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One to Six Wavelength Multicasting of RZ-OOK Based on Picosecond-Width-Tunable Pulse Source with Distributed Raman Amplification*

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SUMMARY All-optical 1-to-6 wavelength multicasting of a 10-Gb/s picosecond-tunable-width converted return-to-zero (RZ)-on-off-keying (OOK) data signal using a wideband-parametric pulse source from a distributed Raman amplifier (DRA) is experimentally demonstrated. Width-tunable wavelength multicasting within the C-band with approximately 40.6-nm of separation with various compressed RZ data signal inputs have been proposed and demonstrated. The converted multicast pulse widths can be flexibly controlled down to 2.67 ps by tuning the Raman pump powers of the DRA. Nearly equal pulse widths at all multicast wavelengths are obtained. Furthermore, wide open eye patterns and penalties less than 1.2 dB at the 10^{-9} bit-error-rate (BER) level are found.

key words: *fiber optics and optical communications, all-optical signal processing, four-wave mixing (FWM), pulse compression, multicast conversion*

1. Introduction

Optical networks such as core, metro, and access networks are categorized by their size. Each network configuration can be differentiated based on the parameters such as transmission distance, capacity, and services provided. The demand for high-speed optical signals requires flexibility and transparency to process data channels in a cost-effective manner [1]. One attractive feature based on wavelength-division multiplexing (WDM) is multicasting, which transmits data with simultaneous wavelength conversions and provides WDM network functionality [2]–[4]. Furthermore, a return-to-zero (RZ) modulation format is more robust to nonlinear impairments and crosstalk compared with a non-RZ (NRZ) encoding [5], [6]. We consider the multicasting scheme as shown in Fig. 1 with the interconnections among nodes that uses the concept of a light tree or light path in a wavelength-routed network, which is connected from one source node to several destination nodes [7]. Node B acts as an intermediate node that links terminal node A to multicasting-destination nodes C, D, and E. At Node B, the switch functions to provide optical signal amplification, wavelength conversion, and signal regeneration. In any installed transmission network, the signal pulse width reacts differently under fiber-dispersion condition, nonlinearities, and receiver characteristics because transmission spans L_{BC}, L_{BD}, and L_{BE} are not the same. Individually and separately processing the channel and adding a new function afterward to circumvent this problem are not feasible because of network complexity and cost. Recent studies in Refs. [8] and [9] have revealed that the transmission performance of different RZ pulse durations showed the existence of an optimum pulse duration for each transmission span with a particular cumulative dispersion. In addition, demonstrations of such necessity have been reported in Refs. [10] and [11] and proven to be beneficial in optimizing system performance. Therefore, the requirement to implement a practical function that flexibly shortens and manipulates width-tunable converted signals over the changes in the transmission distance is necessary. This flexibility also supports wider bandwidth requirements. Different approaches to the on-off-keying (OOK) modulation format have been proposed to achieve wavelength multicasting [12]–[17]. However, no study has presented a practical width-tunable management by deploying such requirement functionality. Thus, the ultimate goal is to simultaneously provide flexibility and tunability in the terminal equipment to optimize the transmission performance of WDM multicast channels via pulse-width management in a wide-wavelength operation range.

One method to fulfill all requirements is to provide widely tunability to the data pulse width launched into an RZ multicast system. Numerous techniques such as supercontinuum, mode-locked lasers, and electro-absorption modulator have been used to generate ultra short optical pulses with high repetition rate [18]–[20]. Nevertheless,

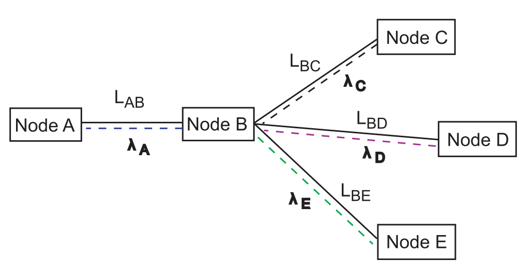

Fig. 1 Multicasting scheme with interconnections among nodes.

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the key limitation associated with these methods is that the achievable duration of the generated pulses is limited. As an alternative method, pulse compression of an RZ data signal by adjusting the distributed Raman amplifier (DRA) gain while offering power amplification in a flexible manner as demonstrated in Ref. [21] is required. Although width-tunable signals have been individually accomplished in this subject before, to the best of our knowledge, sufficient multicast conversion over a wide-wavelength operation has not yet been considered. Replication a single data channel into several different wavelengths of the WDM multicast channels can easily be implemented through four-wave mixing (FWM) in a nonlinear medium. FWM in a highly nonlinear fiber (HNLF) is the best choice among other media owing to its advantageous properties such as fast nonlinear response and high conversion efficiency [22]. By adjusting the Raman pump power inside a DRA, simultaneous results in multicast conversion with width-tunable output can possibly be obtained. Further, because a compressed RZ data signal is used as a pump signal in the FWM process, the multicast idler signals will follow the shape of the compressed RZ data with pedestal-free and narrower width output.

In this paper, based on our obtained preliminary results [21], [23], we present the extension of our studies to provide details of a simple implementation of an all-optical multicasting conversion method with tunability in both wavelength and picosecond pulse-width range. The multicasting scheme is realized using a fiber-based single-parametric-gate HNLF and a DRA pulse compressor. The simultaneous replication of six channel-multicast signals with width-tunable output is successfully carried out by tuning the Raman pump power as a control device up to 0.55 W. The current study contributes to our knowledge by providing the following meritorious factors: (1) the DRA acts as both a tunable pulse width compressor for multicast signals and an amplifier, (2) the adjustable wider range can be implemented for pedestal-free picosecond width-tunable 6 × 10 Gb/s multicast-converted data controlled down to 2.67 ps (seven-fold) and can exhibit approximately the same high quality performance, and (3) transparent operation around 40.6-nm multicast conversion can be achieved over the entire C band with a low power penalty. Producing more than six channel-multicast copies may be possible by adding more probe signals in the HNLF.

2. Operational Principle and Experimental Setup

The operational principle of the proposed scheme is shown in Fig. 2. It is based on a parametric process in a highly nonlinear fiber (HNLF) between RZ-OOK width-adjustable compressed data and six CW probes. In the first stage, a DRA is used. The DRA consists of a constant dispersion fiber, such as a dispersion-shifted fiber (DSF) and does not require any special fibers [24], [25]. The system operation is based on adiabatic soliton compression, which has a high-power output and a width-tunable pulse in the picosecond range by tuning the Raman pump power (P_r). The DRA

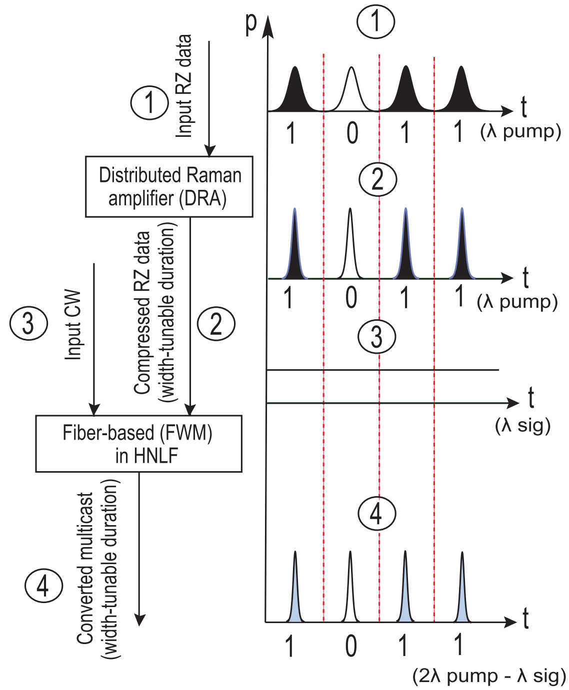

Fig. 2 Operational principle of 1-to-6 wavelength multicasting with picosecond-width-tunable output signals.

acts as a pulse width controller and as an amplifier. Input RZ data is a fundamental soliton (N = 1) of the sech^2 pulse; it is adiabatically amplified in the DSF as the P_r value is increased. Based on the arrangement from the equation in Ref. [26], the relationship between the pulse width τ_{FWHM}, the peak power of the fundamental soliton pulse $P_{N=1}$, and the chromatic dispersion D can be obtained as

$$\tau_{FWHM} \propto \sqrt{\frac{D}{P_{N=1}}} \tag{1}$$

From relation (1), an increase in the soliton peak power $P_{N=1}$ would result in the reduction of pulse width τ_{FWHM}. Thus, it is possible to have flexibility in the picosecond width-tunable output converted RZ data signal from the DRA. Using the combination of strong input pump data produced by the DRA at a wavelength λ_{pump} with several probe input CW signals λ_{sig} into HNLF, the FWM can be achieved. The duplicate multicast data signals will be generated at wavelengths $\lambda_{multicast} = 2\lambda_{pump} - \lambda_{sig}$. According to [27], [28] the multicasting signal power is proportional to the square of the input RZ data signal power, which acts as the pump of the FWM.

From the viewpoint of network node as shown in Fig. 1, the multicast conversion based on a parametric process in a highly nonlinear fiber (HNLF) between RZ-OOK width-tunable compressed data and six CW probes is performed at node B. An RZ-OOK signal from node A will be flexibly compressed by DRA that is located at node B. The transmission characteristics of the signal before node B was not performed in our studies because we mainly concentrate on demonstrating the DRA functionality for the multicast con-

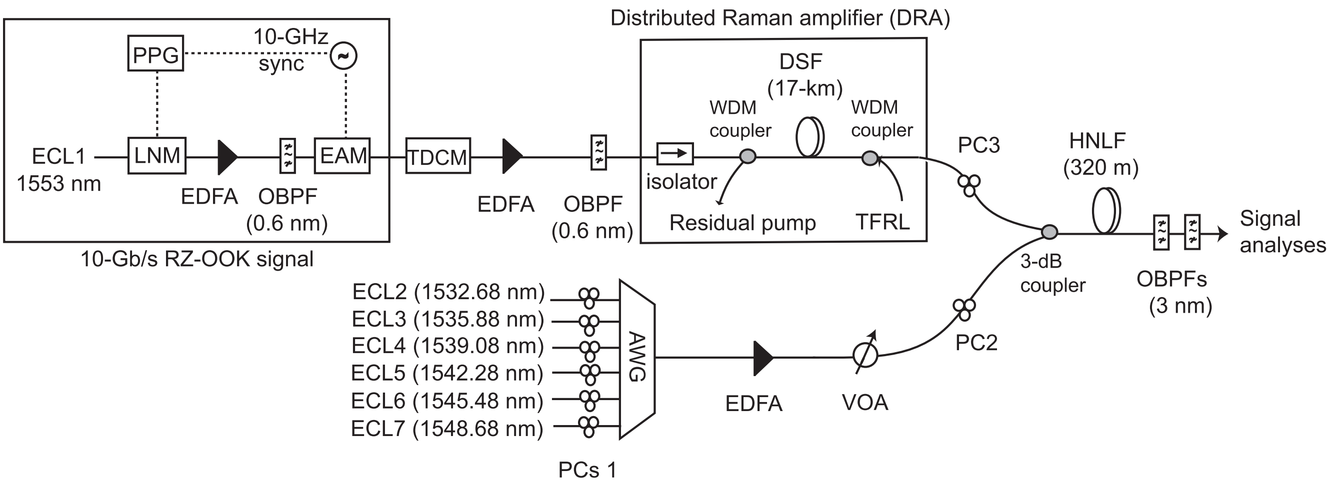

Fig. 3 Experimental setup of 1-to-6 wavelength multicasting with picosecond-width-tunable output.

version application. The experimental arrangement for the multicasting conversion is shown in Fig. 3. A 10-Gb/s non-return-to-zero (NRZ) data signal with 1553-nm wavelength was generated using an external cavity laser diode (ECL) and a $LiNbO_3$ modulator (LNM) driven by electrical data from a pulse pattern generator (PPG). The data signal was amplified and filtered by an erbium-doped fiber amplifier (EDFA) with an optical bandpass filter (OBPF). The data was converted into an RZ format by an electroabsorption modulator (EAM) driven by a 10-GHz synthesizer. A tunable dispersion-compensating module (TDCM) was used to suppress the frequency chirping induced by the EAM. An EDFA and an OBPF were used both to compensate for signal loss due to the EAM and to set the conditions for fundamental soliton power in the DRA. Based on the adiabatic soliton compression operation, the DRA that located at node B consisted of a 17-km dispersion-shifted-fiber (DSF) and a tunable fiber Raman laser (TFRL). The DSF had anomalous dispersion of 3.8 (ps/nm)/km, an a dispersion slope of 0.059 (ps/nm^2)/km at 1553 nm. The Raman pump wavelength was set to 1452 nm to promote high-quality compression performance. The pulse width of the RZ data signal was compressed as its peak power increased with the increment of the Raman pump power because the soliton condition was maintained in the DSF during amplification. The compressed RZ data acted as a pump signal. Six probes of CWs with a wavelength spacing of 400 GHz at a wavelength from 1548.68 to 1532.68 nm were generated and multiplexed with an array waveguide grating (AWG). Polarization controllers 1 (PCs 1) on each CW channel functionality are to maintain polarization orthogonality between that particular CW channel and the compressed RZ data signal. The power of each probe was set to the same value and amplified using an EDFA. Both the compressed input of the RZ data and the CWs were passed through a HNLF to generate the multicast products. The HNLF of 320 m in length had a zero dispersion wavelength of 1553 nm, a dispersion slope of 0.023 (ps/nm^2)/km, and a nonlinear coefficient of 28 $W^{-1} \cdot km^{-1}$. In a real system, an important parameter that needs to be concerned is polarization sensitivity. However, in order to obtain a high conversion efficiency for all the multicast channels, the polarization states of the input signal pump and CW probes of PC 2 and PC 3 need to be adjusted. If not, the conversion efficiency of the multicast channels will be low and may not be practical for a real system. Two OBPFs were used after the HNLF to isolate the FWM product and to remove amplified spontaneous emission (ASE) from the EDFA. The bandwidth of the OBPFs was 3 nm. The quality of the converted pulses was measured using an autocorrelator and a bit error rate tester (BERT) with a preamplified receiver.

3. Results and Discussion

The characteristics of the output data signal from the DRA were investigated using two 3-nm OBPFs for channel selection. The output optical spectra and the corresponding autocorrelation traces are shown in Figs. 4 (a) and (b), respectively. In Fig. 4 (b), the solid line shows the measured waveform and the circles show the sech^2 fitting waveform. As shown in the figure, the pulse width was compressed with an increment of the Raman pump power (P_r values), and the spectral width was broadened relative to the pulse compression. The input RZ data signal with a duration of 18 ps was significantly compressed to 12.4, 9.40, 4.23, and 1.87 ps as P_r was tuned to 0.35, 0.45, 0.55, and 0.60 W, respectively. The compressed pulses were well fitted by sech^2 functions in terms of both spectra and waveforms. The measured spectral bandwidth was 1.40 nm and the time-bandwidth product was 0.33, estimated at a P_r of 0.60 W, which shows that the pulse had a transform-limited sech profile. On the other hand, adiabatic soliton pulse compression in DRA provides a highly compressed pulse with very small pedestals. At a P_r value of 0.60 W, the calculated peak-to-pedestal ratio was 14 dB; this power value can potentially be used for flexible up to higher bit-rate data signals for optical time domain multiplexing (OTDM) or WDM networks [29], [30]. The BER curves of the converted RZ data at different P_r values

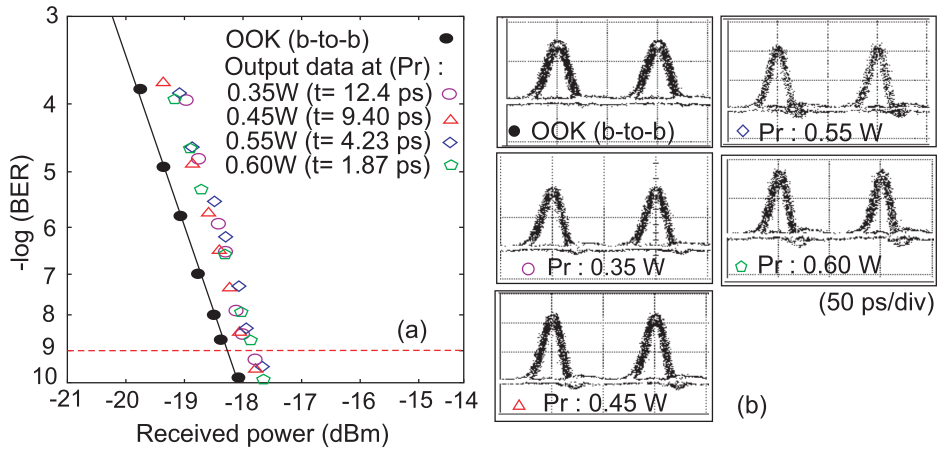

Fig. 5 (a) BER characteristics of the RZ-OOK signal before and after pulse compression at different tuning Raman pump powers. (b) Output eye patterns of the converted pulses for different P_r values.

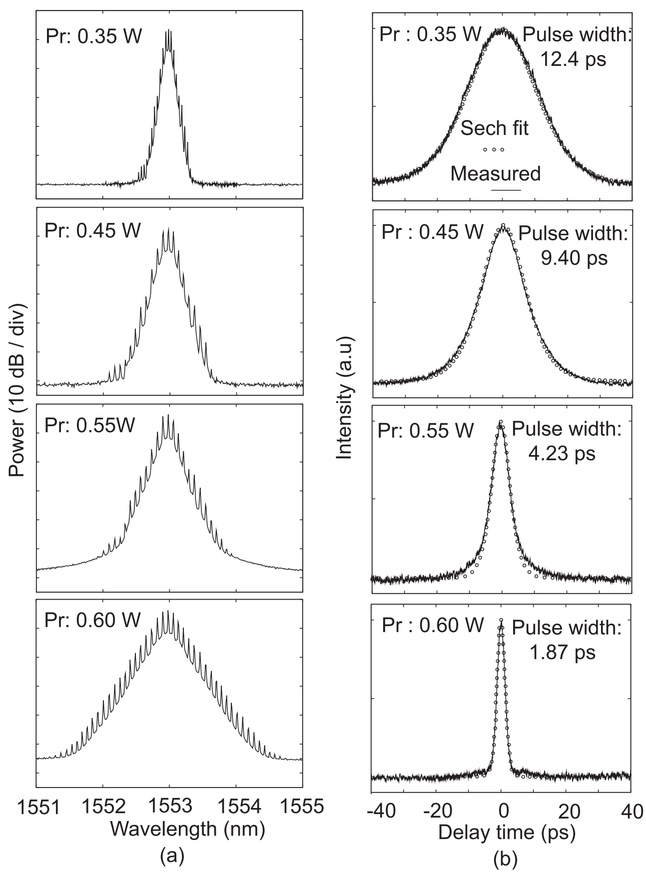

Fig. 4 (a) Spectrum and (b) autocorrelation traces of the data signal at P_r values of 0.35, 0.45, 0.55, and 0.60 W.

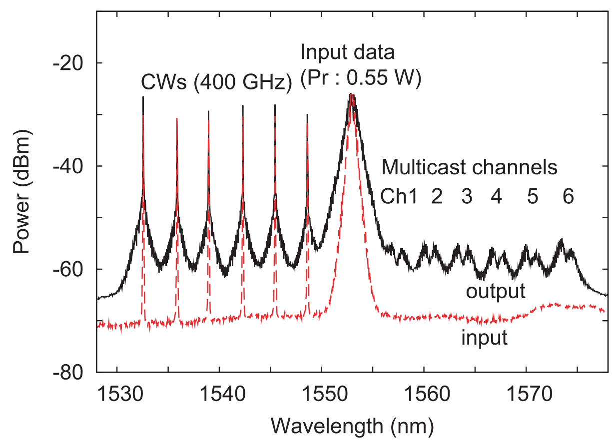

Fig. 6 FWM spectra of the input (dashed line) and output (solid line) at a P_r value of 0.0 and 0.55 W, respectively.

are plotted in Fig. 5 (a). We achieved error-free operation for all compressed RZ data with a small power penalty of less than 0.5 dB compared to the back-to-back input signal. In addition, approximately a 0.1 dB variation of sensitivity among the converted pulses at various P_r values was obtained. Figure 5 (b) shows the eye patterns of the compressed RZ data eye patterns for P_r values of 0.35, 0.45, 0.55, and 0.60 W, respectively. Even though the bandwidth of the employed electrical sampling oscilloscope was limited to 30 GHz, clear eye openings were observed. These openings indicate that the signals generated by the DRA achieved good performance and that they might be used as input data in multicasting applications.

Figure 6 shows the FWM spectra of 1-to-6 multicast channel conversion using the input data signal at a P_r of 0.55 W. The dashed and solid lines represent the input and output of the HNLF, respectively. Six input CWs probe channels at 1532.68 nm (Ch6), 1535.88 nm (Ch5), 1539.08 nm (Ch4), 1542.28 nm (Ch3), 1545.48 nm (Ch2), and 1548.68 nm (Ch1) interacted with the pump data at 1553 nm to yield six converted multicast channels. Six output channels with 400-GHz spacing were individually located at 1557.32 nm (Ch1), 1560.52 nm (Ch2), 1563.72 nm (Ch3), 1566.92 nm (Ch4), 1570.12 nm (Ch5), and 1573.32 nm (Ch6). Nearly the complete 40.6-nm conversion span was realized within our proposed scheme. Additionally, the converted spectral outputs of the 6×10 Gb/s WDM RZ data were broadened at the same time while incrementing the P_r value over the adiabatic soliton compression.

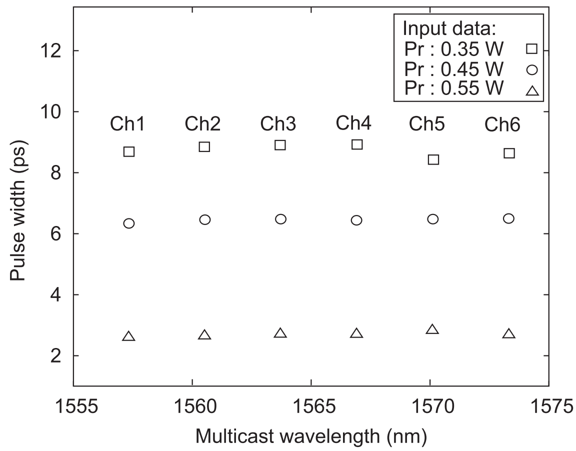

Fig. 7 Variations of wavelength and pulse width multicast channels for the input data signals at different P_r values.

Figure 7 plots the variations of the converted pulse width for three P_r values. The variations of the compressed pulse width were less than 0.1 ps for a constant P_r value. In addition, the multicast converted channel pulse widths were narrower than those of the input data signal. The multicast conversion channels were further quantified by autocorrelation trace measurement for channel 3 (Ch3) at three P_r values of input RZ data, as shown in Fig. 8. For example, at the P_r values of 0.35, 0.45, and 0.55 W, the converted multicast pulse widths were 8.42, 6.34, and 2.67 ps, respectively. The generated copies underwent pulse pedestal suppression and further pulse compression during the parametric process because of the quadratic pump and idler amplitude relation [28], [31]. These traces were well fitted by sech^2 fitting and had free pedestal pulses. The time-bandwidth product of the pulses in all cases was found to be less than 0.41. For example, the calculated time-bandwidth-product was 0.32 for the input data and the multicasting signal at P_r value of 0.55 W. This value was closer to the transform-limited value of the sech^2 pulse profile. Approximately seven-fold pulse compression was obtained from the input data and a P_r value of 0.55 W. These results show that high-quality multicast pulses were obtained using our proposed scheme.

Although the transmission performance after multicast signal is not demonstrated in this paper, it is expected that the experiment can be done using our proposed scheme with different transmission link. It should be noted that in any installed transmission network, the effect of dispersion is cumulative. In a single channel transmission without any dispersion compensation scheme [8], a narrower pulse width such as 2.67 ps is expected to be more sensitive to dispersion at longer transmission distance. In order to optimize the transmission performance under the circumstances of large cumulative dispersion, a wider pulse width up to 8.42 ps is possible. We believe that, with the combination between our proposed scheme and dispersion compensation module in the transmission link, longer achievable transmission distance can be obtained [10], [11]. Furthermore, the advantage of the pedestal free multicast signal at the pulse width

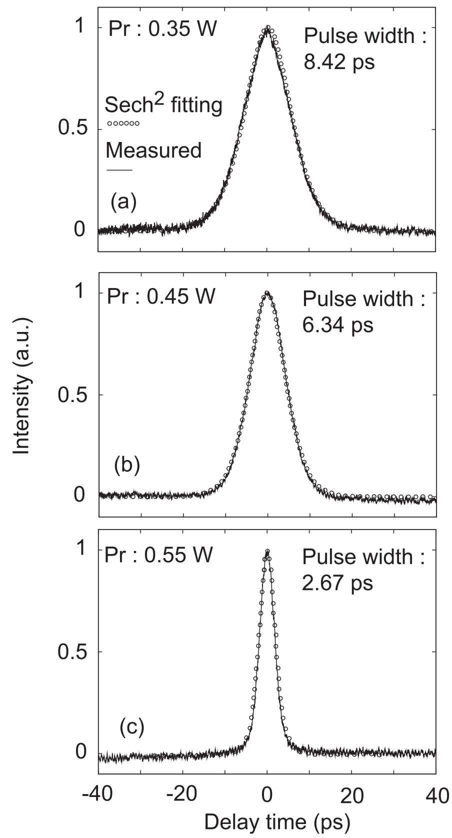

Fig. 8 Variations of pulse width with the converted multicast wavelength in channel 3 (Ch3) for the input data signal at P_r values of (a) 0.35 W, (b) 0.45 W and, (c) 0.55 W.

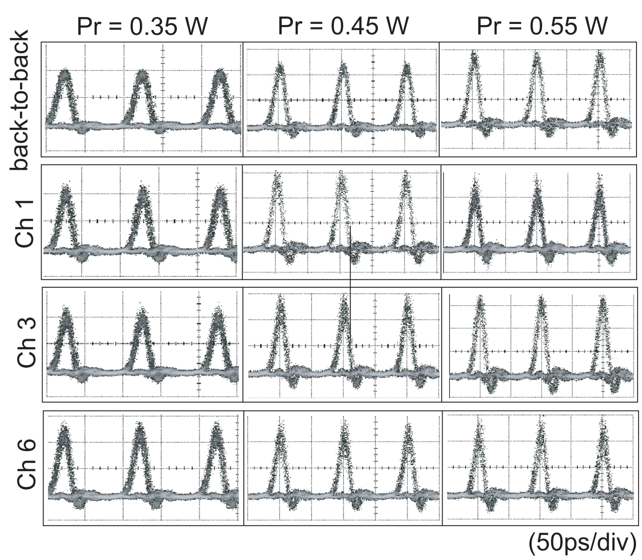

Fig. 9 Multicast channel eye patterns for 10 Gb/s RZ-OOK data input at P_r values of 0.35, 0.45, and 0.55 W

of 2.67 ps is capable of being multiplexed to high bit-rate up to 160 Gb/s.

Figure 9 shows three eye patterns, namely, Ch1, Ch3, and Ch6, compared to the back-to-back input data signal at different P_r values. Clear, widely opened eye patterns of

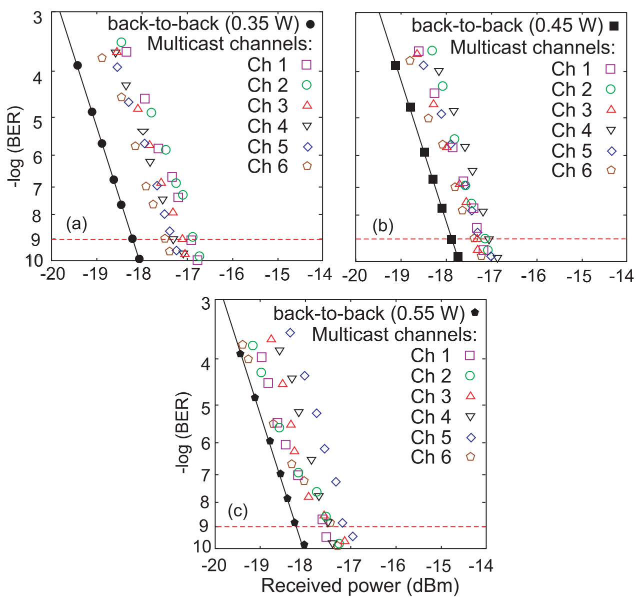

Fig. 10 BER curves of the back-to-back signal and multicast channel at different RZ-OOK pulse source at P_r values of (a) 0.35 W (b) 0.45 W, and (c) 0.55 W.

the multicasting signals were obtained for all channels at a high output quality. The system performance of the proposed wavelength and picosecond-width-tunable converted multicast scheme was further evaluated through BER measurements, as shown in Fig. 10. The signal qualities of the copied multicast signals were investigated at P_r values of 0.35 W, 0.45 W, and 0.55 W. This measurement was performed for a probe wavelength that varied from 1532.68 to 1548.68 nm, which is located in the C-band tuning range. Compared to the back-to-back signals, the converted multicast channels for P_r values of 0.35, 0.45, and 0.55 W had maximum power penalties of 1.2, 0.8, 1.0 dB, respectively. It is apparent that with shorter pulse widths, the converted multicast channel had a slightly higher power penalty. Overall, the power penalties of the converted multicast channels in the different cases mentioned above were not significantly different. The results indicated relatively uniform output performance; they are consistent with the eye pattern measurements. Using our proposed scheme, compressed RZ data from a DRA can be used as a high-speed data stream for multicasting and different applications in future optical networks.

4. Conclusion

We experimentally demonstrated a multicasting conversion method utilizing pulse data from a DRA and a fiber-based FWM switch in an HNLF. Simultaneous multicasting conversion from one to six channels for different cases of input data signals from the DRA was performed. Width-tunable pulse width and wavelength multicasting within the C-band with approximately 40.6 nm of separation for various compressed RZ data inputs have also been demonstrated. Penalties of less than 1.2 dB were obtained for all multicasting outputs from the DRA. Output pulse widths with a flexible tuning range down to 2.67 ps were achieved.

Acknowledgements

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