Chromatic Dispersion Compensation via Mid-span Spectral Inversion with Periodically Poled $LiNbO_3$ Wavelength Converter at Low Pump Power

Min-su Kim, Joon Tae Ahn, Jongbae Kim, Jung Jin Ju, and Myung-Hyun Lee

Mid-span spectral inversion (MSSI) has to utilize high optical pump power, for its operation principle is based on a nonlinear optical wavelength conversion. In this paper, a low pump-power operation of MSSI-based chromatic dispersion compensation (CDC) has been achieved successfully, for the first time to our knowledge, by introducing a noise pre-reduction scheme in cascaded wavelength conversions with periodically poled $LiNbO_3$ waveguides at a relatively low operation temperature. As preliminary studies, phase-matching properties and operation-temperature dependence of the wavelength converter (WC) were characterized. The WC pumped at 1549 nm exhibited a wide conversion bandwidth of 59 nm covering the entire C-band and a conversion efficiency of –23.6 dB at 11 dBm pump power. CDC experiments were implemented with 2.5 and 10 Gb/s transmission systems over 100 km single-mode fiber. Although it is well-known that the signal distortion due to chromatic dispersion is not critical at a 2.5 Gb/s transmission, the clear recovery of eye patterns was identified. At 10 Gb/s transmission experiments, eye patterns were retrieved distinctly from seriously distorted ones, and notable improvements in bit-error rates were acquired at a low pump power of 14 dBm.

Keywords: Chromatic dispersion compensation, 10 Gb/s optical signal transmission, mid-span spectral inversion, cascaded wavelength conversions, periodically poled $LiNbO_3$, low pump power.

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I. Introduction

Future terabit-per-second transmission networks will adopt dense wavelength-division multiplexing (WDM) systems based on higher bit-rate time-division multiplexed channels. Related to higher bit-rate ($\geq$ 10 Gb/s) signal transmission, the chromatic dispersion of standard single-mode fibers (SMFs) becomes the most crucial obstacle because the dispersion-limited transmission distance gets significantly shortened to approximately 60 km at 10 Gb/s and approximately 4 km at 40 Gb/s, which are much shorter than the attenuation-limited transmission distance.

A number of methods have been demonstrated to manage or compensate chromatic dispersion. The most commonly accepted route is to employ dispersion-compensating fibers [1]. The utilization of chirped fiber Bragg gratings [2] is also well-established. Approaches to the extension of transmission distance have also been made by introducing prechirped or precoded signals [3], [4]. Recently, tunable dispersion compensation has attracted much attention and has been demonstrated by various methods such as fiber Bragg gratings [5], virtually imaged phased arrays [6], all-pass etalons [7], ring resonators [8], and so on. However, these approaches cannot be utilized exclusively for long-distance SMF transmission of high bit-rate signals due to their limited amounts of chromatic dispersion compensation (CDC).

The method of mid-span spectral inversion (MSSI) has often been nominated for an influential and cost-effective way to the substitution of dispersion-compensating fibers for long-distance multi-channel optical signal transmission [9]-[13]. It is based on the optical phase conjugation [14] accompanied by nonlinear optical wavelength conversion in a nonlinear medium placed at the middle of a transmission span. A phase-conjugated (or converted) signal carries an inverted spectrum in the same temporal shape as the original signal, and therefore is to be compressed during the second half of the transmission span by the same mechanism of chromatic dispersion that has expanded the original signal during the first half.

MSSI has many advantages over other competitive methods, such as wide bandwidths, wide dynamic ranges, low crosstalk, signal format transparency, ultrafast responses, simultaneous multichannel compensation, and the compensation of nonlinear distortions. These make it appropriate for dense WDM and/or high bit-rate time-division multiplexing systems. MSSI also has some drawbacks such as polarization sensitivity, unwanted wavelength shifts, and a high pump-power operation, each of which is attributed to inherent properties of the nonlinear optical wavelength conversion processes. The resolution of the first two matters has been demonstrated using several schemes [11]-[13]. However, no attempt has been made at low pump-power operation, although it will reduce the cost of an MSSI module considerably and increase the system safety by eliminating the necessity of a high power pump source.

In this paper, we introduce a simple noise pre-reduction scheme for the first realization of an MSSI-based CDC system operating successfully at a low pump power. The wavelength converter (WC) in our MSSI module is based on cascaded second-order nonlinear optical processes, that is, second-harmonic generation (SHG) followed by difference-frequency generation, in periodically poled $LiNbO_3$ (PPLN) waveguides [9], [10], [15]. We present the characteristics and performance of our PPLN WC and the results of CDC experiments at 2.5 and 10 Gb/s transmission over 100 km of SMF.

II. Characterization of PPLN Wavelength Converter

We composed a WC module as a part of our MSSI system depicted in Fig. 1. The PPLN waveguide sample with the periodically poled region of 5 cm in length was employed as the nonlinear optical medium for wavelength conversion. The PPLN sample had to be operated at an elevated temperature to avoid the photorefractive effect in $LiNbO_3$ because this effect causes the attenuation of the propagating optical power and results in a significant reduction of conversion efficiency. Thus the sample was mounted on a compact heating cell, which can be controlled with the resolution of 0.1°C, and was operated at around 90°C. Compared to the previous reports with PPLN WCs [9], [15], [16], our operation was accomplished at a fairly low temperature. This was made possible by our low pump-power operation. A waveguide on the PPLN sample was aligned with a bare SMF at each facet by precise aligning equipment; a typical coupling loss per facet is estimated to be approximately 3.0 dB.

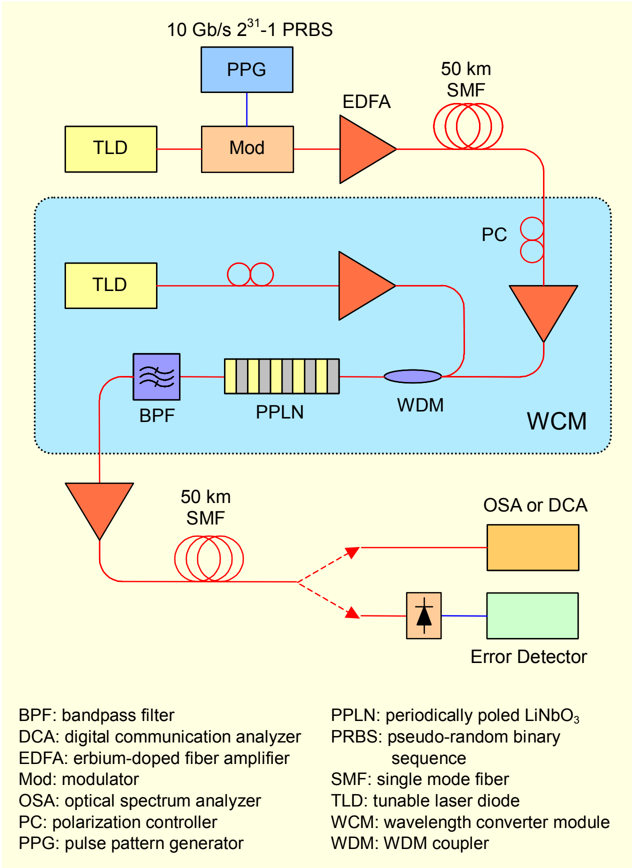

Fig. 1. Experimental setup to demonstrate dispersion compensation system.

Two tunable laser diodes were utilized as the light sources for the CW pump and signal waves. The two waves were amplified with erbium-doped fiber amplifiers (EDFAs) and then combined by a WDM coupler to be incident on the PPLN waveguide. Polarization controllers were used to adjust the polarizations of the pump and signal waves to the TM modes in the PPLN waveguide for maximizing the efficiencies of nonlinear optical interactions.

In the first place, we performed SHG experiments with the PPLN waveguide to evaluate its fundamental characteristics. The pump-wavelength dependence of SHG power is shown in Fig. 2. The measured data were normalized and fitted with the theoretical curve given by the sinc-square function. They show a noticeable discrepancy with the fitting curve, especially on the left side of the peak, which may be caused by some irregularity of the poled period in the PPLN waveguide. The measured phase-matching wavelength is 1548.9 nm at 90°C with a very low pump power, and the spectral acceptance bandwidth (the full

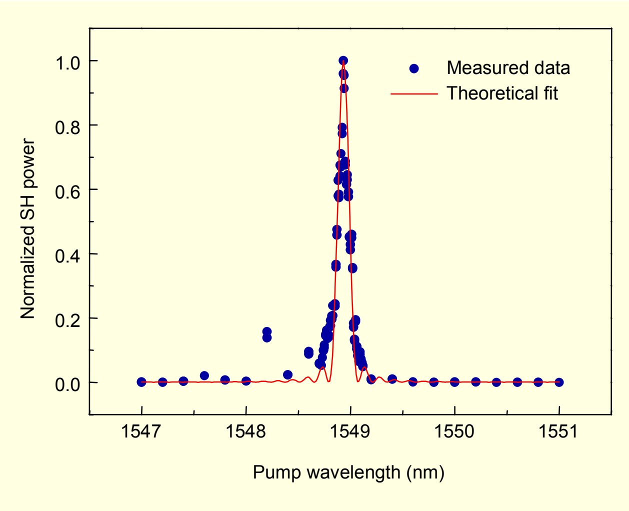

Fig. 2. Phase-matching characteristic of the second-harmonic generation in the PPLN waveguide at 90°C.

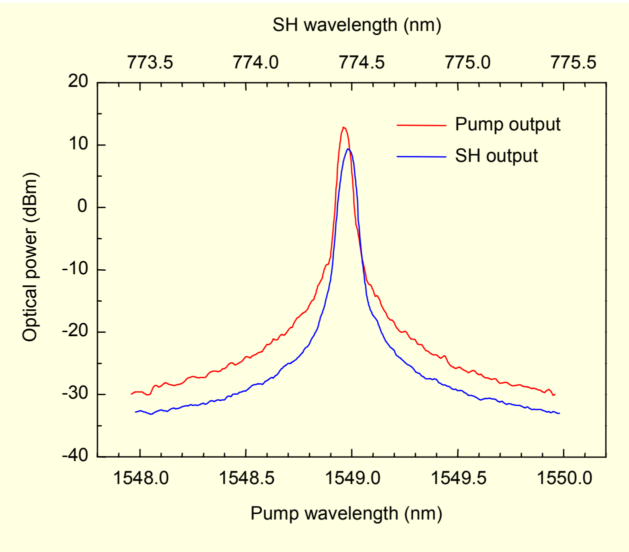

Fig. 3. Pump and second-harmonic power spectra measured from the transmitted wave.

width at half maximum) is given by 0.12 nm. The temperature dependence of the phase-matching wavelength was also measured to be 0.082 nm/°C at around 90°C.

Figure 3 exhibits the power spectra of the transmitted pump and second-harmonic waves measured with an optical spectrum analyzer, which has a resolution bandwidth of 0.05 nm. From the spectral envelope of the second-harmonic wave, we can notice that its peak shows a blunt shape and its bandwidth is larger than that of the pump, although it should be narrower in typical situations of SHG. These facts indicate that the peak region already enters into the saturation regime of the wavelength conversion. Taking into account the coupling losses at the output facets of the PPLN waveguide at both wavelengths, the internal conversion efficiency is estimated to be –4.5 dB at a coupled pump power (into the waveguide) of approximately 16.8 dBm. This value corresponds to the normalized conversion efficiency of approximately 30 %/W·cm^2, which is obtained at a saturated situation, however.

In the PPLN WC device, MSSI was realized by cascaded second-order wavelength conversion processes: SHG ($\omega_p + \omega_p \rightarrow \omega_{sh}$) takes place from the frequency doubling of the pump wave at the first step, and difference-frequency generation ($\omega_{sh} - \omega_s \rightarrow \omega_c$) brings forth the converted signal wave from the nonlinear mixing of the second-harmonic and signal waves at the following step. As a result, the spectrum of the converted signal is to be located in the frequency domain at the symmetric position of that of the original signal with respect to the pump. This can be ascertained by Fig. 4, which shows the measured output spectra of the PPLN WC for several signal wavelengths. At the incident pump power of 14

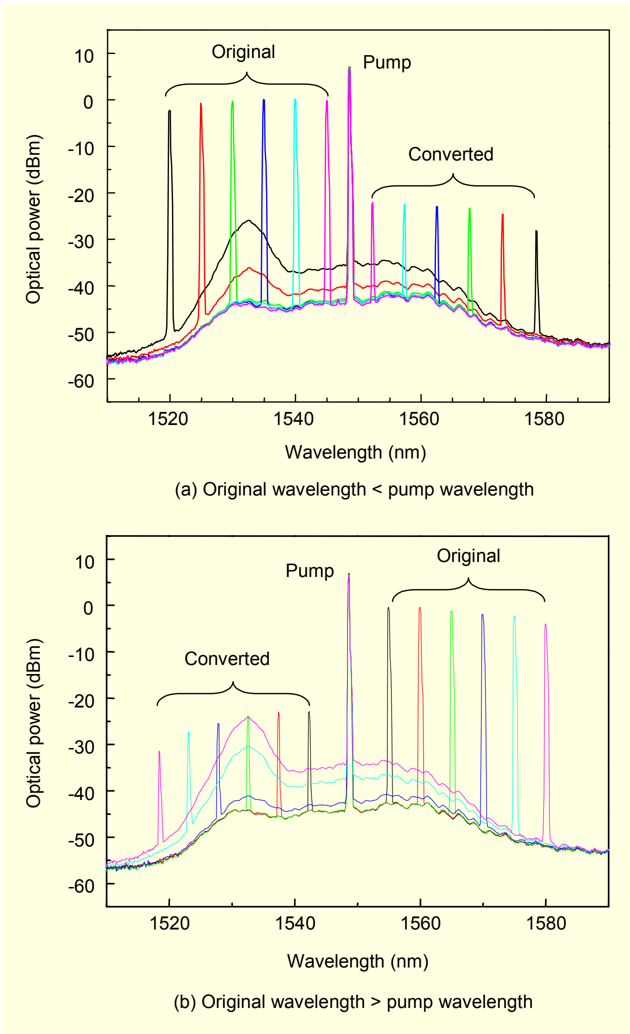

Fig. 4. Transmitted power spectra of the wavelength converter measured for several signal wavelengths.

dBm, which corresponds to the coupled power into the PPLN waveguide of approximately 11 dBm, converted signal power of about –22 dBm was typically obtained with coupled signal power of approximately 4 dBm. By increasing the pump and signal power with our moderate power amplifiers, we could obtain even higher converted power up to –5 dBm. The bumps in the 1530 nm region in Fig. 4 were the amplified spontaneous emission augmented due to the lower gain of the C-band amplifier at the original signal wavelengths deviated from the C-band.

The conversion efficiency of a WC is defined by the ratio between the optical powers of the converted signal at the output and the original signal at the input, and is known to be proportional to the square of the pump power for this kind of cascaded processes. Figure 5 shows the dependence of the internal conversion efficiency on the signal wavelength, together with the result of a theoretical fit. Internal conversion efficiencies of about –23.6 dB were typically obtained in the flat region at the coupled pump power of 11 dBm. In a previous paper, an output-to-output efficiency of –15 dB was reported at a coupled pump power of 20.4 dBm [16]. This value would correspond to an internal conversion efficiency of –35.3 dB at 11 dBm if the degradation of conversion efficiency due to the saturation behavior was not considered. The noticeable difference in the conversion efficiency is supposed mostly due to our WC operation at an unsaturated conversion efficiency regime and a highly suppressed photorefractive effect, both of which are closely related to the low pump-power operation of our PPLN WC module. The 3 dB acceptance bandwidth of the signal wavelength was obtained as 59 nm from the theoretical fit as shown in Fig. 5. It also should be noted that the plateau region sufficiently covers the entire C-band with negligible deviations.

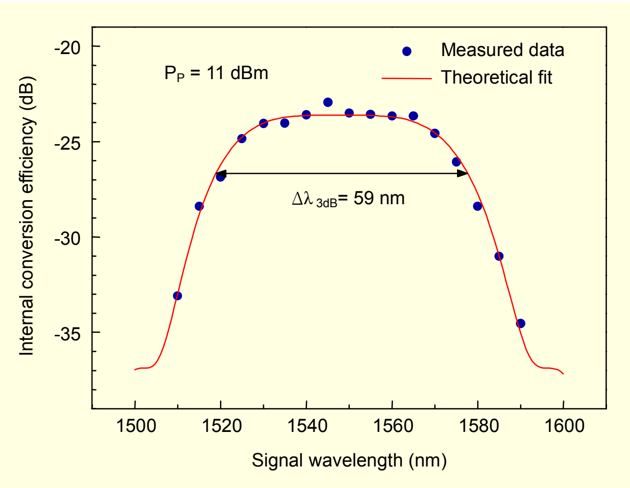

Fig. 5. Internal conversion efficiency of the cascaded wavelength conversion as a function of the original signal wavelength.

III. Dispersion Compensation at a 10 Gb/s Transmission over 100 km SMF

Our WC module seems to exhibit very low conversion efficiencies due to our low pump-power operation. However, we should take notice that MSSI-based CDC systems typically include optical amplifiers after their WC modules to boost the power of the converted signal waves. Hence, high conversion efficiencies (or high converted signal powers) accompanied by the high power pumping are not essential for the purpose of the CDC if a sufficient signal-to-noise ratio (SNR) can be guaranteed at the converted signal. That is to say, the noise reduction at the converted wavelength region can be a convincing alternative to the high power pumping for the implementation of economic MSSI systems. Thus, we modified the above-mentioned WC module by introducing a WDM filter just before the PPLN sample for filtering out the noise considerably at the converted wavelength region. This brought forth a noise reduction of – 42 dB near 1560 nm before the WC module and therefore guaranteed sufficient SNRs for the converted signal waves in this region. The result of our experiment showed that the SNR degradation after the WC module was reduced considerably to only approximately 2 dB by adopting the noise pre-reduction scheme.

Our CDC system shown in Fig. 1 was constituted on the basis of this modified WC module. The signal from a tunable laser diode was modulated at 10 Gb/s with a 2^{31}–1 pseudorandom binary sequence, preamplified to a power level of approximately 10 dBm by an EDFA, and transmitted through the first 50 km span of SMF. After the transmission, it was incident on the WC module along with the CW pump to generate the converted signal. Then, the converted signal was filtered out with a bandpass filter, amplified, and transmitted through the second 50 km span of SMF.

The eye patterns for the converted signal were measured with a digital communication analyzer after the second half of the 100 km transmission line. Figures 6 and 7 present the results, together with those for the original signal at each stage, obtained at 2.5 and 10 Gb/s transmission experiments, respectively. According to the increase of the transmission distance through SMF, the original signal at 10 Gb/s suffers serious distortion due to the chromatic dispersion, as is expected. Although the original signal at 2.5 Gb/s is also distorted to some extent, the eye opening can be still clearly identified after a 100 km SMF transmission. Meanwhile, the converted signal, which was generated by the original signal at the WC module located at the 50 km distance, shows nearly the same patterns after the 100 km transmission as the original back-to-back signal. Although a much scattered pattern is shown in Fig. 6(d), it is attributed to just the low optical power

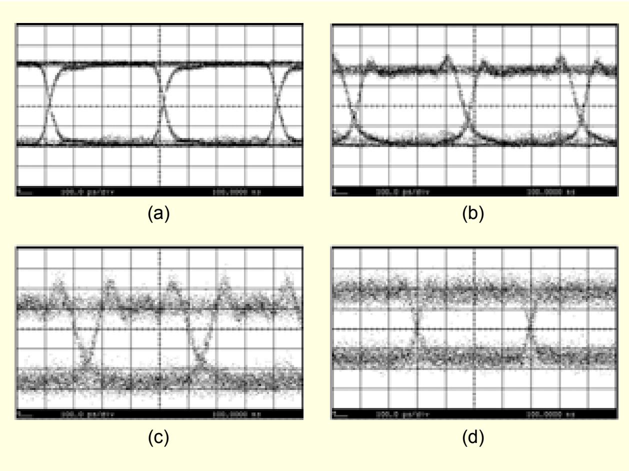

Fig. 6. Eye patterns measured at the 2.5 Gb/s transmission experiment: the original signals (a) measured back-to-back, (b) after 50 km SMF, and (c) after 100 km SMF without MSSI, and (d) the converted signal after 100 km SMF with MSSI at the midpoint.

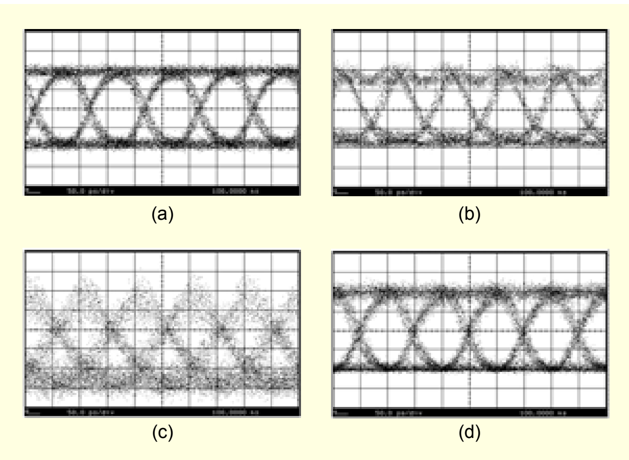

Fig. 7. Eye patterns measured at the 10 Gb/s transmission experiment: the original signals (a) measured back-to-back, (b) after 50 km SMF, and (c) after 100 km SMF without MSSI, and (d) the converted signal after 100 km SMF with MSSI at the midpoint.

received. Hence, we could conclude that the chromatic dispersion seemed to be nearly compensated.

We then measured the bit-error rates (BERs) by coupling the original and converted signals to an error detector. Figure 8 shows the BER curves measured at a 10 Gb/s signal transmission with an original signal wavelength of 1536.6 nm. The coupled pump and signal powers were approximately 14 dBm and approximately 12 dBm, respectively, and the converted signal power was approximately –10 dBm after the PPLN WC. The converted signal after the full 100 km SMF transmission exhibited apparent improvement in BER in comparison with the original signal after the 100 km transmission. However, against our expectation, there still remained a power penalty of approximately 1.2 dB at 10^{-9} BER with respect to the original signal measured back-to-back. Such an insufficient CDC in MSSI was also reported in a previous work adopting a high pump power of approximately 19 dBm [9]. Hence we could ascertain that our low pump-power operation did not aggravate seriously the performance of our transmission experiment. Our additional inspection proved that the residual power penalty was due to the performance of our laboratory-composed EDFA just before the second span of 50 km SMF, from the measurement of the BERs before and after it. A power penalty of approximately 1.8 dB at 10^{-9} BER was obtained before it, which is a worse value than that for the dispersion-compensated signal after 100 km SMF. Moreover, the BERs increased by roughly 10^3 times after the EDFA. Owing to this noticeable deterioration in BER caused by the EDFA, our CDC system still yielded the excess power penalty after the full 100 km SMF transmission, although the dispersion effect seemed to be nearly compensated as observed in Fig. 7. Anyway, our MSSI-based CDC system adopting a low power pump showed off a comparable CDC performance with the previous result using a high power pump [9]. This demonstrated that our approach to lowering the pump power can be an effective way to constitute MSSI-based CDC systems.

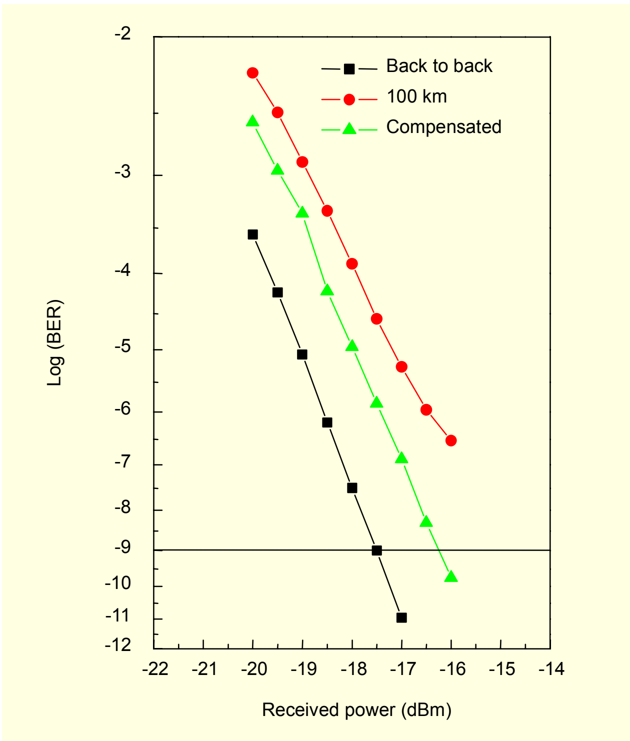

Fig. 8. Bit-error rates measured at 10 Gb/s signal transmission for the original signals measured back-to-back and after 100 km SMF, and the dispersion-compensated (converted) signal after 100 km SMF.

IV. Conclusion

We have demonstrated successfully, for the first time, the low pump-power operation of an MSSI module with a PPLN WC by introducing a simple noise pre-reduction scheme. This result will contribute toward a significant reduction in the cost of practical MSSI modules for CDC and an increase of the system safety by replacing a high power EDFA with a typical EDFA with a moderate power level. Besides, the alleviation of the pump-power requirement allows a relatively low temperature operation of PPLN. From the evaluation of the SHG performance of our PPLN WC, we obtained a phase-matching wavelength of 1548.9 nm at 90°C and an SHG internal conversion efficiency of –4.5 dB at a pump power of 16.8 dBm. The fabricated WC exhibited internal conversion efficiencies, from original signals to converted signals, of about –23.6 dB over the entire C-band at an 11 dBm pump power and a wide acceptance bandwidth of 59 nm for the signal wavelength. Based on this WC module, the proposed CDC system was established by introducing an additional WDM filter for the noise pre-reduction just before the PPLN waveguide device. The CDC experiments adopting a low pump power of 14 dBm were performed at 2.5 and 10 Gb/s transmission over 100 km SMF. The eye patterns for the converted signal after the full 100 km transmission showed nearly perfect restoration to the extent of that for the original signal measured back-to-back. The result of the BER measurement at a 10 Gb/s transmission also exhibited remarkable improvement by virtue of the CDC effect based on MSSI, but the improvement was limited by the non-optimized characteristic of EDFA. Despite this limitation, our system resulted in CDC characteristics matchable to other systems adopting high power pumps, and this fact proves our approach is appropriate to solve the problem of high pump-power operation in MSSI-based CDC systems.

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