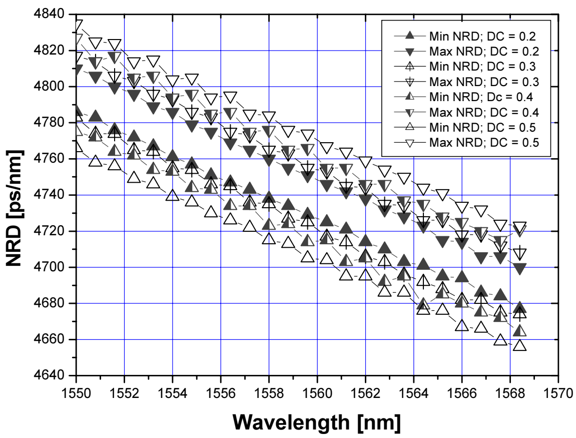
(b) RDPS = 50 ps/nm; postcompensation



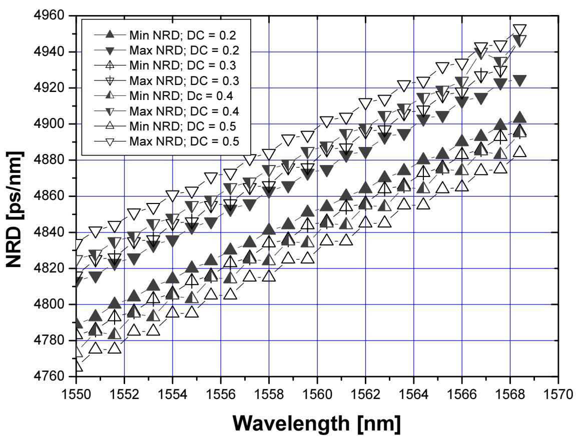
(c) RDPS = 200 ps/nm; precompensation



(d) RDPS = 200 ps/nm; postcompensation



(e) RDPS = 400 ps/nm; precompensation

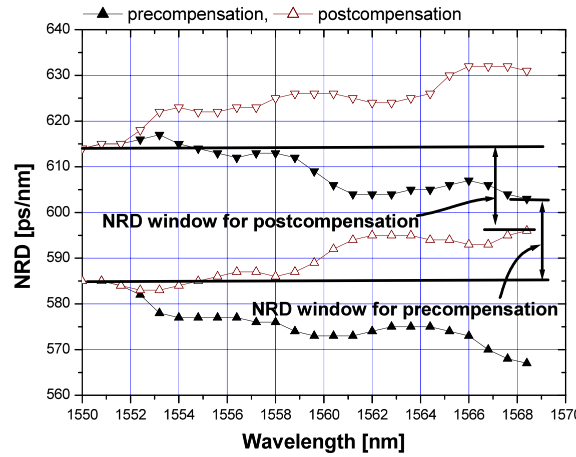


(f) RDPS = 400 ps/nm; postcompensation

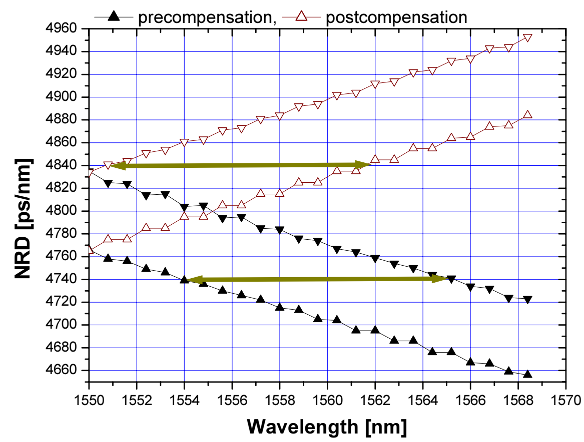
Fig. 3. NRD resulting 1 dB EOP as a function of wavelength in optical transmission links of various RDPS.

is selected to be 4,740 ps/nm then signal wavelengths of 1,554.0 ~ 1,556.6 nm are transmitted with system performance below 1 dB EOP.

For the effective designing optical transmission links with DM controlled by only one fiber span, it is required to induce optimal NRD window for various duty cycle of RZ and RDPS through the method used in Fig. 4. Table 1 summarizes this optimal NRD window.



(a) RDPS = 50 ps/nm : DC = 0.3



(b) RDPS = 400 ps/nm : DC = 0.5

Fig. 4. Optimal NRD as a function of wavelengths in optical transmission links of RDPS = 50 ps/nm for duty cycle of 0.3 and 400 ps/nm for duty cycle of 0.5.

From the results in Table 1, it is confirmed that optimal NRD window is more broadened as RDPS is more decreased and duty cycle of RZ is larger. That is, best transmission condition in optical links with NRD controlled by only one fiber span is RDPS of 50 ps/nm and duty cycle of RZ of 0.5. In this case, optimal windows are obtained to be 46 ps/nm and 49 ps/nm for NRD controlled by pre- and postcompensation, respectively.

Also, in transmission links with RDPS designed to be 200 ps/nm and 400 ps/nm, in which optimal NRD window do not exist, if duty cycle of RZ is selected to be large value, number of signal wavelengths simultaneously transmitted at arbitrarily NRD are more increased. In this case, optical link with NRD controlled by only precompensation is more advantageous than NRD controlled by only postcompensation, because number of transmitted signal wavelengths are increased under the same condition of RDPS and duty cycle of RZ.

TABLE. 1
OPTIMAL NRD WINDOWS FOR RDPS AND DUTY CYCLE OF RZ

RDPS [ps/nm]	DC	precompensation						postcompensation					
		best NRD [ps/nm]			wavelength [nm]			best NRD [ps/nm]			wavelength [nm]		
		from	to	width	from	to	# of ch.	from	to	width	from	to	# of ch.
50	0.2	588	595	7	1550.0	1568.4	24	602	611	9	1550.0	1568.4	24
	0.3	585	603	18	1550.0	1568.4	24	596	614	18	1550.0	1568.4	24
	0.4	575	605	30	1550.0	1568.4	24	593	624	31	1550.0	1568.4	24
	0.5	567	613	46	1550.0	1568.4	24	584	633	49	1550.0	1568.4	24
200	0.2	2380	-	-	1552.4	1559.6	10	2420	-	-	1552.4	1559.6	10
								2430	-	-	1555.6	1562.8	10
								2440	-	-	1558.8	1566.0	10
	0.3	2360	-	-	1557.2	1568.4	15	2420	-	-	1557.2	1568.4	15
		2370	-	-	1554.0	1565.2	15	2430	-	-	1554.0	1565.2	15
		2380	-	-	1550.8	1562.0	15						
	0.4	2370	-	-	1552.4	1566.8	19	2430	-	-	1552.4	1567.6	20
	0.5	2360	2374	14	1550.0	1568.4	24	2426	2434	8	1550.0	1568.4	24
400	0.2	4700	-	-	1564.4	1568.4	6	4820	-	-	1551.6	1554.8	5
		4750	-	-	1555.6	1559.6	6	4830	-	-	1553.2	1556.4	5
		4760	-	-	1554.0	1558.0	6	4840	-	-	1554.8	1558.0	5
								4850	-	-	1556.4	1559.6	5
								4860	-	-	1558.0	1561.2	5
								4870	-	-	1559.6	1562.8	5
								4880	-	-	1561.2	1564.4	5
								4890	-	-	1562.8	1566.0	5
								4900	-	-	1564.4	1567.6	5
	0.3	4710	-	-	1562.0	1567.6	8	4820	-	-	1550.8	1555.6	7
								4830	-	-	1552.4	1557.2	7
								4840	-	-	1554.0	1558.8	7
								4850	-	-	1555.6	1560.4	7
								4860	-	-	1557.2	1562.0	7
								4870	-	-	1558.8	1563.6	7
								4880	-	-	1560.4	1565.2	7
								4890	-	-	1562.0	1566.8	7
								4900	-	-	1563.6	1568.4	7
	0.4	4720	-	-	1559.6	1566.8	10	4830	-	-	1550.8	1558.0	10
								4840	-	-	1552.4	1559.6	10
								4860	-	-	1555.6	1562.8	10
	0.5	4730	-	-	1555.6	1566.8	15	4840	-	-	1550.8	1561.2	14
		4740	-	-	1554.0	1565.2	15	4850	-	-	1552.4	1562.8	14
		4750	-	-	1552.4	1563.6	15	4860	-	-	1554.0	1564.4	14
		4760	-	-	1550.8	1562.0	15	4870	-	-	1555.6	1566.0	14
								4880	-	-	1557.2	1567.6	14

IV. CONCLUSION

This paper discussed applying DM with NRD controlled by only one fiber span into optical transmission links. It was confirmed that the proposed DM scheme could be sufficiently applied into optical transmission links, and in optical transmission system with this DM scheme, optimal NRD window is more broadened as RDPS is more decreased and duty cycle of RZ is larger, that is, best transmission condition in optical links with NRD controlled by only one fiber span is RDPS of 50 ps/nm and duty cycle of RZ of 0.5.

Furthermore, even though RDPS is designed to be large, numbers of signal wavelengths simultaneously transmitted at arbitrarily NRD are more increased by selecting RZ with large duty cycle.

Thus, it is expects that optical transmission system is simple designed and implemented by applying the proposed DM scheme into real optical transmission links.

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