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Waveform Conversion and Wavelength Multicasting with Pulsewidth Tunability Using Raman Amplification Multiwavelength Pulse Compressor*

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SUMMARY A combination of nonreturn-to-zero (NRZ)-to-return-to-zero (RZ) waveform conversion and wavelength multicasting with pulsewidth tunability is experimentally demonstrated. A NRZ data signal is injected into a highly nonlinear fiber (HNLF)-based four-wave mixing (FWM) switch with four RZ clocks compressed by a Raman amplification-based multiwavelength pulse compressor (RA-MPC). The NRZ signal is multicast and converted to RZ signals in a continuously wide pulsewidth tuning range between around 12.17 and 4.68 ps by changing the Raman pump power of the RA-MPC. Error-free operations of the converted RZ signals with different pulsewidths are achieved with negative power penalties compared with the back-to-back NRZ signal and the small variation among received powers of RZ output channels at a bit-error-rate (BER) of 10^{-9}. The NRZ-to-RZ waveform conversion and wavelength multicasting without using the RA-MPC are also successfully implemented.

key words: *fiber optics and optical communication, optical signal processing, four-wave mixing, pulse compression, distributed Raman amplification*

1. Introduction

Multi-function optical signal processing which realizes simultaneously different functionalities such as wavelength-waveform conversions, wavelength multicasting, and pulsewidth tunability have been shown to be beneficial for applications in future all-optical networks [1]–[4]. Indeed, all-optical wavelength multicasting could significantly improve the flexibility and efficiency of wavelength-division-multiplexing (WDM) networks, particularly in wavelength-routed networks by increasing the network throughput [5], [6]. Furthermore, optical waveform conversions between nonreturn-to-zero (NRZ) and return-to-zero (RZ) [7]–[12], which are two widely-used waveforms in fiber-optics communication systems, would be one of key processes to realize all-optical interfaces between different networks. From the results in [13]–[16], it is obvious that the transmission performances of communication links are strongly dependent on the pulsewidth of the RZ signals at the transmitters due to the influences of dispersion and nonlinearities of fibers and characteristics of optical receivers. Integration of pulsewidth tunability in the waveform conversion and wavelength multicasting is, therefore, particularly desirable to provide flexibility for system performance optimization and network reconfigurability through pulsewidth management.

All-optical wavelength multicasting with NRZ-to-RZ waveform conversion has been demonstrated by using various nonlinear effects in photonic crystal fiber [17] and highly nonlinear fiber (HNLF) [18], but the pulsewidth management has not been considered. One-to-four multicast RZ channels with tunable pulsewidths have been implemented in [3], [4]. In detail, the authors in [3] and [4] have reported 4x10 Gb/s wavelength multicasting and NRZ-to-RZ with the pulsewidth tunable ranges from 17.9 to 22.2 ps and from 33 ps to 67 ps, respectively. However, offering pulsewidth tunability at picosecond range is still a technical challenge in these demonstrations since such the picosecond pulsewidth range is required for high-speed data signals at symbol rate over 100 Gbaud [19], [20]. To achieve short pulsewidth wavelength multicasting RZ signals after conversion, multiwavelength pulsewidth-short RZ clocks are requested. Various techniques were reported to optically generate short pulsewidth RZ clocks such as using mode-locked laser diodes (MLLDs) [21], [22]. However, the use of MLLDs is restricted in terms of pulsewidth flexibility. Recently, Raman amplification-based multiwavelength pulse compressor (RA-MPC) has attracted much attention in generating high quality RZ clocks with the tunable pulsewidth in the order of a few picoseconds [23], [24].

In this paper, we realize simultaneously a one-to-four wavelength multicasting with NRZ-to-RZ waveform conversion with pulsewidth tunability in a wide range from 12.17 ps to 4.68 ps using the RA-MPC. We employ the RA-MPC to generate four synchronous 10 GHz WDM pulse trains with the pulsewidth adjustably compressed down to 3.50 ps. These four compressed pulse trains are then used to interact with an input 10 Gb/s NRZ data signal by four-wave

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mixing (FWM) effect in a HNLF. Since the idler waves have the data of the input signal and the waveform of the compressed RZ clocks through FWM, wavelength multicasting signals with short pulsewidth at picosecond range are obtained at the idler waves. Error-free operations are achieved for all multicast channels with negative power penalties compared with error-free operation of the NRZ signal and small variation among converted RZ channels at bit-error-rate (BER) of 10^{-9}. While our preliminary results have been presented [25], in this work, we also realize the NRZ-to-RZ waveform conversion and wavelength multicasting in case of without using the RA-MPC to compare with the quality of the converted-compressed RZ data signals using the RA-MPC. The results indicate that the receiver sensitivites of the compressed RZ data signals are better than those of the uncompressed RZ data signals.

2. Operation Principle

The concept of NRZ-to-RZ conversion and wavelength multicasting with tunable pulsewidth is shown in Fig. 1. It consists of the RA-MPC, which is a multiwavelength pulse compressor, and a HNLF-based FWM switch. The improved feature of the proposed scheme compared to the previously reported setup [3], [4] is on the use of RA-MPC to get multiwavelength RZ clocks with a widely pulsewidth-picosecond tuning range. Firstly, the RA-MPC which is based on adiabatic soliton compression technique takes advantage of high power amplification for multiwavelength RZ clocks using a distributed Raman amplifier (DRA). The multiwavelength RZ clocks are fundamental soliton pulses, which are amplified adiabatically in an anomalous dispersion fiber by using the DRA. One fundamental soliton pulse of sech^2 pulse (N = 1) has a peak power [26]

$$P_1 = \frac{3.11\,|\,\beta_2\,|}{\gamma\tau_{\mathrm{FWHM}}^2} \tag{1}$$

where P_1, τ_{FWHM}, β_2 and γ are the peak power of the fundamental soliton pulse, the pulsewidth of pulse, the group velocity dispersion coefficient and the nonlinear coefficient of fiber, respectively. From Eq. (1), the relationship between the pulsewidth τ_{FWHM} of the pulse and the peak power of the fundamental soliton pulse P_1 is as follow.

$$\tau_{\mathrm{FWHM}} \propto \sqrt{\frac{1}{P_1}} \tag{2}$$

From the relation (2), it can be seen that the pulsewidth τ_{FWHM} of the soliton pulse is inversely proportional to the square-root of the peak power of the optical pulse P_1. Therefore, the pulsewidth of the RZ clock pulse can be compressed as its peak power increases with the increase of the Raman pump power since the soliton condition is maintained during the amplification. By changing the Raman pump power, it is also possible to adjust the pulsewidth of the input RZ clock source. The characteristics of multiwavelength pulse compression are also similar as those of one pulse compression.

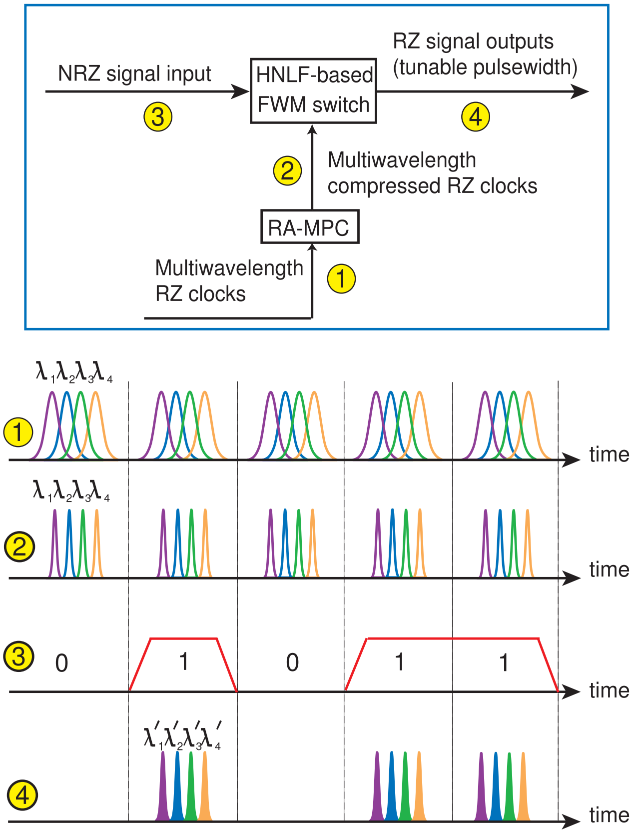


Fig. 1 Operation principle of the proposed scheme.

In the HNLF-based FWM switch, the RZ clocks with pulsewidth tunability generated from the RA-MPC is nonlinearly interacted with the input NRZ data signal over FWM. The input NRZ signal is multicast and converted to RZ signals at four FWM products at different wavelengths. When the NRZ signal and RZ clock with wavelengths of λ_{NRZ} and λ_{clk}, respectively are launched into a fiber with length L, a new FWM product is generated due to the FWM process. The power of this new generated FWM signal P_{FWM} is generally given by the following expression [27]:

$$P_{\mathrm{FWM}} = \eta\gamma^2 P_{\mathrm{NRZ}}^2 P_{\mathrm{clk}} e^{-\alpha L}\left[\frac{(1-e^{-\alpha L})^2}{\alpha^2}\right] \tag{3}$$

where η is the FWM efficiency, γ is the nonlinear coefficient of the fiber, and α is the attenuation coefficient of the fiber. P_{NRZ} and P_{clk} denote the powers of the NRZ signal set as a pump and the probe signal, respectively. From the Eq. (3), it can be seen that the FWM products have the data of the input NRZ signal and the waveform of the compressed clocks through FWM process. The wavelength multicasting RZ signals with short pulsewidth at picosecond range are obtained at the idler waves since the pulsewidths of these RZ signals inherit those of the RZ clocks sources. By compressing the clocks sources with different puleswidths using the RA-MPC before the switch, it is possible to get the converted RZ signals with tunable pulsewidth by controlling the

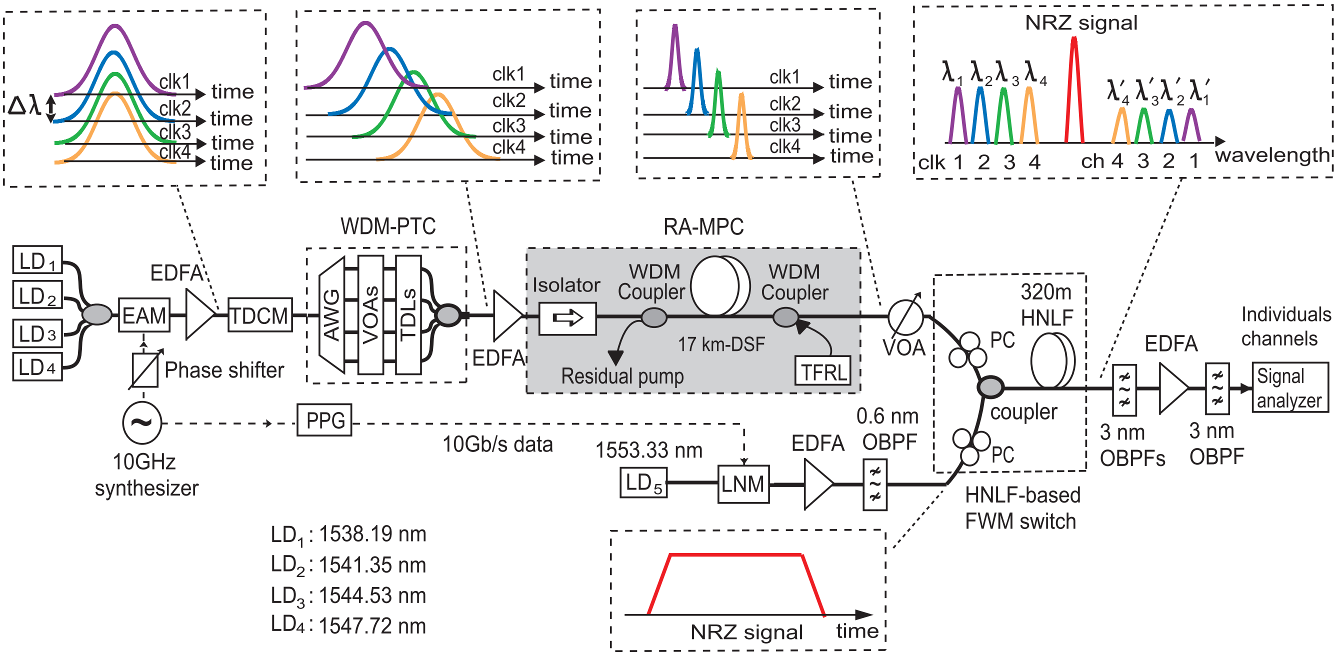


Fig. 2 Experimental setup of pulsewidth-tunable NRZ-to-RZ conversion and wavelength multicasting using Raman amplification-based multiwavelength pulses compressor (RA-MPC).

Raman pump power.

3. Experimental Setup

The experimental setup of wavelength multicasting with pulsewidth-tunable NRZ-to-RZ waveform conversion is shown in Fig. 2. Four 10 GHz WDM-RZ clocks at wavelengths of 1538.19 (λ_1), 1541.35 (λ_2), 1544.53 (λ_3), and 1547.72 nm (λ_4) are modulated from fours laser diodes (LDs) by an electroabsorption modulator (EAM). An erbium-doped fiber amplifier (EDFA) is used to amplify the four RZ clocks which then are sent to the input of a tunable dispersion compensating module (TDCM) used to compensate frequency chirping induced by the EAM. Powers and time locations of the WDM clock pulse trains are controlled individually by a WDM power and time controller (WDM-PTC) to guarantee the fundamental soliton powers and time interleaving among the clock pulse trains. The WDM-PTC consists of an arrayed waveguide grating (AWG), variable optical attenuators (VOAs) in series with tunable delay lines (TDLs), and a coupler. The chirping-compensated RZ clocks are amplified to fundamental soliton power by an EDFA and then are injected into the RA-MPC. The RA-MPC compresses the RZ clocks using adiabatic soliton compression technique. The RA-MPC consists of a 17 km dispersion-shifted fiber (DSF) with a tunable fiber Raman laser (TFRL) operating at 1454 nm in counter-propagation using a WDM coupler. The Raman pump wavelength is optimized at 1454 nm for the pulse compression to achieve high-quality compression performance. The DSF has the parameters as shown in Table 1. A phase shifter provides a continuously variable time delay for controlling the time delay of the RZ clocks in order to get overlap of the RZ clocks and the NRZ signal in FWM process.

Table 1 Characteristics of dispersion-shifted fiber (DSF).

Parameter	Value	Unit
Length	17	km
Attenuation	0.197	dB/km
Dispersion at 1552 nm	3.8	ps/nm/km
Dispersion slope at 1552 nm	0.059	ps/nm^2/km

Table 2 Characteristics of highly nonlinear fiber (HNLF).

Parameter	Value	Unit
Length	320	m
Attenuation	0.82	dB/km
Dispersion at 1550 nm	−0.06	ps/nm/km
Dispersion slope at 1550 nm	0.023	ps/nm^2/km
Nonlinear coefficient (γ)	28	$W^{-1} \cdot km^{-1}$
Effective core area of fiber (A_{eff})	9	μm^2

On the other hand, a NRZ signal at wavelength of 1553.33 nm is generated by a LiNbO$_3$ modulator (LNM) driven by electrical NRZ data from a pulse pattern generator (PPG) and is amplified by an EDFA and filtered by a 0.6 nm optical band pass filter (OBPF). The powers of the NRZ signal and compressed RZ clocks are optimized to obtain good output waveforms and the largest FWM efficiency by an EDFA and a VOA. Meanwhile, two polarization controllers (PCs) are used to optimize polarization state of both the clocks and NRZ signal to maximize the interaction between these signals. The NRZ signal is set as a pump for FWM process in the HNLF which has the parameters as shown in Table 2. After the FWM process, the converted RZ data signals are filtered and amplified individually by OBPFs and an EDFA, respectively. These signals are analyzed to obtain the spectra, waveforms, eye patterns, and BER of the output signals.

4. Experimental Results and Discussions

In our experiment, the multiwavelength RZ clocks compression was based on adiabatic soliton compression in the DRA. Since the energy of the pulses was increased by the DRA, the soliton pulses were compressed. Fundamental soliton pusles (N = 1) were required for this technique. The relationship between the peak power and pulsewidth of each RZ pulse was expressed by the Eqs. (1) and (2). Figure 3 shows autocorrelation traces of each of four RZ clocks after compressing at the output of the RA-MPC when the Raman pump power was set at 0.82 W. The RZ clock 1 (clk 1), clock 2 (clk 2), clock 3 (clk 3), and clock 4 (clk 4) at the wavelengths of 1538.19, 1541.35, 1544.53, and 1547.72 nm with the pulsewidth of around 20.0 ps were compressed down to 3.43, 3.78, 3.34, and 3.50 ps, respectively. It is obvious to see that our RZ clocks pulses were the high quality pulses since their waveforms were well fit to sech^2 fitting. These four compressed RZ clocks interacted with the 10 Gb/s NRZ data signal by FWM effect in the HNLF. The time spacing between adjacent compressed RZ clocks were set to 15 ps to ensure that all these clocks were sampled at flat-top of the NRZ waveform signal by the FWM process.

The spectrum at the output of the HNLF is shown in Fig. 4 in case the Raman pump power (P_r) was set to 0.82 W. It is clearly seen that the spectral shapes of RZ clocks and converted RZ channels after multicasting were well fit to sech^2 function. It is stated again that before the FWM process, the pulsewidth of compressed RZ clocks was around 3.50 ps as the Raman pump power was 0.82 W. After the FWM process, channel 1, 2, 3 and 4 (ch 1, 2, 3, and 4) at wavelengths of 1568.47 (λ'_1), 1565.31 (λ'_2), 1562.13 (λ'_3), and 1558.94 nm (λ'_4) were simultaneously generated. Each channel of the multicasting outputs was individually filtered for eye patterns, the pulsewidths and BER characteristics measurements.

Figure 5 shows clear eye patterns of the multicast RZ signals at wavelengths of 1568.47, 1565.31, 1562.13, and 1558.94 nm. When the Raman pump power was set at 0.82 W, the pulsewidth of around 4.68 ps was obtained for the multicast signals. To investigate the successful demonstration of the multicasting process, BER curves of the multicast signals were measured as a function of received power as shown in Fig. 6. Good BER characteristics were obtained with small received power variation of around 0.5 dB at BER of 10^{-9} among the multicast signals. Negative power penalties within 1 dB were observed with respect to the back-to-back NRZ input signal. Our results are well reasonable compared with the results in [9], [28]–[31] whose receiver sensitivities for RZ signals could be enhanced by several dB compared to NRZ signals. It was found that these receiver sensitivity improvements of around from 2 to 3 dB in both theoretical and experimental demonstration [28], 3 dB in experimental work [29], up to 3.2 dB in theoretical works [30], [31], and 1.5 dB in experimental work [9] could be obtained. These come from the fact as follows. At the same average optical power at the receiver, the RZ pulse will have a higher peak power compared with that of the

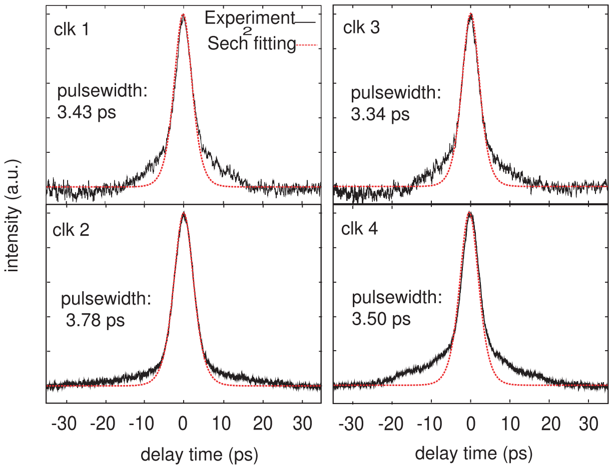


Fig. 3 Autocorrelation traces of four RZ clocks after compressing at the output of the RA-MPC with the Raman pump power of 0.82 W.

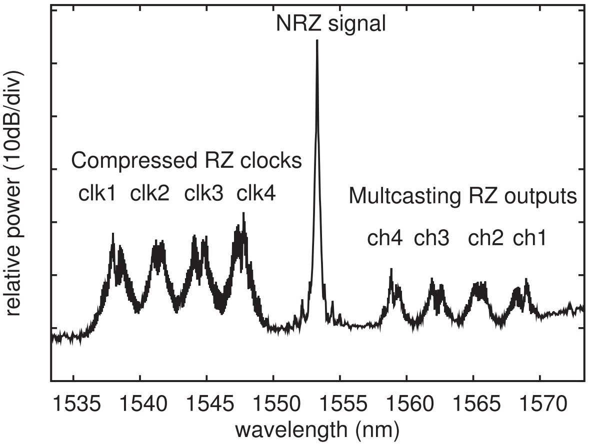
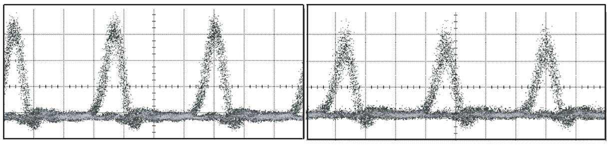
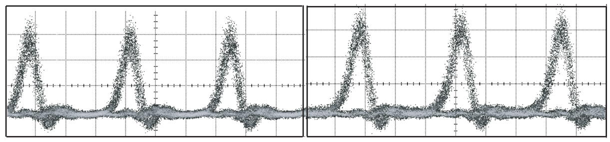


Fig. 4 FWM spectrum at the output of HNLF with the Raman pump power of 0.82 W.



(a) ch 1 (1568.47 nm) (c) ch 3 (1562.13 nm)



(b) ch 2 (1565.31 nm) (d) ch 4 (1558.91 nm)

time (30 ps/div.)

Fig. 5 Eye patterns of the all converted RZ signals with the pulsewidth of around 4.68 ps.

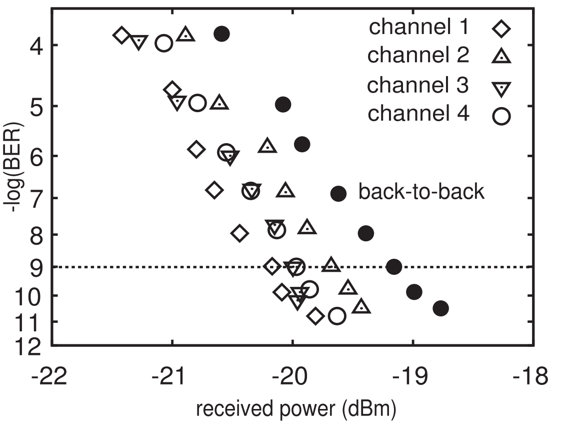
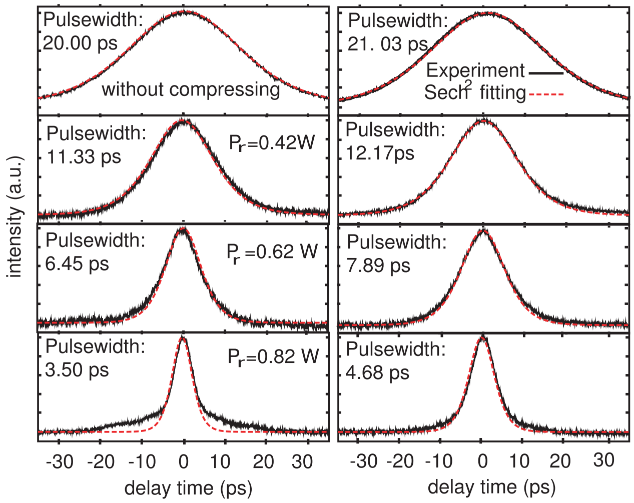


Fig. 6 BER characteristics of the converted RZ channels with the pulsewidth of around 4.68 ps at the Raman pump power of 0.82 W.



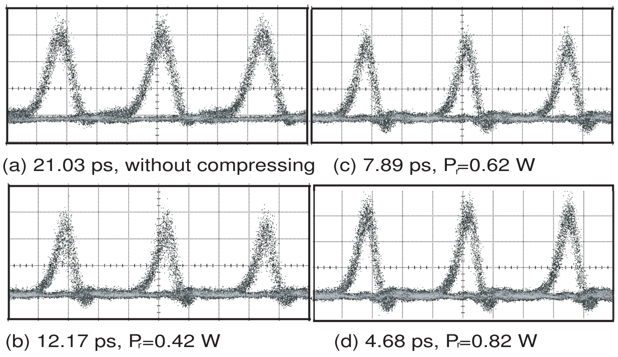
(a) RZ clk 4 before FWM

(b) RZ ch 4 after FWM

Fig. 7 Autocorrelation traces of the various pulsewidths of RZ clock 4 (clk 4) after RA-MPC (before FWM) and channel 4 (ch 4) after HNLF (after FWM) at various Raman pump powers (P_r).

NRZ one. Since the received electrical power is proportional to the square of the incident optical power, the electrical power of the RZ pulse will be higher that of the NRZ one [9]. Therefore, in a comparison to NRZ pulse, RZ pulse has a signal-to-noise ratio (SNR) gain which means a receiver sensitivity enhancement [30].

Figures 7 (a) and (b) show the autocorrelation traces of clock 4 after the RA-MPC and channel 4 after multicasting at the output of the HNLF at various Raman pump powers (P_r). Increasing P_r causes a decrease in the pulsewidths of the WDM clock pulses, therefore, those of multicast signals were compressed. For instance, the clock pulse at channel 4, whose pulsewidth was 20.00 ps at the input of the RA-MPC, was compressed to 12.17 ps, 7.89 ps, and 4.68 ps as P_r was set to 0.42, 0.62, and 0.82 W, respectively. Pulsewidth of the multicast signals was, therefore, decreased from 21.03 ps (without pulse compression) to 12.17, 7.89, and 4.68 ps at the output correspondingly. The pulsewidth waveforms as


(a) 21.03 ps, without compressing

(c) 7.89 ps, P_r=0.62 W

(b) 12.17 ps, P_r=0.42 W

(d) 4.68 ps, P_r=0.82 W

time (30 ps/div.)

Fig. 8 The eye patterns of converted RZ signal at channel 4 with various pulsewidths (a) 21.03 ps (without pulse compression), (b) 12.17 ps, (c) 7.89 ps and (d) 4.68 ps corresponding to Raman pump power of 0.42, 0.62 and 0.82 W, respectively.

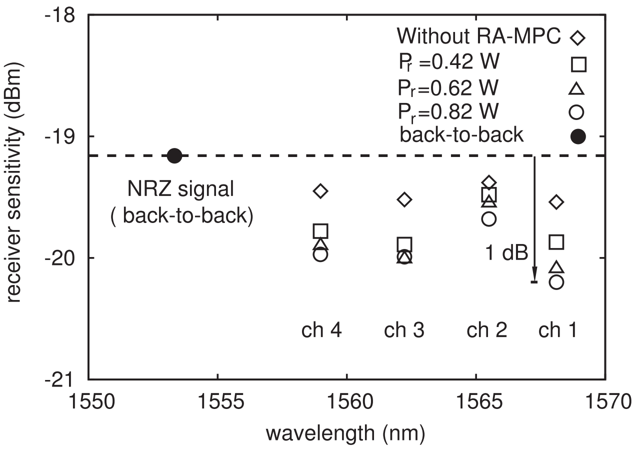


Fig. 9 Receiver sensitivities at BER = 10^{-9} of all RZ signals output compared to the NRZ signal in cases of without using RA-MPC and with using the RA-MPC at the Raman pump power of 0.42, 0.62 and 0.82 W.

shown in solid lines were well fit to sech^2 function as shown in dash lines. The similar characteristics were also obtained for the remain channels with different pulsewidths. Figure 8 shows eye patterns of the multicast signal channel 4 in the cases without compression (in Fig. 8 (a)), and with compression at P_r of 0.42 W, 0.62 W, and 0.82 W (in Figs. 8(b), (c), and (d)). Due to the limited bandwidth of the sampling oscilloscope with 30 GHz bandwidth, the eye patterns of these RZ signals were observed almost invariant.

We have also measured the receiver sensitivity at BER of 10^{-9} of the multicast signals at different pulsewidths by changing the Raman pump power. We also realized NRZ-to-RZ waveform conversion and wavelength multicasting in case of without using the RA-MPC to compare with the quality of the converted-compressed RZ data signals using the RA-MPC. Sensitivities at BER of 10^{-9} of all RZ outputs at different pulsewidths of around 21.03, 12.17, 7.89, and 4.68 ps compared to that of the back-to-back NRZ signal were shown in Fig. 9. The small variations among sensitivities of the converted RZ signals at four output were achieved and the best sensitivity of RZ signal at channel 1 was about 1 dB better than the sensitivity of the NRZ signal when the Raman pump power was set to 0.82 W. The results indicate that the receiver sensitivites of compressed RZ data signals are better than those of the uncompressed RZ data signals. It has been shown in [28], [30], [31] that the receiver sensitivity can be enhanced for shorter pulse RZ compared to longer one, even if the receiver bandwidth is only 0.7 times data rate. Our BER measurement system employs an optical receiver that has a receiver bandwidth of around 8 GHz. The pulsewidth of our all converted RZ signals was tunable from around 21.03 to 12.17, 7.89, 4.68 ps leading to the negative power penalties compared to the input back-to-back NRZ signal. The shorter pulsewidth of the multicast signal made the receiver sensitivity become smaller compared with that of longer one. The obtained results in the improvement of the receiver sensitivity for the shorter pulsewidth signals were consistent with the previous works [9], [28], [30], [31], and have also been discussed in the previous part for Fig. 6. However, it can be seen that there was a small difference in the amount of receiver sensitivity improvement when the pulsewidth was compressed to 4.68 ps in comparison with the other longer pulsewidths. The reason is that as such a short pulsewidth range, the signal bandwidth is excessively wider than the receiver bandwidth, causing the less impact of pulsewidth on the receiver sensitivity. This dependence of pulsewidth on the receiver sensitivity has been analyzed in details in [31].

5. Conclusion

We have successfully demonstrated 4x10 Gb/s pulsewidth-tunable NRZ-to-RZ and wavelength multicasting using the RA-MPC with a large pulsewidth tuning range which is from around 4.68 to 12.17 ps by changing the Raman pump power in the range between 0.82 and 0.42 W. Error-free operations are achieved for all multicast channels with negative power penalties compared with error-free operation of the NRZ signal and small variation among converted RZ channels at BER of 10^{-9}. The waveform conversion and wavelength multicasting without using the RA-MPC have also been done. In comparison with the converted RZ signals without compression, the better receiver sensitivities of the compressed RZ signals with using the RA-MPC were obtained. Our scheme is potential to increase more RZ data channels due to the flexibility of more multiwavelength compressed RZ clocks by the RA-MPC.

Acknowledgments

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References

[1] H.N. Tan, M. Matsuura, T. Katafuchi, and N. Kishi, "Multi-channel optical signal processing with wavelength-waveform conversions, pulsewidth tunability, and signal regeneration," Opt. Express, vol.17, no.25, pp.22960–22973, Dec. 2009.

[2] Y. Yu, X. Zhang, and D. Huang, "Pulse-width tunable multi-channel NRZ-to-RZ conversion with duplicate output," Opt. Commun., vol.285, no.2, pp.109–112, Jan. 2012.

[3] G.K.P. Lei and C. Shu, "4 × 10 Gb/s wavelength multicasting with tunable NRZ-to-RZ pulse format conversion using time- and wavelength-interleaved pulses," Opt. Commun., vol.285, no.10-11, pp.2525–2529, May 2012.

[4] S. Liu, S. Fu, M. Tang, P. Shum, and D. Liu, "4 × 10 Gb s^{-1} wavelength multicasting with tunable NRZ-to-RZ format conversion using nonlinear polarization rotation in an SOA," Laser Phys., vol.23, no.8, 085103, Aug. 2013.

[5] L.H. Sahasrabuddhe and B. Mukherjee, "Light-trees: Optical multicasting for improved performance in wavelength-routed networks," IEEE Commun. Mag., vol.37, no.2, pp.67–73, Feb. 1999.

[6] G.N. Rouskas, "Optical layer multicast: Rationale, building blocks, and challenges," IEEE Netw., vol.17, no.1, pp.60–65, Jan./Feb. 2003.

[7] S.B. Jun, K.J. Park, H. Kim, H.S. Chung, J.H. Lee, and Y.C. Chung, "Passive optical NRZ-to-RZ converter," Proc. Optical Fiber Communication Conference (OFC), ThN1, Feb. 2004.

[8] G.-W. Lu, L.-K. Chen, and C.-K. Chan, "Novel NRZ-to-RZ format conversion with tunable pulsewidth using phase modulator and interleaver," Proc. Optical Fiber Communication Conference (OFC), JThB32, 2006.

[9] Q. Nguyen-The, M. Matsuura, H.N. Tan, and N. Kishi, " All-optical NRZ-to-RZ data format conversion with picosecond duration-tunable and pedestal suppressed operations," IEICE Trans. Electron., vol.E94-C, no.7, pp.1160–1166, July 2011.

[10] H.N. Tan, M. Matsuura, and N. Kishi, "Transmission performance of a wavelength and NRZ-to-RZ format conversion with pulsewidth tunability by combination of SOA- and fiber-based switches," Opt. Express, vol.16, no.23, pp.19063–19071, Nov. 2008.

[11] Y. Yu, X. Zhang, J.B. Rosas-Fernández, D. Huang, R.V. Pemty, and I.H. White, "Single SOA based 16 DWDM channels all-optical NRZ-to-RZ format conversions with different duty cycles," Opt. Express, vol.16, no.20, pp.16166–16171, Sept. 2008.

[12] H.N. Tan, M. Matsuura, and N. Kishi, "Parallel WDM signal processing in mixed NRZ and RZ transmission networks using a single optical gate with multiple switching windows," IEEE J. Sel. Topics Quantum Electron., vol.18, no.2, pp.926–934, March/April 2012.

[13] L.-S. Yan, S.M.R.M. Nezam, A.B. Sahin, J.E. McGeehan, T. Luo, Q. Yu, and A.E. Willner, "Performance optimization of RZ data format in WDM systems using tunable pulse-width management at the transmitter," J. Lightwave Technol., vol.23, no.3, pp.1063–1067, March 2005.

[14] M. Matsuura, N. Kishi, and T. Miki, "Performances of a widely pulsewidth-tunable multiwavelength pulse generator by a single SOA-based delayed interferometric switch," Opt. Express, vol.13, no.25, pp.10010–10021, Dec. 2005.

[15] T.-R. Gong, F.-P. Yan, D. Lu, M. Chen, P. Liu, P.-L. Tao, M.-G. Wang, T.-J. Li, and S.-S. Jian, "Demonstration of single channel 160-Gb/s OTDM 100-km transmission system," Opt. Commun., vol.282, no.17, pp.3460–3463, Sept. 2009.

[16] C. Yu, L.-S. Yan, T. Luo, Y. Wang, Z. Pan, and A.E. Willner, "Width-tunable optical RZ pulse train generation based on four-wave mixing in highly nonlinear fiber," IEEE Photon. Technol. Lett., vol.17, no.13, pp.636–638, March 2005.

[17] Z.Q. Hui, "All-optical NRZ-to-RZ format conversion with dual channel wavelength multicasting functions exploiting cross-phase modulation in a dispersion-flattened nonlinear photonic crystal fiber," Laser Phys., vol.21, no.7, pp.1219–1229, July 2011.

[18] L.-S. Yan, A.-L. Yi, W. Pan, B. Luo, and J. Ye, "Simultaneous NRZ-to-RZ format conversion and one-to-six error-free channel multicasting using a single pump in a highly nonlinear fiber," Opt. Express, vol.18, no.20, pp.21404–21409, Sept. 2010.

[19] T. Richter, E. Palushani, C. Schmidt-Langhorst, R. Ludwig, L. Molle, M. Nolle, and C. Schubert, "Transmission of single-channel 16-QAM data signals at Terabaud symbol rates," J. Lightwave Technol., vol.30, no.4, pp.504–511, Feb. 2012.
[20] H.N. Tan, T. Inoue, T. Kurosu, and S. Namiki, "Transmission and pass-drop operations of mixed baudrate Nyquist OTDM-WDM signals for all-optical elastic network," Opt. Express, vol.21, no.17, pp.20313–20321, Aug. 2013.
[21] E.P. Ippen, D.J. Eilenberger, and R.W. Dixon, "Picosecond pulse generation by passive mode locking of diode lasers," Appl. Phys. Lett., vol.37, no.3, pp.267–269, Aug. 1980.
[22] I. Ogura, H. Kurita, T. Sasaki, and H. Yokoyama, "Precise operation-frequency control of monolithic mode-locked laser diodes for high--speed optical communication and all-optical signal processing," Opt. Quant. Electron., vol.33, no.7-10, pp.709–725, July 2001.
[23] Q. Nguyen-The, H.N. Tan, M. Matsuura, and N. Kishi, "All-optical WDM-to-OTDM conversion using a multi-wavelength picosecond pulse generation in Raman compression," IEEE Photon. Technol. Lett., vol.24, no.24, pp.2235–2238, Dec. 2012.
[24] H.N. Tan, Q. Nguyen-The, M. Matsuura, and N. Kishi, "Reconfigurable all-optical OTDM-to-WDM conversion using a multiwavelength ultrashort pulse source based on Raman compression," J. Lightwave Technol., vol.30, no.6, pp.853–863, March 2012.
[25] Q.N.Q. Nhu, Q. Nguyen-The, H.N. Tan, M. Matsuura, and N. Kishi, "Parametric NRZ-to-RZ wavelength multicasting with pulsewidth tunability using Raman amplification multiwavelength pulse compressor," 2014 International Topical Meeting on Microwave Photonics/The 9th Asia-Pacific Microwave Photonics Conference (MWP/APMP), pp.276–279, Oct. 2014.
[26] G.P. Agrawal, "Effect of intrapulse stimulated Raman scattering on soliton-effect pulse compression in optical fibers," Opt. Lett., vol.15, no.4, pp.224–226, Feb. 1990.
[27] A. Bogris and D. Syvridis, "Regenerative properties of a pump-modulated four-wave mixing scheme in dispersion-shifted fibers," J. Lightwave Technol., vol.21, no.9, pp.1892–1902, Sept. 2003.
[28] A. Sano, Y. Miyamoto, T. Kataoka, and K. Hagimoto, "Long-span repeaterless transmission systems with optical amplifiers using pulse width management," J. Lightwave Technol., vol.16, no.6, pp.977–985, June 1998.
[29] T. Matsuda, A. Naka, and S. Saito, " Comparison between NRZ and RZ signal formats for in-line amplifier transmission in the zero-dispersion regime," J. Lightwave Technol., vol.16, no.3, pp.977–985, March 1998.
[30] P.J. Winzer and A. Kalmar, "Sensitivity enhancement of optical receivers by impulsive coding," J. Lightwave Technol., vol.17, no.2, pp.171–177, Feb. 1999.
[31] M. Pauer, P.J. Winzer, and W.R. Leeb, "Bit error probability reduction in direct detection optical receivers using RZ coding," J. Lightwave Technol., vol.19, no.9, pp.1255–1262, Sept. 2001.

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