Wavelength Multicasting of RZ-DPSK Signal with Tunable Pulsewidth Using Raman Amplification Pulse Compressor

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***Abstract*—We have demonstrated a 4x10 Gb/s RZ-DPSK wavelength multicasting using Raman amplification-based compressor with adjustable pulsewidth down to around 7.89 ps. Bit-error-rate at 10^{-9} of multicast signals are achieved with low power penalties.**

Keywords: fiber optics and optical communication; optical signal processing; four-wave mixing; signal compression; distributed Raman amplification.

1. Introduction

All-optical wavelength multicasting is one of the potential candidates to implement light trees which support point-to-multipoint connections directly at the physical layer and improve flexibility of wavelength-routed networks [1][2]. Recently, differential phase-shift-keying (DPSK) signal is widely used in high bit-rate optical communication systems owing to its larger robustness to fiber nonlinearities and also owing to its better receiver sensitivity compared with on-off-keying signal [3]–[6]. Wavelength multicasting of the return-to-zero (RZ)-DPSK signal has been experimentally demonstrated in nonlinear devices in a lot of researches [7]–[9]. On the other hand, from the results in [10]–[12], it is unquestionable that the transmission performances of communication links are strongly dependent on the pulsewidth of the RZ signals due to the influences of dispersion and nonlinearities of fibers and characteristics of optical receivers. Integration of pulsewidth tunability in wavelength multicasting is, therefore, particularly desirable to provide flexibility for system performance optimization and network reconfigurability through pulsewidth management. However, the tunable picosecond-pulsewidth for the multicast RZ-DPSK signal has not been demonstrated so far. The demand of short pulsewidth signals for high bit-rate signals is crucial to increase the overall capacity of optical networks. It is, therefore, necessary that the process of wavelength multicasting is implemented simultaneously with the replication of the same input data to different wavelengths at the network interfaces for the optical multicasting with the flexibility tunable pulsewidth [13].

For the first time, we have realized a 4x10 Gb/s pulsewidth-tunable RZ-DPSK wavelength mulitcasting using a Raman amplification-based pulses compressor (RA-PC) and a highly nonlinear fiber (HNLF). We employ the RA-PC to compress RZ-DPSK signal with the pulsewidth adjustably which is then used to interact with two continuous wave (CW) pump signals by four-wave mixing (FWM) effect in the HNLF. Pulsewidths of the multicast signals were, therefore, compressed down to around 12.5 and 7.89 ps after wavelength multicasting. Error-free operations at two pulsewidths of multicast RZ-DPSK signals are achieved with low received power variations between them. Power penalties compared to the input back-to-back signal before compressing are less than 3 dB at bit error rate (BER) of 10^{-9}. The improved feature of the proposed scheme compared to the previous reported setup [7]–[9] is on the use of RA-PC to get RZ-DPSK signal compression with a widely pulsewidth picosecond tuning range. Thus, the 4x10 Gb/s pulsewidth-tunable RZ-DPSK wavelength mulitcasting is achieved.

2. Operation principle

The concept of RZ-DPSK signal wavelength multicasting with pulsewidth tunability using RA-PC and HNLF is shown in Fig. 1(a). It consists of the RA-PC, which is a pulse compressor, and a HNLF-based FWM switch. The RA-PC which is based on adiabatic soliton compression technique takes advantage of high power amplification for RZ-DPSK signal using a distributed Raman amplification (DRA). The RZ-DPSK signal is fundamental soliton pulse which is amplified adiabatically in an anomalous dispersion fiber. Therefore, the pulsewidth of the RZ signal 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 RZ-DPSK signal after compression.

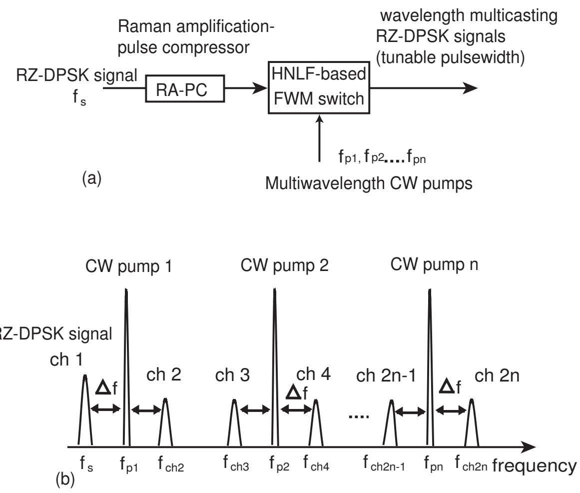

Figure 1. (a) Operation principle of wavelength multicasting of the pulsewidth-tunable RZ-DPSK signal using RA-PC.
(b) Schematic spectrum of RZ-DPSK signal wavelength multicasting after four-wave mixing.

In the HNLF-based FWM switch, the RZ-DPSK signal with pulsewidth tunability generated from the RA-PC is nonlinearly interacted with multiwavelength CW signals over non-degenerated FWM. In the non-degenerate FWM process, multiawavelength continuous wave (CW) pumps at frequencies of f_{p1}, f_{p2},... and f_{pn} interact with the RZ-DPSK data signal at frequency f_s in the HNLF. The input RZ-DPSK signal is multicast to many RZ signals with different wavelengths at FWM products. The wavelengths of these new generated FWM signals are generally given by the following expressions [14]

$$f_{ch2} = 2f_{p1} - f_s = f_{p1} + \Delta f \quad (1)$$

For n$\geq$ 2

$$f_{ch2n-1} = f_{pn} + f_s - f_{p1} = f_{pn} - \Delta f \quad (2)$$

$$f_{ch2n} = f_{pn} + f_{p1} - f_s = f_{pn} + \Delta f \quad (3)$$

where Δf is the frequency separation between the CW pump 1 and RZ-DPSK signal ($\Delta f = f_{p1} - f_s$), n is the number of CW pump. After FWM, the electric field amplitude of the multicast outputs is governed by following expression [14]

$$E_{ch2}(t) = {E_{p1}}^2 E_s^*(t) \quad (4)$$

$$E_{ch2n-1}(t) = E_{p1}^* E_s(t) E_{pn} \quad (5)$$

$$E_{ch2n}(t) = E_{p1} E_s^*(t) E_{pn} \quad (6)$$

where * denotes the complex conjugate of the electric field amplitude. Thus, the new RZ-DPSK signals are generated simultaneously in the multi-pump scheme resulting in both phase-conjugating and non-phase-conjugating wavelength multicasting. The FWM products have the data of the input RZ-DPSK signal and the pulsewidths of these converted RZ-DPSK signals inherit those of the RZ-DPSK signal at the input of the HNLF-based FWM switch. The pulsewidths of the RZ-DPSK signal at the input of this switch are compressed by continuously increasing the Raman pump power of the RA-PC. Therefore, the tunable pulsewidths of these wavelength converted RZ-DPSK signals are obtained.

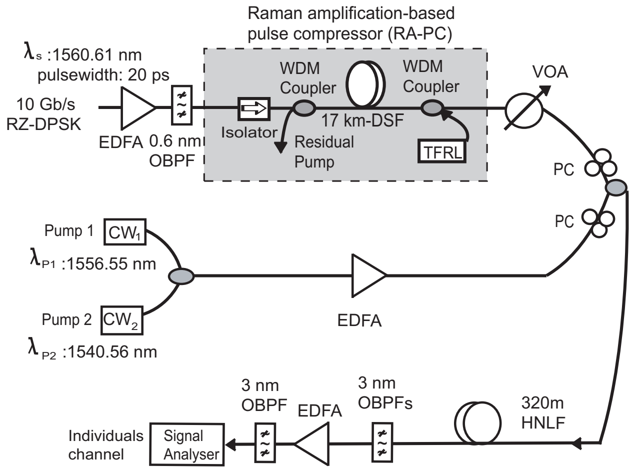

Figure 2. Experimental setup of the RZ-DPSK wavelength multicasting with pulsewidth tunability using Raman amplification-based pulse compressor (RA-PC).

3. Experimental setup

The experimental setup of the RZ-DPSK signal wavelength multicasting width pulsewidth tunability using RA-PC and HNLF is shown in Fig. 2. A 10 Gb/s RZ-DPSK signal at wavelength of 1560.61 nm with the pulsewidth of 20 ps is amplified by an erbium-doped fiber amplifier (EDFA) followed by an 0.6 nm optical band pass filter (OBPF) and then is sent to the RA-PC. The RA-PC consists of a 17 km dispersion-shifted fiber (DSF) with a tunable fiber Raman laser (TFRL) operating at 1462 nm in counter-propagation using a wavelength division multiplexing (WDM) coupler. The DSF has anomalous dispersion of 3.8 ps/nm/km, dispersion slope of 0.059 ps/nm^2/km at 1552 nm. The RA-PC which is based on adiabatic soliton compression technique takes advantage of the high gain of the Raman amplification. After the compression process, the RZ-DPSK signal with pulsewidth tunability generated from the RA-PC is nonlinearly interacted with two CW pump signals over non-degenerated FWM. The powers of the compressed RZ-DPSK signal and two CW pump signals are optimized to obtain good output waveforms and the largest FWM efficiency by an EDFA followed by an OBPF and a variable optical attenuation (VOA). Meanwhile, two polarization controllers (PCs) are used to optimize polarization state of both the CW pumps and compressed RZ-DPSK signal to maximize the interaction among these signals. The 320 nm HNLF has dispersion of -0.06 ps/nm/km at 1550 nm, dispersion slope of 0.023 ps/nm^2/km at 1550 nm, and nonlinear coefficient of 28 W^{-1}.km^{-1}. After wavelength multicasting process, the converted signals with tunable

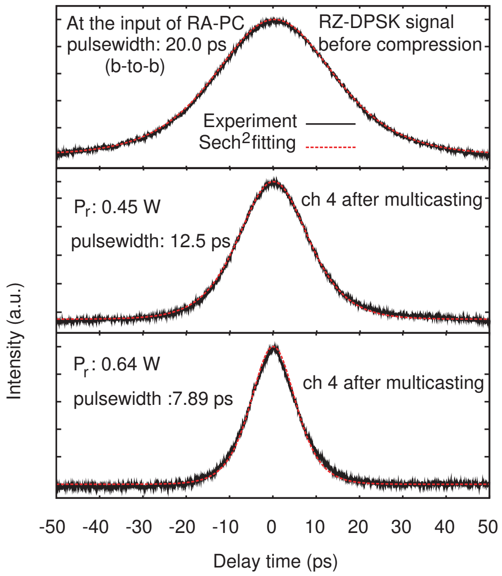

Figure 3. Autocorrelation traces of RZ-DPSK signal at the input of RA-PC (before compression) and the multicast signal at channel 4 (ch 4) with pulsewidths of 12.5 and 7.89 ps corresponding to the Raman pump power (P_r) of 0.45 and 0.64 W, respectively.

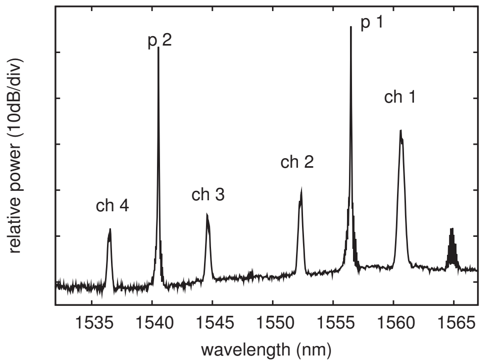

Figure 4. Spectrum at the output of HNLF corresponding to the Raman pump power of RA-PC (P_r) of 0.45 W.

pulsewidths are analyzed to get spectra, waveforms, eye patterns, and BER characteristics.

4. Experimental results and discussions

Fig. 3 shows autocorrelation traces of the RZ-DPSK signal with the pulsewidth of 20 ps at the input of the RA-PC and the multicast signal at channel 4 (ch 4) with pulsewidths of 12.5 and 7.89 ps. The increase of the Raman pump power (P_r) made the pulsewidth of RZ-DPSK signal outputs shorter over the adiabatic soltion compression. Therefore, the pulsewidths of the multicast signals were compressed to 12.5 and 7.89 ps corresponding to the Raman pump power of 0.45, 0.64 W, respectively. It is important to note that the pulse waveforms after wavelength multicasting were well-fit to sech^2 function and with low pedestals as shown in Fig. 3.

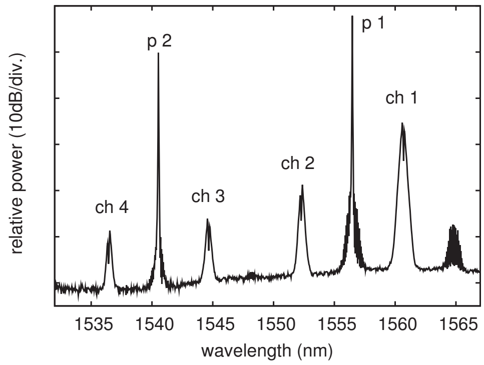

Figure 5. Spectrum at the output of HNLF corresponding to the Raman pump power of RA-PC (P_r) of 0.64 W.

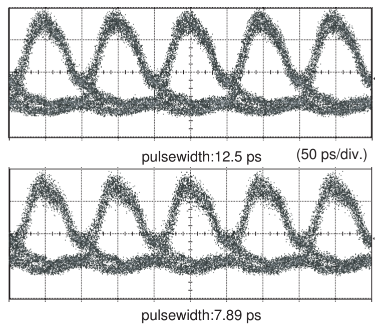

Figure 6. Eye patterns of demodulated multicast RZ-DPSK signal at channel 4 (ch 4) with different pulsewidths of 12.5 ps and 7.89 ps.

The spectra at the output of the HNLF are shown in Figs. 4 and 5 when the Raman pump power (P_r) was set to 0.45 and 0.64 W, respectively. The pulsewidth of the multicast RZ-DPSK signals in Fig.4 and 5 were around 12.5 ps and 7.89 ps, repesctively. Each channel of four multicast outputs with at the wavelength of 1560.61 nm (channel 1), 1552.52 nm (channel 2), 1544.53 nm (channel 3), and 1536.61 nm (channel 4), respectively was individually filtered for obtaining the eye patterns, pulsewidths and BER characteristics. Our proposal method offers an advantage in that the number of output channels are double that of the input CW pumps with the converted pulsewidth-tunable RZ-DPSK signals.

The clear-opened eye patterns of the demodulated RZ-DPSK signal at channel 4 (1536.61 nm) after wavelength multicasting with the two pulsewidths of 12.5 ps and 7.89 ps are also shown in Fig. 6. Due to the limited bandwidth of the sampling oscilloscope with 30 GHz bandwidth, the eye patterns of this RZ-DPSK signal with these two pulsewidths were observed almost invariant. To investigate the successful demonstration of the compression and wavelength multicasting processes, the BER characteristics of the multicast RZ-DPSK signals with different pulsewidths were measured as a function of received power as shown in Figs. 7 and 8. At each value of the Raman pump power, the receiver power of

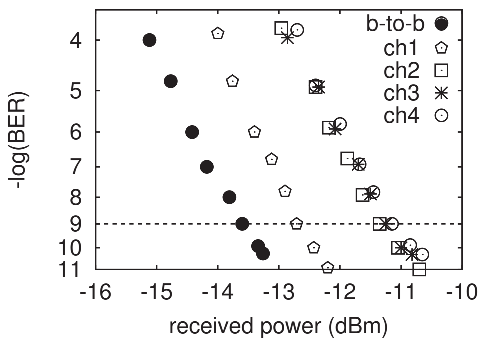

Figure 7. BER characteristics of multicast RZ-DPSK signals with the pulsewith around of 12.5 ps at the Raman pump power (P_r) of 0.45 W

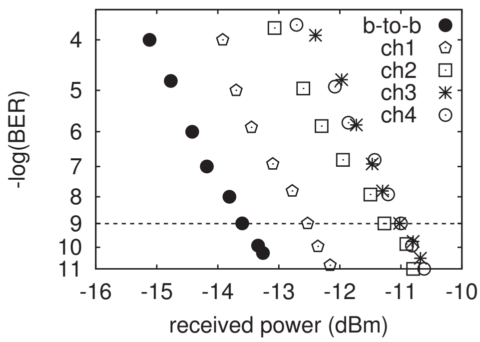

Figure 8. BER characteristics of multicast RZ-DPSK signals with the pulsewith around of 7.89 ps at the Raman pump power (P_r) of 0.64 W

channel 1 was the best and the receiver power of channel 2 was very slightly better than those of channels 2 and 3. Main concerns would be noise in FWM process and differences in power, and polarization of CW pump signals. There were very small differences in amount of received power of each channel signal with these two different pulsewidths. For instance, at channel 4, the receiver power of RZ-DPSK signal with the pulsewidth of 12.5 ps was 0.15 dB larger than that of RZ-DPSK signal with the pulsewidth of 7.89 ps. The results indicate that the quality of multcast signals is maintained through the pulsewidth tuning process.

5. Conclusion

A 4x10 Gb/s pulsewidth-tunable RZ-DPSK wavelength multicasting using RA-PC with pulsewidth range from around 7.89 ps to 12.5 ps by changing only the Raman pump power. The tunable pulsewith-short multicast RZ-DPSK signal is satisfied in generating higher bit rate signals up to 80 Gb/s. Moreover, it is desirable to provide flexibility for system performance optimization through pulsewidth management. Our proposed scheme is flexibly located along the transmission line such as inline wavelength multicasting. Error-free operations for all multicast signals at BER of 10^{-9} with low power penalties of less than 3 dB and small power variations among outputs. Good performance with the waveforms of pulsewidths which are well-matched with sech^2 function is obtained. Multiple pumps using non-degenerated FWM offers the advantage in that the number of output channels are double that of the CW pumps. By arrangement the frequency separations among CW pumps and RZ-DPSK signals, we could get multicast signals with different located frequencies. Our scheme is also potential to increase more outputs by using more CW pump signals.

References

[1] G. N. Rouskas et al., "Optical layer multicast: rationale, building blocks, and challenges," IEEE Network, vol.17, no.1, pp.60–65, 2003.

[2] L. H. Sahasrabuddhe et al., "Light-trees: Optical multicasting for improved performance in wavelength-routed networks," IEEE Commun. Mag., vol.37, no.2, p.67-73, 1999.

[3] C. Xu et al., "Differential phase-shift keying for high spectral efficiency optical transmissions," IEEE J. of Sel. Topic in Quant. Electron., vol.20, no.2, pp.281–293, 2004.

[4] A. H. Gnauck et al., "Optical phase-shift-keyed transmission," J. of Lightwave Technol., vol.23, no.1, pp.115–130, 2005.

[5] W. A. Atia et al., "Demonstration of return-to-zero signaling in both OOK and DPSK formats to improve receiver sensitivity in an optically preamplified receiver," in IEEE Lasers and Electro-Optics Society 12th Annual Meeting, paper TuM3, vol.1, 1999.

[6] A. H. Gnauck at el., "Demonstration of 42.7-Gb/s DPSK receiver with 45 photons/bit sensitivity," IEEE Photon. Technol. Lett., vol.15,no.1, pp.99-101, 2003.

[7] M. P. Fok et al., "Performance investigation of one-to-six wavelength multicasting of ASK-DPSK signal in a highly nonlinear bismuth oxide fiber," J. of Technol. Lightwave, vol.27, no.15, pp.2953–2957, 2009.

[8] Y. Dai et al., "Polarization-insensitive wavelength multicasting of RZ-DPSK signal based on four-wave mixing in a photonic crystal fiber with residual birefringence," in Proc. of of Optical Fiber Communication Conference and Exposition (OFC), paper OWP7, 2010.

[9] C.-S. Bres et al., "320 Gb/s RZ-DPSK data multicasting in self seeded parametric mixer," in Proc. of Optical Fiber Communication Conference and Exposition (OFC), pp.OThC7, 2011.

[10] L.-S. Yan et al., "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, 2005.

[11] M. Matsuura et al., "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, 2005.

[12] C. Yu et al., "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, 2005.

[13] Q. N. Q. Nhu et al. "Waveform conversion and wavelength multicasting with pulsewidth tunability using Raman amplification multiwavelength pulse compressor," IEICE Trans. on Electron., vol.E98-C, no.8, pp.824–831, 2015.

[14] A. E. Willner et al., "All-optical signal processing," J. of Technol. Lightwave, vol.32, no.4, pp.660–680, 2014.