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Performance of an Inline RZ-DPSK Pulse Compression Using Raman Amplifier and Its Application in OTDM Tributary

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SUMMARY We experimentally investigate the performance of a distributed Raman amplifier (DRA)-based pulse compressor for a phase modulated signal. A 10 Gb/s return-to-zero (RZ)-differential phase shift keying (DPSK) signal is compressed to picosecond range after transmission. Pulsewidth is continuously compressed in a wide range from 20 to 3.2 ps by changing the pump power of the DRA while the compressed waveforms are well-matched with sech^2 function. Error-free operations at bit-error-rate (BER) of 10^{-9} are achieved for the compressed signals of various pulsewidths with low power penalties within 2.3 dB compared to the back-to-back. After the compression, the 10 Gb/s signal is used to generate a 40 Gb/s RZ-DPSK optical time division multiplexing (OTDM) signal. This 40 Gb/s OTDM signal is then successfully demultiplexed to 10 Gb/s DPSK signal by using an optical gate based on four-wave mixing (FWM) in a highly nonlinear fiber (HNLF).

key words: *fiber optics and optical communication, optical signal processing, four-wave mixing, pulse compression, Raman amplifier, pulsewidth tunability*

1. Introduction

All-optical pulse compression has been widely investigated as one of the key elements to enable ultra-high baud-rate signal overcoming electronics limits [1], [2]. High-quality short-width pulses in the order of a few picoseconds have been generated by using soliton compression based on the two main techniques. The first technique is that the dispersion value along the fiber is gradually decreased by using a dispersion-decreasing fiber (DDF) [3], [4], a step-like dispersion profiled fiber (SDPF) [5] or a comb-like dispersion profiled fiber (CPF) [6]. The second one is increasing the peak power of the soliton pulse during the pulse propagation in an anomalous dispersion fiber by an erbium-doped fiber amplifier (EDFA) [7] or a distributed Raman amplifier (DRA) [8]. The width of the compressed pulse could be managed in the picosecond range by tuning the optical amplifier gain. DRA-based pulse compressor (DRA-PC) has an advantage over other techniques thanks to the possibility of the high output power since the pulse is amplified during the compression. It has also been shown to be a powerful technique to compress multiwavelength pulses simultaneously [9], [10], which played an important role in the multiplexing exchange between optical time division multiplexing (OTDM) and wavelength division multiplexing (WDM) [11], [12] or for the integration of pulsewidth tunability waveform conversion and wavelength multicasting [13]. This technique enables us to compress the width of pulse down to a few of picoseconds with adjustable pulsewidth by controlling the Raman pump power of the DRA. The pulsewidth tunability is one of the solutions to optimize the performance in return-to-zero (RZ) data transmission due to its influence on signal behaviors under the impacts of chromatic dispersion, fiber nonlinearities during transmission [14]–[17].

To cope with the current evolution to more advanced modulation format for higher spectral efficiency [18], [19], it is attractive to investigate the performance of the pulse compressors for phase-modulated signals which have not been focused on previously reported works. Different from the compression of on-off-keying (OOK) signals [10], [20], phase noises induced during the pulse compression process would cause degradation on the phase information of the phase-modulated signals. Main concerns would be the residual phase noise due to imperfect dechirping of self phase modulation through the fiber dispersion, and the transfer of amplitude noise to phase noise due to the gain fluctuation [18], [19]. Therefore, the investigation on the possibility of the soliton pulse compressors, particularly DRA-PC, for phase-modulated signals is attractive due to their applications in highly spectral efficient optical networks. Practically, optical pulse compression is often used before data modulation at the transmitter to generate high symbol-rate signals. On the other hand, this paper investigates the possibility of the pulse compression for data-modulated signal, specifically for phase-modulated signal, for inline applications. A desirable application of the data pulse compression is to generate an aggregate high-speed data rate based on optical time multiplexing of many channels with lower speed data rates. In the case of the paper, a low data rate 10 Gb/s differential phase shift keying (DPSK) signal with long pulsewidth of 20 ps was compressed to picosecond range for generating a higher data rate optical time division multiplexing (OTDM) signal at 40 Gb/s. However, differ-

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ent from pulse compression before data modulation, pulse compression after data modulation is more challenging because the pulse compression process would directly affect the quality of the modulated data signal. This paper is, in fact, the first effort to directly compress the pulse of phase modulated signal for the aforementioned application.

In this paper, we experimentally investigate the performance of the DRA-PC for inline compression of a 10 Gb/s RZ-DPSK signal. The RZ-DPSK signal with the pulsewidth of 20 ps is transmitted over 30 km standard single mode fiber (SSMF) and then compressed down to a few of picoseconds by controlling the Raman pump power. Error-free operations at various pusewidths of 12, 7.0, and 3.2 ps are achieved with low power penalties within 2.3 dB compared to the back-to-back signal at the transmitter at bit-error-rate (BER) of 10^{-9}. To clearly investigate the quality of the compressed RZ-DPSK signal in higher speed applications, after the compression, the 10 Gb/s signal is used to generate a 40 Gb/s RZ-DPSK OTDM signal. This OTDM signal is then successfully demultiplexed to 10 Gb/s DPSK tributaries by using an optical gate based on four-wave mixing (FWM) in a highly nonlinear fiber (HNLF). The error-free operation of demultiplexed 10 Gb/s signal is obtained with a 1.2 dB-power penalty compared to the 10 Gb/s base-band compressed signal before multiplexing to 40 Gb/s OTDM signal.

2. Operation Principle and Experimental Setup

2.1 Operation Principle of RZ-DPSK Pulse Compression Using Distributed Raman Amplifier

The different feature of our proposed scheme compared to the previously reported setup [9]–[13], [20] is on the use of DRA-PC to investigate its performance for phase-modulated signal. The RZ-DPSK signal is fundamental soliton pulse, which is adiabatically amplified in an anomalous dispersion fiber by using the DRA. Since the energy of the pulse is increased by the amplification in the DRA, the soliton pulse, based on adiabatic soliton compression technique, is obtained. The fundamental soliton pulse with sech^2 function has a peak power [21]

$$\tau_{\mathrm{FWHM}} \sqrt{P_1} = 2.9\lambda^{3/2} \sqrt{|\, D \,|\, A_{eff}} \tag{1}$$

where τ_{FWHM}[ps], P_1[mW], λ [μm], D [ps/nm/km], $A_{eff}[\mu m^2]$ are the full width at half maximum of pulse considered as the pulsewidth of the pulse in practice, peak power of the fundamental soliton pulse, wavelength of pulse signal, dispersion coefficient, and effective core area of fiber, respectively. From Eq. (1), the relationship between the pulsewidth τ_{FWHM} and the peak power of the fundamental soliton pulse P_1 is described as follow.

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

From the relation (2), it could 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-DPSK signal is compressed when its peak power is larger by increasing the Raman pump power owing to the maintenance of the soliton condition during the amplification. By changing the Raman pump power, the pulsewidth of the RZ-DPSK signal is adjustable at the output of the DRA-PC.

2.2 Experimental Setup

The experimental setup of the inline RZ-DPSK signal compression that operates on the basis of adiabatic pulse compression in the DRA is shown in Fig. 1 (a). A 10 GHz seed pulse from a laser diode (LD) at a wavelength of 1560.61 nm is modulated by an electro-absorption modulator (EAM) driven by a 10 GHz synthesizer to generate an RZ clock. This RZ clock is amplified by an erbium-doped fiber amplifier (EDFA) followed by a 0.6 nm optical band pass filter (OBPF) and then sent to a DPSK modulator, which is driven by 10 Gb/s data with pseudorandom bit sequence of $2^{31} - 1$ from a pulse pattern generator (PPG). An RZ-DPSK signal with the pulsewidth of 20 ps is generated by this DPSK modulator. This RZ-DPSK signal is then amplified by an EDFA followed by a 0.6 nm OBPF. The PPG is synchronized with a 10 GHz synthesizer. After 30 km SSMF transmission, a tunable dispersion-compensating module (TDCM) is used to compensate dispersion of the RZ-DPSK signal. The DRA-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 WDM coupler. The parameters of DSF are shown as in Table 1. The DRA-PC, which is based on adiabatic soliton compression technique, takes advantage of the high gain of the DRA. After the compression process, the compressed RZ-DPSK signal with different pulsewdiths is analyzed to get the spectra, waveforms, eye patterns, and BER curves.

To investigate application of the compressed RZ-DPSK signals in generating a higher bit-rate signal, a 40 Gb/s OTDM stream based on the 10 Gb/s compressed RZ-DPSK signal is composed by a 4:1 bit-rate multiplexer. As shown in Fig. 1 (b), this 40 Gb/s OTDM signal is then demultiplexed by using FWM in a HNLF. The OTDM signal is then amplified by an EDFA followed by a 3 nm OBPF before sending to a demultiplexing gate. To generate a pulsewidth-short RZ clock which is applicable for demultiplexing the OTDM stream, an optical comb generator (OCG) is used. A continuous wave at a wavelength of 1551.33 nm from an LD is modulated in the OCG by 10 GHz clock from the PPG. An EDFA is used to compensate for OCG insertion loss. Two 1.0 nm OBPFs are centered at a wavelength of 1553.33 nm to engineer the OCG spectrum to obtain 10 GHz RZ clock with the pulsewidth of 3.5 ps. Polarization controllers (PCs) are used to optimize polarization state of both clock and data signal. This RZ clock at the wavelength of 1553.33 nm is set as a pump for FWM in the HNLF which is a demultiplexing gate. The parameters of the HNLF are shown in Table 2. Af-

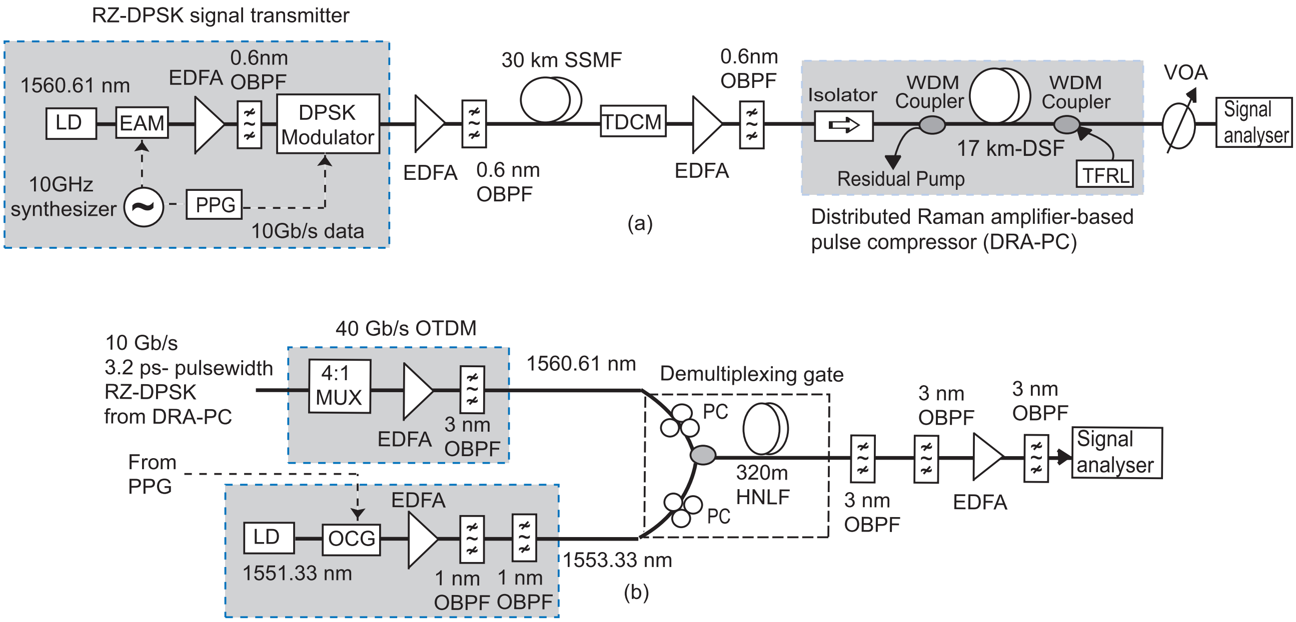


Fig. 1 (a) Experimental setup of the inline pulse compression for RZ-DPSK signal. (b) Experimental setup for multiplexing and demultiplexing of a 40 Gb/s OTDM signal based on the compressed RZ-DPSK signal.

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

ter the FWM process, the demultiplexed RZ-DPSK signal is filtered and amplified by OBPFs and an EDFA, respectively. This signal is analyzed to obtain waveform, eye patterns, and BER characteristic.

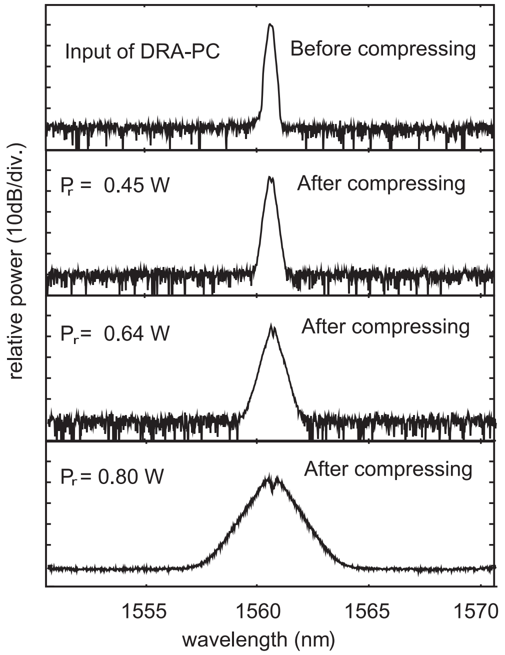


Fig. 2 The spectrum of RZ-DPSK signal at the input of DRA-PC (before compressing) and at the output of DRA-PC (after compressing) with various the Raman pump powers (P_r).

3. Experimental Results and Discussions

In our experiment, after transmission over 30 km SSMF and compensating dispersion induced along the transmission by the TDCM, the RZ-DPSK signal was sent to the DRA-PC. The compressed RZ-DPSK signal was obtained owning to the adiabatic soliton compression in the DRA. Fundamental soliton pulse is required for this compression technique. The dependence of the pulsewidth of the RZ-DPSK signal on its peak power is described in Eqs. (1) and (2). Figures 2 and 3 show the spectra and autocorrelation traces of the RZ-DPSK signal at the input of DRA-PC (before compressing) and at the output of DRA-PC (after compressing) with different pulsewidths corresponding to various values of the Raman pump power (P_r). The transmitted RZ-DPSK signal with the pulsewidth of 20 ps was compressed down to different pulsewidths of 12, 7.0 and 3.2 ps corresponding to the P_r of 0.45, 0.64, and 0.80 W, respectively. The spectra of the compressed signals became broader meanwhile

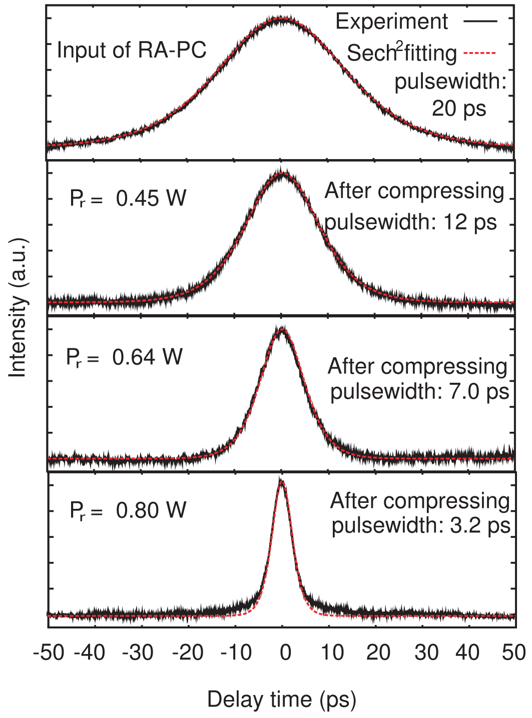


Fig. 3 Autocorrelation traces of RZ-DPSK signal at the input of DRA-PC (before compressing) and at the output of DRA-PC (after compressing) with different pulsewidths of 12, 7,0 and 3.2 ps corresponding to the Raman pump power (P_r) of 0.45, 0.64 and 0.80 W, respectively.

their pulsewidths became shorter when increasing P_r. The increase of P_r made the pulsewidth of RZ-DPSK signal output decrease owing to adiabatic soliton compression in the DRA. It is obviously seen that our compressed RZ-DPSK signals were the high-quality pulses since their spectra and pulsewidth waveforms were well-matched with sech^2 function with low pedestals, showing that the compressed pulses are suitable for high-speed signal applications. Comparison to another method that needed additional scheme to suppress the pedestal [4], the present technique was not associated with any signal regenerator to produce high-quality pulses. Figure 4 presents the eye patterns of the RZ-DPSK signals with pulsewidths of 12, 7.0, and 3.2 ps which were captured by a 30 GHz bandwidth electronics sampling oscilloscope. Although the oscilloscope had a limited bandwidth compared to the broad spectra of the compressed signals, the wide opening eye patterns indicate that impact such as patterns effect on the phase shift of signal during the pulse compression is negligible. The reason is that such effect is hard to observe due to the strong tolerance to phase noises of RZ-DPSK signal.

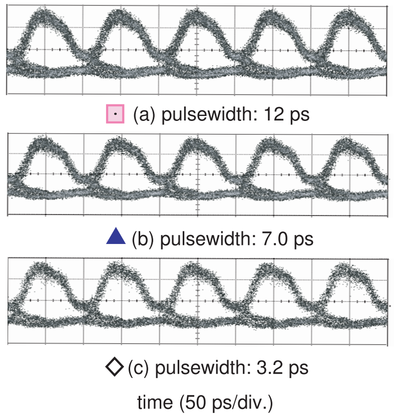


Fig. 4 Eye patterns of the demodulated RZ-DPSK signal after compressing to 12 ps (a), 7.0 ps (b), and 3.2 ps (c).

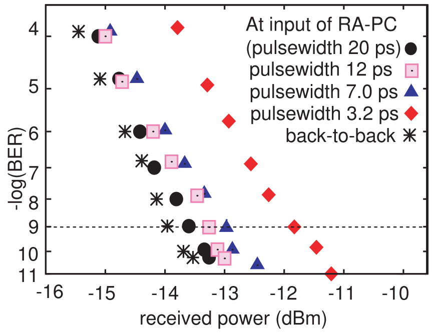


Fig. 5 BER characteristics of RZ-DPSK signal at the input and output of DRA-PC with different pulsewidths of 20, 12, 7,0 and 3.2 ps compared to the back-to-back signal at the transmitter.

To investigate whether phase noises induced during the pulse compression process would cause degradation on the receiver sensitivity of the compressed RZ-DPSK signal, the BER characteristics of the RZ-DPSK signals with many pulsewidths were measured as a function of received power. The BER characteristics of signals at the transmitter (back-to-back), at the input of the DRA-PC (after 30 km SSMF transmission with dispersion compensating), and at the output of the DRA-PC (after compressing) with the pulsewidths of 12, 7.0, and 3.2 ps are shown in Fig. 5. Power penalties within 2.3 dB were observed with respect to the back-to-back signal at the transmitter. The power variations among the compressed signals with different pulsewidths were less than 1.5 dB. The received power increased when the pulsewidth of the compressed signal was shorter. The primary reason is due to amplified spontaneous emission noise of the Raman amplifier. Similar results were also observed in the RZ-OOK signal compression at the transmitters in Refs. [10], [20] in which multiwavelength and single wavelength signals were compressed, respectively. The well-matched waveforms compared to sech^2 function and successful error-free operations at BER of 10^{-9} of the compressed RZ-DPSK signals evidently concluded that the phase-preserving was maintained through the compression process. To evaluate the performance of the compressor to shorter pulsewidth range, we continued increasing the Raman pump power and measured the autocorrelation traces as shown in Fig. 6. The high-quality waveforms of the compressed RZ-DPSK signal were also obtained with pulsewidth of 2.53 ps and 1.83 ps corresponding to P_r of 0.85 W and 0.9 W, respectively. However, a stable BER measurement was difficult to be achieved because the em-

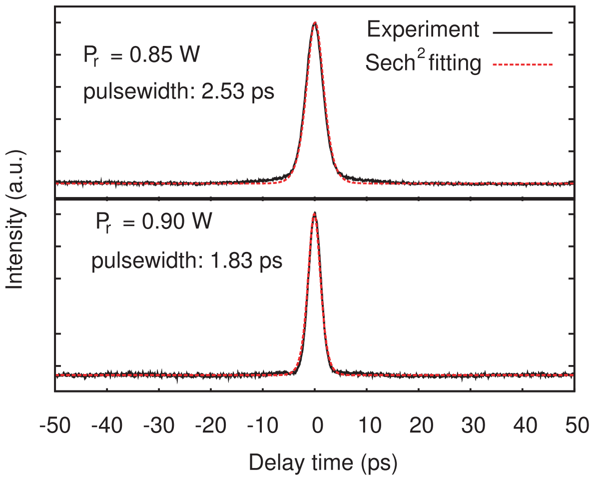


Fig. 6 Autocorrelation traces of compressed RZ-DPSK signal at pulsewidths of 2.53 and 1.83 ps.

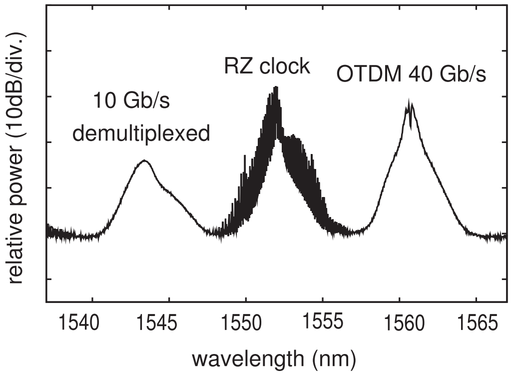
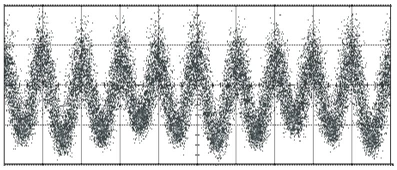
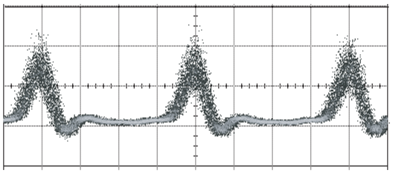


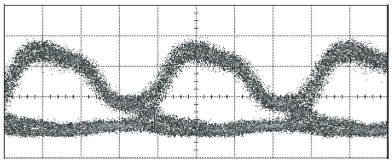
Fig. 7 Spectrum at the output of HNLF for demultiplexing 40 Gb/s OTDM signal.



(a) multiplexed 40 Gb/s OTDM signal



(b) demultiplexed RZ-DPSK before demodulation



(c) demultiplexed RZ-DPSK after demodulation

time (25ps/div.)

Fig. 8 Eye patterns of multiplexed 40 Gb/s OTDM signal (a), and its demultiplexed 10 Gb/s tributary before (b) and after (c) signal demodulation.

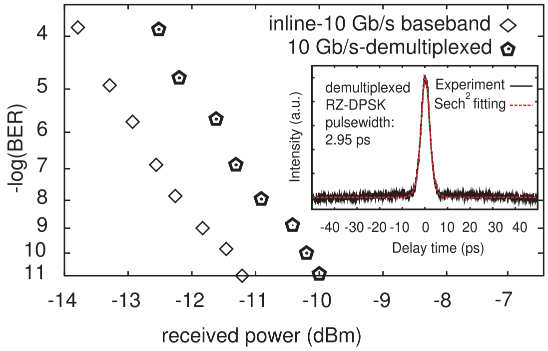


Fig. 9 BER characteristics of inline 10 Gb/s base-band signal and 10 Gb/s signal demultiplexed from 40 Gb/s OTDM tributary. Inset is an autocorrelation trace of demultiplexed RZ-DPSK signal with pulsewidth of 2.95 ps.

ployed 1-bit delay interferometer might not support demodulation of DPSK signals with such short pulsewidths.

To value the quality of the compressed RZ-DPSK signal in generating OTDM tributaries, we composed a 40 Gb/s OTDM signal from the 10 Gb/s compressed signal with the pulsewidth of 3.2 ps corresponding to the Raman pump power of 0.80 W and then demutiplexed this OTDM signal using the setup shown in Fig. 1 (b). The spectrum of 40 Gb/s OTDM signal demultiplexed by using FWM in the HLNF was shown in Fig. 7. The eye patterns of the multiplexed OTDM stream and its demultiplexed 10 Gb/s RZ-DPSK signal before and after signal demodulation are shown in Fig. 8 (a), (b) and (c), respectively. The BER curves of 10 Gb/s demultiplexed signal and the inline 10 Gb/s base-band compressed RZ-DPSK signal with the pulsewidth of 3.2 ps were shown in Fig. 9. The low power penalty and clear-opened eye patterns of the demultiplexed RZ-DPSK signal indicated that our proposed compressor could provide a new compression technique of phase-modulated signal based on the DRA. Thanks to the inline compressor, the 40 Gb/s OTDM signal based on the 10 Gb/s compressed RZ-DPSK signal could be generated at the intermediate node in which higher bit-rate signals are required. It is noticed that the compressor in our scheme could generate the RZ-DPSK signal with tunable pulsewidth with by controlling the Raman pump power, therefore, it is flexible for generating different higher bit-rate OTDM signals.

Finally, a discussion of soliton stability under various conditions was mentioned. To ensure the fundamental soliton pulse compression, the relation between the peak power and the pulsewidth of initial signal were described in Eq. (1). The interesting fact is that even if the values of the peak power and pulsewidth of initial signal is fluctuated around those of the fundamental soliton pulse described in Eq. (1), the signal compression also would be obtained. The reason is that the fundamental soltion could form for values of power and pulsewidth of initial pulse in these variations without hindering soliton formation [22]. Therefore, the pulse compression of the signals such as 33%, 50%, 66% RZ signals could also be obtained with different performances of compressed signals in terms of pedestal and compression factor. In case of this paper, resulting from dispersion compensation after transmission, the residual dispersion could affect the width and the shape of pulse. However, even if the shape of the pulse is not fitted with sech^2 function, the pulse compression could be obtained with different performance compared to the case of pulse compression of fundamental soliton signal [22].

In addition, scaling to the pulse compression of nPSK signal is interesting. However, it is challenging due to nonlinear interaction between the neighboring pulses when phase is randomly modulated in nPSK formats. For phase-modulated signal on the fiber-optic communication system, nonlinear interaction between the neighboring pulses in a single channel such as intra-channel cross-phase modulation (IXPM) and intra-channel four-wave mixing (IFWM) are one of the primary limiting factors for high bit-rate transmission [23]–[27]. The pulse compression is possible to nPSK signal with constant amplitude and OOK signal. It is not operational for multi-level signals like quadrature amplitude modulation (QAM), pulse amplitude modulation (PAM) signals due to the amplitude variation of these signals.

4. Conclusion

Performance of the pulse compressor based on adiabatic pulse compression in the DRA has been investigated for phase-modulated signal. An inline 10 Gb/s RZ-DPSK signal with an initial pulsewidth of 20 ps has been successfully compressed to 3.2 ps with a low penalty. In the wide pulsewidth tuning range, high compression performance is achieved with low power variations among compressed signals compared to the initial signal before compressing within 1.5 dB at BER of 10^{-9}. The pulsewidth waveforms are also well-matched with sech^2 fitting with low pedestals. Unquestionably, this proposed scheme is highly desirable to manage pulsewidths of RZ-DPSK signal on transmission for applications of generating higher bit-rate OTDM streams. Our scheme is potential in multiwavelength RZ-DPSK signals compression with pulsewidth tunability and in a variety of all-optical signal processing such as wavelength multicasting, wavelength conversion with pulsewidth compression in WDM and OTDM systems.

Acknowledgments

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