Journal of the Optical Society of Korea, Vol. 10, No. 3, September 2006, pp. 112-117

Comparison with Dispersion Compensation Scheme Using 10 Gbit/s × 40 Channels Wavelength Division Multiplexing Transmission over 323 km of Field Installed Non-Zero Dispersion Shift Fiber

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(Received August 25, 2006 : revised September 18, 2006)

We experimentally investigated the transmission characteristics of 400 Gbit/s (10 Gbit/s X 40 channels) WDM signals with 100 GHz channel spacing over 323 km of installed NZ_DSF. The installed fiber has optical properties of 0.28 dB/km attenuation, 4.3 ps/nm/km dispersion, 0.083 $ps/nm^2/km$ dispersion slope and less than 0.05 $ps/km^{1/2}$ PMD coefficient. In this experiment, two cases of dispersion compensation schemes, the lumped type and the distributed type, were compared. The results implied that the distributed type dispersion compensation in which dispersion compensation devices are inserted at the end of the each span showed better transmission performance than the lumped one in which dispersion compensation devices are located at the transmitter and receiver sites. From the analysis of the experimental results, we verified that different transmission performance comes from the power penalty induced by XPM in the distributed scheme is lower than the lumped scheme case.

OCIS codes : 060.2330

I. INTRODUCTION

Along with the transmission capacity increasing up to terabit/s, many fiber manufacturers concentrate on the development of new types of fibers with novel optical characteristics such as NZ_DSF (Non-Zero Dispersion Shifted Fiber) to improve the optical transmission performance of the medium [1.2]. Among the many physical factors limiting the transmission performance, chromatic dispersion and nonlinearities are considered significant factors in recent high speed optical transmission systems. In order to reduce the cost for the dispersion compensation, we have to use the fiber with lower dispersion value [3]. Since, deploying fiber with low dispersion would invoke system penalty due to nonlinear interaction caused by the modulation of refractive index such as SPM (Self Phase Modulation), XPM (Cross Phase Modulation), and FWM (Four Wave Mixing), there exists the trade-off between dispersion and optical nonlinearity. [4,5,6]. As a result, the selection of optimized fiber type and dispersion compensation scheme arises as an important issue [7].

In this paper, we investigated experimentally the transmission characteristics of 400 Gbit/s (10 Gbit/s × 40 channels) WDM signals with 100 GHz channel spacing over 323 km of installed NZ_DSF.

II. TRANSMISSION EXPERIMENT

The experimental configuration used to evaluate the dispersion compensation scheme is shown in Fig. 1. The optical link was composed of mainly four sections, the optical transmitter section, installed 323 km NZ_DSF fiber, optical amplifiers, and the optical receiver section. Each of the 40 DFB lasers used in this experiment has 100 GHz channel spacing, modulated with a 2^{31}-1 10 Gbit/s pseudo random bit stream (PRBS) by a LiNbO3 external modulator. The wavelength of the channels extends from 1=1530.33 nm to 40=1561.42 nm and channels are multiplexed by a temperature stabilized AWG (Arrayed Waveguide Grating) with about 4 dB insertion loss per port. The optical power difference between the channels was adjusted automatically to fall within 1 dB by computer controlling the driving current, based on the optical characteristics of each channel sent from the OSA (Optical Spectrum

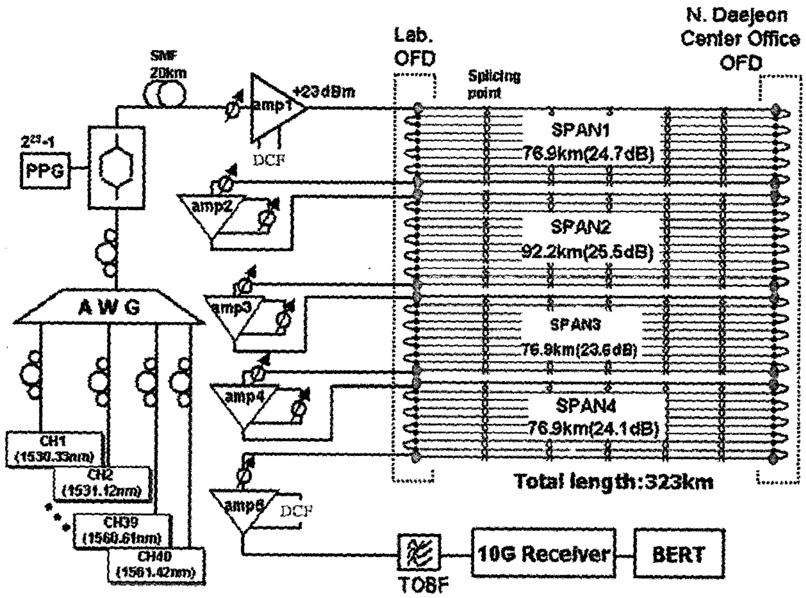

FIG. 1. Experimental setup of 400 Gb/s (10 Gb/s × 40 channels) over 323 km of NZ-DSF.

Analyzer) through the GPIB. The 20 km field installed SMF was used to ensure obtaining the completely de-correlated data patterns between each adjacent channel.

144 cores of NZ_DSF of a typical effective area 72 μm in loose tube type cable installed between OFD at KT Laboratory and OFD at the North Daejeon Telephone office were used as a optical link by looping the end of each fiber, so that it forms a span. 4 spans of optical link were constructed as mentioned above. The average distance between these OFDs was 7.6 km and total distance of transmission link was 323 km. The characteristics of the optical link were as follows: average optical loss of 0.28 dB/km including splice loss, chromatic dispersion of 4.3 ps/nm/km, dispersion slope of 0.083 ps/nm^2/km at 1550 nm, reflection loss of less than 45 dB at OFD and splicing point, spectral attenuation of less than 0.014 dB/km within the used bandwidth, and PMD (Polarization Mode Dispersion) coefficient of less than 0.05 ps/km$^{1/2}$. We used commercialized instruments to measure optical loss, chromatic dispersion, dispersion slope, and PMD. The span loss including optical fiber link loss and splicing loss, was 24.7 dB, 25.5 dB, 23.6 dB, and 24.1 dB for each span. The distance of the span 2 was 92.2 km and rest of the other span have the same distance of 76.9 km.

A dual stage optical amplifier with 26 dB gain and 6.9 dB noise figure, consisted of pre, post amplifier, and dispersion compensation modules (DCM) placed between pre and post amplifier, were used in this experiment, since the excess gain of the first stage can be used to overcome the relatively high DCM losses of optical amplifier. The output powers per channel of the pre- and post-amplifier were 1.5 dBm and 7 dBm, respectively. Three types of DCM distinguished by dispersion compensation length were used. The dispersion and dispersion slope at 1550 nm of the DCM60 used were 90.8 ps/nm/km and 0.166 ps/nm^2/km, respectively. With the dual stage amplifier without DCM at middle stage, a variable optical attenuator (VOA) was used to adjust the total input power level into the post amplifier to 4.5 dBm, corresponding to an average channel power of approximately 7.5 dBm.

The optical receiver section consisted of a tunable optical bandpass filter (TOBF), optical amplifier, 10 Gbit/s optical receiver, and error detector. Here, TOBF was used for channel selection, and had 3 dB bandwidth of 1 nm. Optical amplifier was used to compensate insertion loss of the TOBF. The receiver sensitivity of the 10 Gbit/s optical receiver was 17.5 dBm at 10^{-12} BER.

III. RESULTS AND DISCUSSION

Fig. 2 shows the accumulated dispersions of channel 1 (1530.33 nm), channel 25 (1545.32 nm), and channel 40 (1561.42 nm) after transmission over 323 km NZ_DSF for the two dispersion compensation schemes. Two schemes of dispersion compensation, lumped type (a) distributed type (b) were tested. The dispersion and dispersion slope of the DCM60 at the Tx terminal are -1038.9 ps/nm and -1.89 ps/nm^2, respectively. Furthermore, Those of the DCM40 at Rx terminal are -684.2 ps/nm and -0.61 ps/nm^2, respectively. In case of distributed schemes, DCM20 that has -346.8 ps/nm dispersion and -0.452 ps/nm^2 dispersion slope was

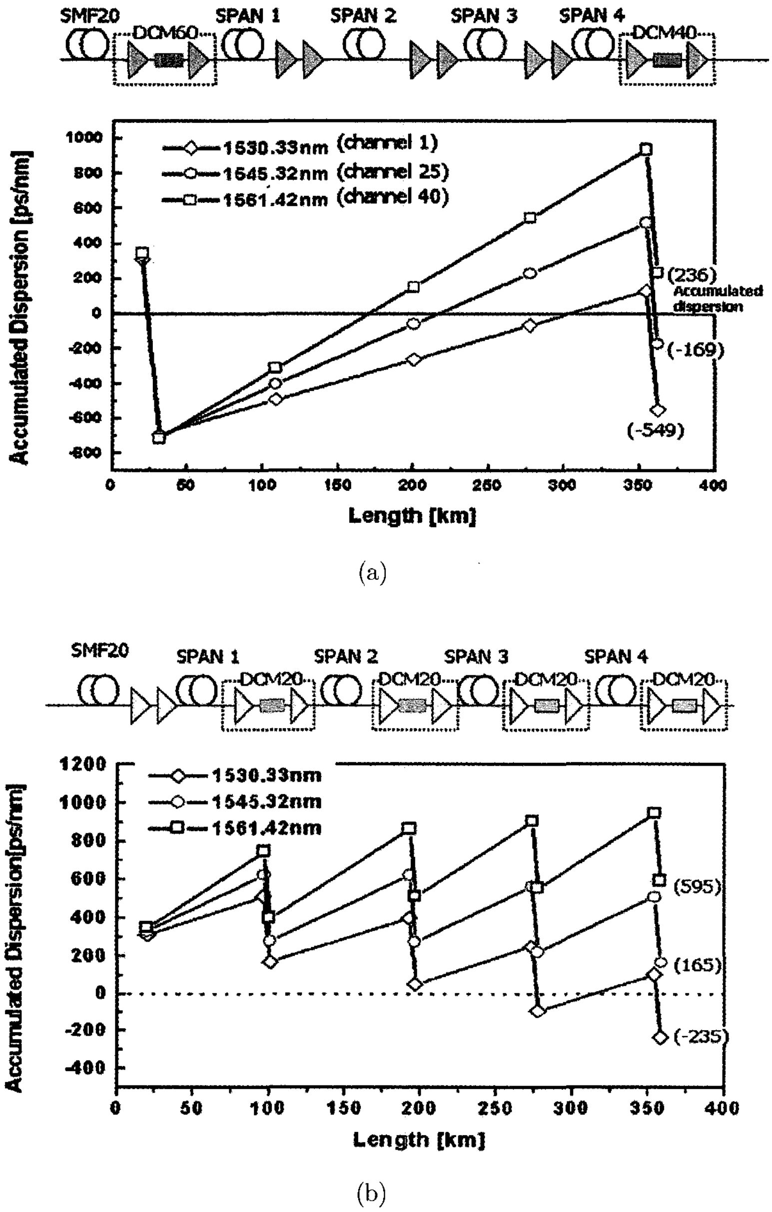

FIG. 2. Accumulated dispersion of the channel 1, 25, 40 after the transmission over 323 km of NZ_DSF. (a) A lumped type dispersion compensation. (b) A distributed type dispersion compensation.

placed in each span.

Fig. 2 (a) shows the amount of residual dispersion versus channel wavelength, which caused by dispersion slope, extends from 236 ps/nm to -549 ps/nm after the transmission over the 323 km NZ_DSF. In the case of the distributed scheme, the residual dispersion varies from 595 ps/nm to 235 ps/nm. In both case, dispersion map is built to satisfy the required dispersion criteria for 10 Gbit/s transmission.

The optical spectrum at the input of amplifier 1 is shown in Fig. 3 (a). The maximum output power difference between the channels caused by polarization dependence of the modulator is about 1.1 dB. On the other hand, after the transmission over 323 km NZ_DSF, estimated maximum power difference from the measured optical spectrum between channels increased to 13.1 dB in Fig. 3 (b). Also, we can observe power/ch is proportional to the wavelength. Some candidates which might be causing this phenomenonare as follows: spectral attenuation of the NZ_DSF, gain tilt of the amplifier itself, spectral attenuation of the DCM, and Raman gain tilt, which transfer a power from to short to the longer wavelength. Spectral attenuation for each span is 1.46 dB (0.019 dB/km × 76.9 km), 0.92 dB, 1.08 dB, and 0.92 dB, amount to total 4.4 dB, and tends to decrease toward longer wavelength as shown

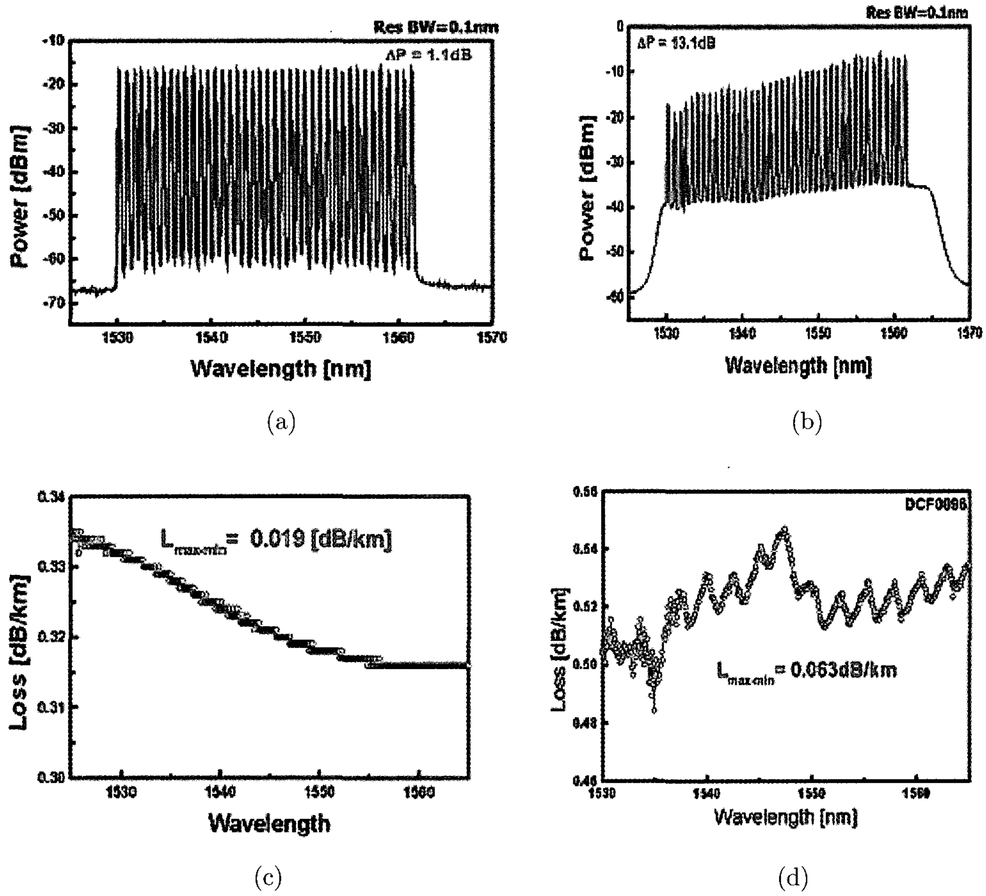

FIG. 3. The measured optical spectrum. (a) After multiplexing of the 40 channels. (b) After the transmission over 323 km of NZ_DSF. (c) Spectral attenuation for span. (d) Spectral attenuation for DCM60.

in Fig. 3 (c). The average of the measured spectral attenuation for DCM was 0.72 dB, and shows almost no variation within the used bandwidth as shown in Fig. 3 (d).

Fig. 4 shows the maximum power difference between channels as a function of span. The dotted curve, which describes the signals which pass through four spans and two DCFs like our experimental configuration, shows greater power difference than the lined one which is the case of sending the signal through five concatenated amplifiers only without any fiber and DCM. The induced optical gain tilt of five concatenated amplifiers was 5.8 dB. On the concatenated amplifiers, we used VOA without spectral attenuation to adjust the input power level of the dual stage amplifier. From the figures. 3 (c), (d), and fig. 4, by subtracting 4.4 dB spectral attenuation for the link, 0.72 dB spectral attenuation for the DCM60, and 5.8 dB gain tilt for the concatenated amplifier from the total power difference of 13.1 dB, we can estimate the Raman gain tilt of 1.1 dB occurred in the same band. This gain tilt will be suppressed by using pre-emphasis at the transmitter or gain flattening filter within the amplifier. However, for our experiment, the power difference between channels cannot influence our result, because the OSNR of all channels satisfy OSNR criteria.

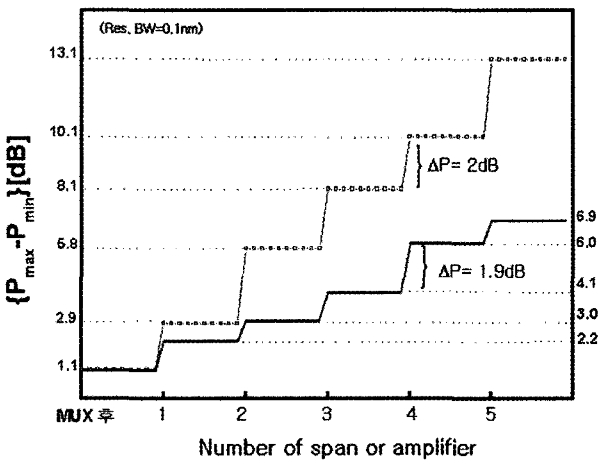

FIG. 4. The output power difference measured for each span (dot: signal pass through 4 spans and 2 DCF, line: signal pass through 5 amplifiers).

The OSNR of all channels, which was measured for every span, is shown in Fig. 5. After the transmission over 323 km, all channels, except four channels within the short wavelength region, satisfied 25 dB OSNR criteria that is required for 10 Gbit/s transmission. Concerning this criterion includes the system margin of 4~5 dB, as well as four channels have OSNR more than 22.5 dB, OSNR requirement for 10 Gbit/s transmission is satisfied.

Fig. 6 shows received eye diagrams for channel 18 and 32 after transmission over 323 km NZ_DSF. In

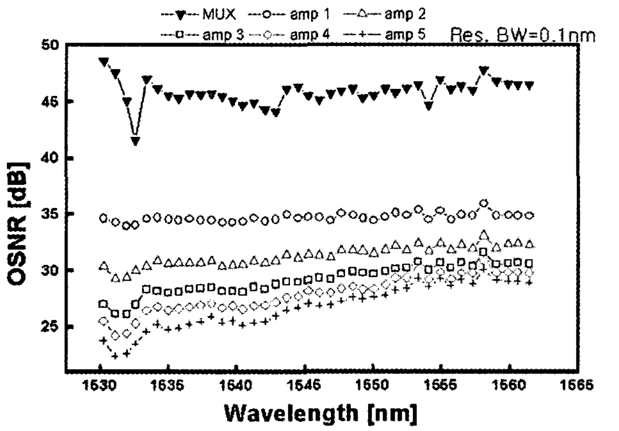

FIG. 5. The measured OSNR as a function of channel after each span.

channel 18, as can be seen in the figure, no significant difference was observed on eye diagram between the lumped scheme and the distributed scheme. Otherwise, in channel 32, the clearer eye opening was observed in the distributed dispersion scheme.

Fig. 7 shows the measured power penalty for each channel after transmission over 323 km NZ_DSF. The reason for the poor power penalty at both end side of the used wavelength band comes from the insufficient filtering at end channels due to bandwidth of TOBF, which was limited from 1530 nm to 1560 nm. Since the dispersion and channel spacing are 4.3 ps/nm/km and 100 GHz, signal degradation caused by FWM can be ignored. Therefore, the power penalty induced by XPM becomes dominant. As can be seen in the Fig. 7, in the short wavelength region, no significant improvement of BER was observed between the lumped scheme and the distributed scheme. Otherwise, in the long wavelength region, significant improvement of the BER was observed in the distributed scheme rather than the lumped scheme. This seems to be coming from the fact that the power penalty induced by XPM in the distributed scheme is lower than in the lumped scheme. It can be explained in detail as follows. The signal degradation due to XPM is mainly decided by signal power and dispersion of the fiber. The high dispersion causes increased pulse walk-off whereby the pulses spend less time together, having less interaction, causes

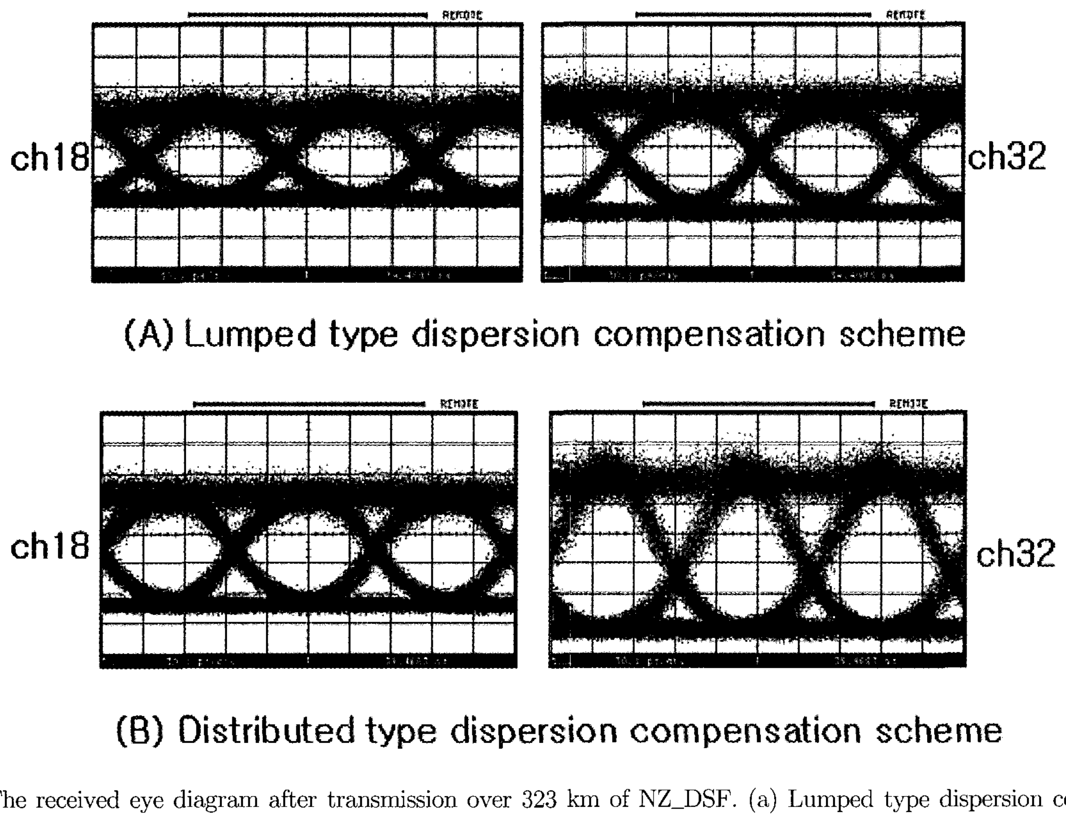

FIG. 6. The received eye diagram after transmission over 323 km of NZ_DSF. (a) Lumped type dispersion compensation scheme. (b) Distributed type dispersion compensation scheme.

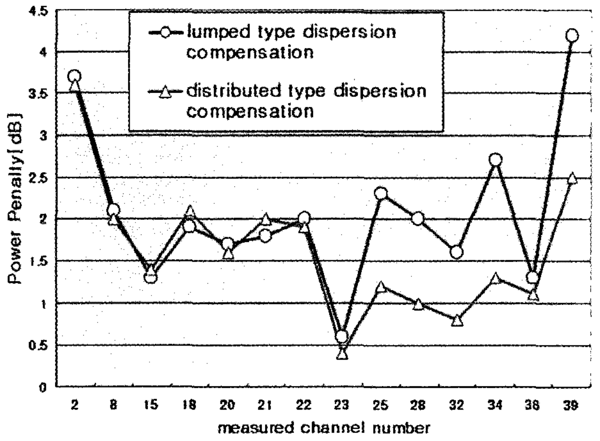

FIG. 7. The measured power penalty for each channel after transmission over 323 km of NZ_DSF (circle: a lumped type dispersion compensation, triangle: a distributed type dispersion compensation).

a lower XPM penalty. On the other hand, the nonlinear interaction is significant almost exclusively in the first walk off length in the beginning of each fiber span. In the rest of the fiber the nonlinear interaction can be neglected for all practical reasons and only dispersion plays a dominant role in transforming the phase modulation due to XPM into an intensity modulation. Therefore, at the end of the span, low dispersion, which can be seen on the signal, decrease the signal distortion caused by XPM. Consequently, the transmitted signal experiences the low dispersion at the end of the span for the distributed scheme rather than the lumped scheme, resulting in improvement of the transmitted signal quality.

IV. CONCLUSION

We investigated experimentally the transmission characteristics of 400 Gbit/s (10 Gbit/s × 40 channels) WDM signals with 100 GHz channel spacing over 323 km of field installed NZ_DSF. The fiber has optical properties of 0.28 dB/km optical loss, 4.3 ps/nm/km of chromatic dispersion, 0.083 ps/nm^2/km of dispersion slope, less than 0.05 ps/km$^{1/2}$ of PMD coefficient. Two cases of dispersion compensation schemes, the lumped type and the distributed type, were compared. The results implied that the distributed type dispersion compensation showed better transmission performance than the lumped one. From the analysis of the experimental results, we verified that different transmission performance comes from the power penalty induced by XPM in the distributed scheme is lower than for the lumped scheme case.

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