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Simultaneous Compression of Multiple Pulse Streams for All-Optical Serial/Parallel Data Exchanges

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Abstract– **We present our recent development of a simultaneous compression of multiple pulse streams utilizing the distributed Raman amplifier (DRA) for applications in serial/parallel high-speed data exchange. The optical clock pulse compression is operated based on adiabatic soliton compressor using DRA with pulsewidth tunable and multiple wavelength operations. We show an experimental demonstration of a simultaneous compression up to four 10 GHz clock pulse trains to picosecond pulsewidth range. The compressed multiple pulse streams are then used for applications in serial-to-parallel and parallel-to-serial data conversions which are one of key functionalities to realize all-optical wavelength/time-division trans-multiplexing in heterogeneous optical networks.**

Keywords– **Fiber optics communications, optical pulse compression, distributed Raman amplification, all-optical signal processing.**

1 Introduction

The growing demand for high bandwidth applications from end-users place an immense importance to construct ultrafast optical networks that offer ultrahigh speed connections among users without any optical-electronic-optical (O/E/O) devices [1]. Such networks are not necessary to stand alone, but can coexisted with conventional optical networks based on parallel wavelength-division multiplexed (WDM) channels. Compare to WDM, high-speed serial data channels using optical time-division multiplexing (OTDM) seems more suitable for optical local area networks (O-LANs) to form ultrafast OTDM channels due to a number of advantages [2]. Network management and control are conceptually simpler for a single serial data channel than parallel WDM channels. This trend is also true for realization of functionalities such as digital regeneration, digital buffering, switching, and logic. Furthermore, good-quality ultrafast serial data transmissions are possible within a range of a few hundred kilometers, depending on the bit rate, making it well suited for LANs, or even metropolitan area networks (MANs).

One of the key design issues is the development of an efficient optical interconnections capable of actively or dynamically switching optical paths from an ultrafast serial data LAN to its parallel end-users or to other WDM-based optical networks, and vice versa. The ultimate goal is to realize ultrafast photonic gateways providing flexible high-speed data exchanges between OTDM and WDM format signals, or the so-called serial/parallel data conversions. To provide a full access into every time-slots of the serial data stream and every wavelengths of parallel channels, in either directions of OTDM and WDM conversions, it requires a multi-wavelength ultrashort pulse source that performs as a central synchronization controlling system for the operation of the whole gateway. The multiwavelength pulse source providing pulsewidth tunability and wavelength reconfigurability would be highly desirable for various applications, e.g. WDM/OTDM trans-multiplexing or optical sampling, in future photonic networks.

So far, various approaches have been proposed to realize the multiple wavelength pulse generation. Straightforward methods to generate a multi-wavelength pulse would be to use a lithium niobate-based intensity modulator (LNM) or an electroabsorption modulator (EAM) modulating a continuous lightwave. However, such methods have a limit of the response speed mainly due to the bandwidth limit of the electrical driver circuits. Several researches have reported on generation of multi-wavelength lasing in an actively mode-locked ring laser based on erbium-doped fiber (EDF) [3] or semiconductor optical amplifier (SOA) [4]. Although a mode-locked laser can generate a high-quality ultrashort optical pulse, the use of its is restricted in terms of cost, stability, and wavelength tunability, regardless the number of wavelengths. Multi-channel pulse sources are also generated by using super-continuum (SC) [5], or nonlinear optical loop mirror (NOLM) [6]. The SC based on the interaction of multiple nonlinear effects such as self-phase modulation (SPM), four-wave mixing

(FWM) and stimulated Raman scattering (SRS) in a highly nonlinear fiber (HNLF). However, the technique using SC requires specialty nonlinear fibers and WDM filter for spectrum slicing. The pulsewidths of the generated pulse sources by using NOLM have been broaden due to the dispersion. Moreover, work in [7] have demonstrated a pulsewidth-tunnable multi-wavelength synchronized pulse generation utilizing a single SOA-based delayed interferometric switch. However, it is difficult to realize pulsewidth tunability in picosecond pulsewidth range.

Recently, adiabatic soliton compression techniques have attracted much attention to generate high-quality short-width pulse trains in the order of a few picoseconds. There are two well-known methods to generate an ultrashort optical pulse by using adiabatic soliton compression technique. The first method is gradually decreasing the dispersion value along the fiber by using dispersion profiled fibers, such as dispersion decreasing fiber (DDF) [8], comb-like dispersion profiled fiber (CDPF) [9], and step-like dispersion profiled fiber (SDPF) [10]. However, this technique requires special fibers with optimized dispersion profiles. As a simpler alternative, the second method is using a distributed Raman amplifier (DRA) to increase the peak power of the soliton pulse during the pulse propagation in an anomalous dispersion fiber [11–13]. This technique is possible to tune the pulsewidth of compressed pulse in the picosecond range by control of the Raman pump power. Recently, we have demonstrated the compression for multi-wavelength pulse trains at bit rate of 10 Gb/s by using a Raman amplification-based adiabatic soliton compressor [14] and its application to NRZ-to-RZ data format conversion with picosecond pulse [15, 16].

In this paper, we present our recent development of a simultaneous compression of multiple pulse streams utilizing the distributed Raman amplifier (DRA) for applications in serial/parallel high-speed data exchange. In Section 2, we describe a concept of parallel pulse generation using Raman amplification-based adiabatic soliton compressor (RA-ASC) with pulsewidth tunable and multiple wavelength operations. The DRA is experimentally demonstrated to compress simultaneously several 10 GHz clock pulse trains to picosecond pulsewidth range. The number of operating wavelengths is also investigated for the RA-ASC scheme. The compressed multiple pulse streams are then used for applications in serial-to-parallel and parallel-to-serial data conversions are presented in Sections 3 and 4, respectively. Section 5 summarizes the obtained results in this paper.

2 Multiwavelength Soliton Pulse Compression

2.1 Operation Principle

The RA-ASC operates on the basis of adiabatic soliton compression in distributed Raman amplifier (DRA). The adiabatic soliton compression is based on the relation the dispersion length ($L_D = T_0^2/\beta_2$) and the nonlinear length ($L_{NL} = 1/(\gamma P)$) when a fundamental soliton pulse is propagated in anomalous dispersion fiber ($\beta_2 < 0$) [17]:

$$\frac{T_0^2}{\beta_2} = \frac{1}{\gamma P}, \quad (1)$$

where P, T_0, β_2, and γ are the soliton peak power, pulsewidth of the soliton pulse, the group velocity dispersion coefficient and the Kerr coefficient of the fiber, respectively. From the relation (1), adiabatic soliton compression can be achieved via propagation along a dispersion profiled fiber such as a DDF, SDPF, or CDPF: the pulsewidth of the soliton pulse T_0 is reduced as the group velocity dispersion coefficient β_2 is made to properly decrease along the fiber. However, it is difficult to design and manufacture that dispersion profiled fiber. On the other hand, the pulsewidth of the soliton pulse T_0 is inversely proportional to the soliton peak power P in Equation (1). In our scheme (see Figure 1), we use the RA-ASC, which employs a dispersion-shifted fiber (DSF) and a wavelength tunable Raman fiber laser (TRFL) to obtain the adiabatic soliton compression. In the RA-ASC, the pulsewidth of the pulse could 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 perform the pulsewidth-tunable multi-wavelength pulse generation.

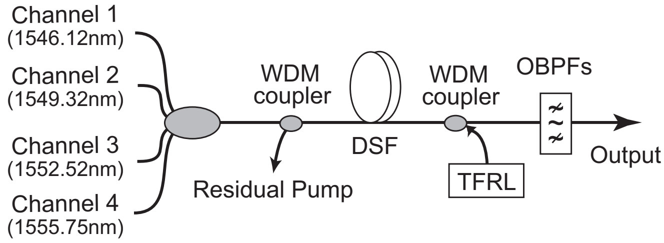

Figure 1. Schematic diagram of experimental setup for multiwavelength soliton pulse compression in DRA. DSF: dispersion-shifted fiber; TFRL: tunable fiber Raman laser; WDM: wavelength-division-multiplexing; OBPFs: optical bandpass filters.

2.2 Experimental Setups and Results

The experimental setup for multiwavelength pulse compression using RA-ASC is shown in Figure 1. To generate seed pulse trains of 10 GHz repetition rate for the multiwavelength pulse compression, continuous waves (CWs) at wavelengths: $\lambda_1 = 1546.12$ nm (channel 1), $\lambda_2 = 1549.32$ nm (channel 2), $\lambda_3 = 1552.52$ nm (channel 3), and $\lambda_4 = 1555.75$ nm (channel 4) from external-cavity lasers (ECLs) were simultaneously modulated by a 10 GHz clock in an electroabsorption modulator (EAM). It is important to ensure fundamental soliton powers of the seed pulse trains for adiabatic soliton compression. Before injected into the RA-ASC, the pulsewidth of the 10 GHz optical clock pulse trains were around 18 ps full width at half maximum (FWHM). The RA-ASC operates on the basis of adiabatic soliton com-

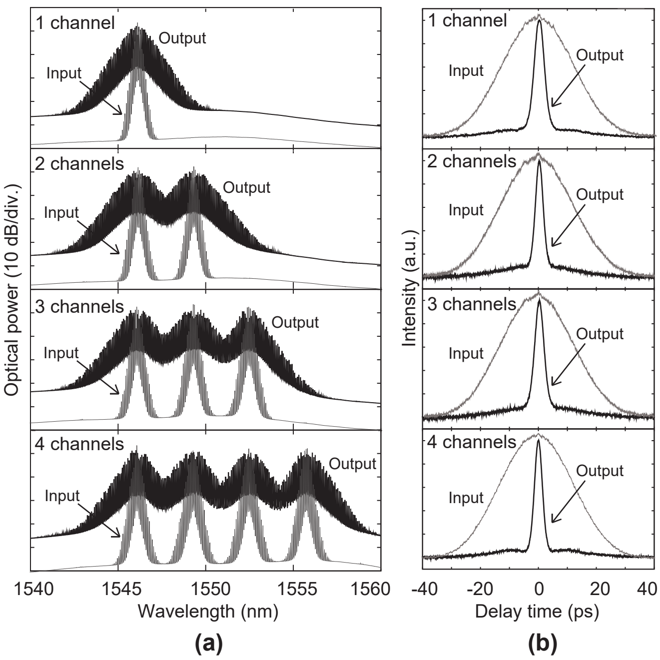

Figure 2. (a) Optical spectra at input/output of the RA-ASC, (b) autocorrelation traces of the channel 1 with different number of wavelength.

pression in DRA. In the RA-ASC, a 17 km dispersion-shifted fiber (DSF) was employed for adiabatic soliton compression technique. The second- and third-order dispersions of the DSF are 3.8 ps/nm/km and 0.059 ps/nm^2/km, respectively. The Raman pump signal generated by a tunable fiber Raman laser (TFRL) was injected into the counter-propagating direction by using a WDM coupler. The wavelength of TFRL can be tuned in the range between 1425 nm and 1495 nm. To achieve high quality compression performance, Raman pump wavelength was optimized for the seed pulse trains. The pulsewidths of the seed pulse trains are compressed as its peak power increases with the increase of the Raman pump power since the soliton condition is maintained in the DSF during the amplification. At the output of RA-ASC, the compressed pulses are filtered by two 3-nm optical bandpass filters (OBPFs) for pulse measurements.

To evaluate the quality of the compressed pulses, we used a a spectrum analyzer and an autocorrelator to measure the output spectra and waveforms. The obtained results are shown in Figure 2 for different cases of the number of operating wavelengths. Figure 2(a) shows the optical spectra of the input and output pulses of the RA-ASC for the number of operating wavelengths from 1 to 4. As can be seen in Figure 2(a), the optical spectra of the compressed pulses are well fitted to hyperbolic secant (sech^2) functions, suggesting the transform-limited property of the compressed pulses as well as the well operation of the RA-ASC. Compare with the input signals, the output spectra of all pulse channels were significantly broadened at the same time over the adiabatic soliton compression. The autocorrelation traces at channel 1 of the input/output pulses with different number of wavelength are shown in Figure 2(b). The input pulse trains with pulsewidths of 18.03 ps, 18.05 ps, 18.02 ps, and 18.03 ps at channel 1 are considerably compressed to 2.30 ps, 2.35 ps, 2.45 ps, and 2.60 ps for the number of wavelength of 1, 2, 3, and 4, respectively. It can be seen that over the adiabatic soliton compression, output spectra of the all input pulse trains were broadened at the same time while their pulsewidths were compressed.

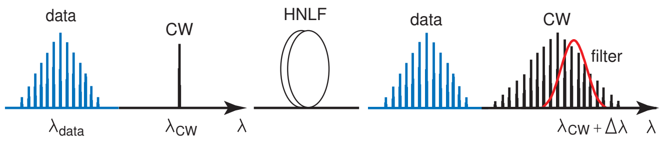

Figure 3. Operating principle of cross-phase modulation-based WDM-to-OTDM conversion. CW: continuous wave; HNLF: highly nonlinear fiber.

3 All-Optical Parallel-to-Serial Data Conversion

As presented in the Introduction, an all-optical parallel-to-serial data conversion is desirable in photonic gateways of optical networks employing different modulation and multiplexing formats. For instance, it could help to directly translate signal format from WDM low-data rate channels to one high-speed serial OTDM channel in optical domain without the use of low-speed O/E/O conversions [18]. So far, there have been many reports demonstrating parallel-to-serial conversion using a combination of high repetition rate monolithic hybrid mode-locked semiconductor laser (HML-SL) and a nonlinear optical loop mirror (NOLM) with total throughput of 33 Gb/s [19], gain compression in SOA achieved 350-700 Mbit/s [20], FWM in a HNLF for conversion from 2 $\times$ 10 Gb/s NRZ WDM parallel signals to a 20-Gb/s OTDM serial signal [21]. Another approaches are to use of time-domain optical Fourier transformation (OFT) for WDM-to-OTDM conversion with achieved 10-160 Gb/s has also been reported in [22]. However, optical networks will contain many data streams of different bit-rates. Therefore, a more flexible WDM-to-OTDM conversion is required for WDM and OTDM trans-multiplexing. To provide the parallel-to-serial conversion with flexible functions, the ultrashort pulses with tunable pulsewidth is useful. The adiabatic soliton compression techniques in distributed Raman amplification have attracted much attention due to the possibility to generate high-quality short-duration pulse trains in the order of a few picoseconds, which is crucial for the formation of WDM and OTDM networks. In this secsion, we experimentally demonstrate the conversion of 4 $\times$ 10 Gb/s WDM parallel channels to one OTDM serial channel by using RA-ASC.

3.1 Operating Principle

The concept of all-optical parallel-to-serial data conversion using RA-ASC is shown in Figure 3. It is comprised of a RA-ASC and highly nonlinear fiber

(HNLF) used as a nonlinear medium for cross phase modulation (XPM). A data signal from the RA-ASC and a continuous wave (CW) pump at the wavelength of λ_{CW} are launched together into a highly nonlinear fiber (HNLF). The data signal is amplified to achieve sufficient peak power in the data marks to cause XPM in the fiber. The XPM will act to broaden the spectrum of the CW probe, where a mark has copropagated with it through the fiber. In this way, spectral sidebands are generated on the probe signal through the modulation of the phase in the fiber. At the output of the HNLF, the sidebands on the CW probe can be extracted by spectral filtering, generating an amplitude-modulated signal from the phase modulation of the CW probe. This amplitude-modulated signal will thus form a wavelength-converted replica of the original data signal. The XPM phase shift of the probe is localized to the part of the probe that has co-propagated with a strong pulse through the fiber. In this way, if the strong pulses represent an ON-OFF keying (OOK) data signal, the phase modulation of the probe will represent the same data logic as the original pulses.

Since the WDM RZ data signals are shifted relative to each other in the time-domain, no interactions occur between them during the nonlinear process. Spectral sidebands are generated on the CW pump through the phase modulation due to the WDM RZ data signals. This phase modulation is then converted to intensity modulation by filtering the spectral sidebands at the wavelength of $\lambda_{CW} + \Delta\lambda$. In this way, the phase modulation of the CW pump will has the same data as the WDM RZ data signals. Therefore an OTDM signal can be achieved at the output of the XPM-based WDM-to-OTDM stage.

3.2 Experiment Setup

The experimental configuration of the conversion of 4×10 Gb/s WDM parallel channels to one 40 Gb/s OTDM serial channel is described in Figure 4. The combined four 10 Gb/s WDM RZ data signals at different wavelength were compressed by the RA-ASC as decribed in Section 2. Neighbour channels in the compressed WDM RZ data signals were shifted relative to each other by 25 ps. The compressed WDM RZ data signals were coupled with a CW pump at the wavelength of 1557.5 nm before injected into the parallel-to-serial data conversion. In the parallel-to-serial conversion, a 500 m long HNLF was used as an optical nonlinear medium for the XPM interaction between the compressed WDM RZ data signals and the CW pump. One of the spectral sidebands generated on the CW pump through XPM was extracted by two 3 nm optical bandpass filters (OBPFs) positioned at a center wavelength of $\sim$ 1560 nm. By this way, the converted 40 Gb/s serial data signal was achieved at the output of the filters. After filtering, the 40 Gb/s serial data signal was demultiplexed to 10 Gb/s base rate by using a FWM-based demultiplexing. The demultiplexed signals were then sent to a 10 Gb/s receiver for bit error rate (BER) measurement.

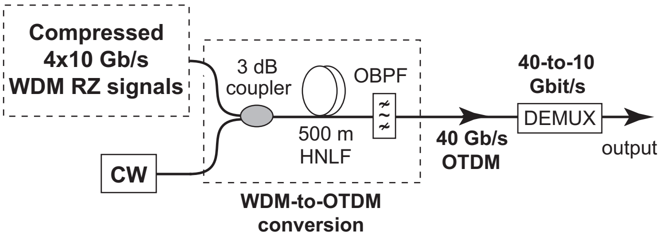

Figure 4. Schematic diagram of experimental setup for 4×10 Gb/s WDM parallel channels to one OTDM serial channel. CW: continuous wave, OBPF: optical bandpass filter, HNLF: highly nonlinear fiber, DEMUX: demultiplexing.

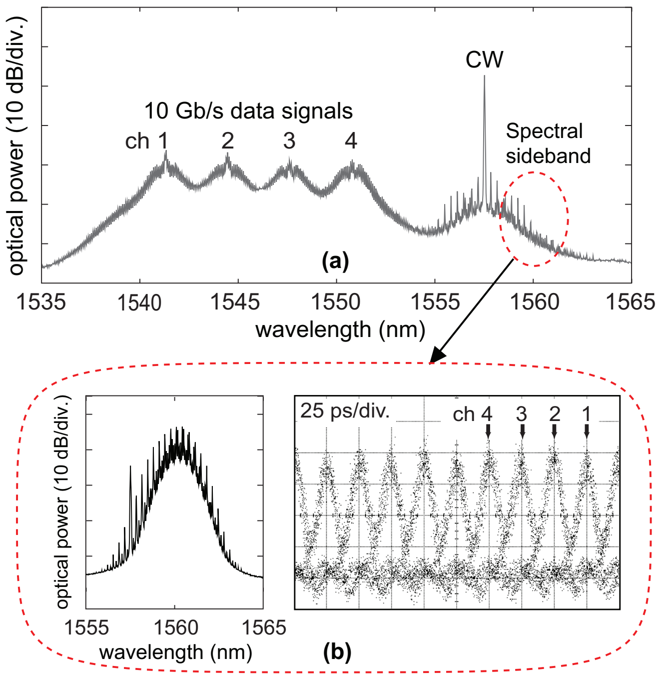

Figure 5. a) Optical spectra at the output of the HNLF, and (b) spectra and output eye pattern of 40 Gb/s OTDM serial data signal at the output of XPM-based HNLF stage.

3.3 Results and Discussion

Figure 5(a) shows the optical spectra at the output of the HNLF. The combined four 10 Gb/s WDM RZ signals can be seen on the left-hand side. The WDM RZ data signals modulated the phase of CW pump, leading to the broadened spectrum of the CW pump as seen on the right-hand side. Figure 5(b) shows the optical spectra and eye pattern of the converted 40 Gb/s serial data signal at the output of XPM-based HNLF stage after filtering at $\sim$1560 nm. The strong modulation peaks with 40 GHz spacing can be seen in the spectra at the output of XPM-based HNLF stage, showing a successful conversion to one 40 Gb/s OTDM serial data signal. The eye pattern of the 40 Gb/s serial data signal was captured by a 30 GHz-bandwidth digital sampling oscilloscope. Clear eye-opening in the Figure 5(b) shows that the present system successfully perform the conversion of 4×10 Gb/s parallel channels to one 40 Gb/s serial channel. Due to the limited resources, we could not show autocorrelation traces of the 40 Gb/s OTDM signal pulse at the time of this experiment. However, it is expected that the 40 Gb/s

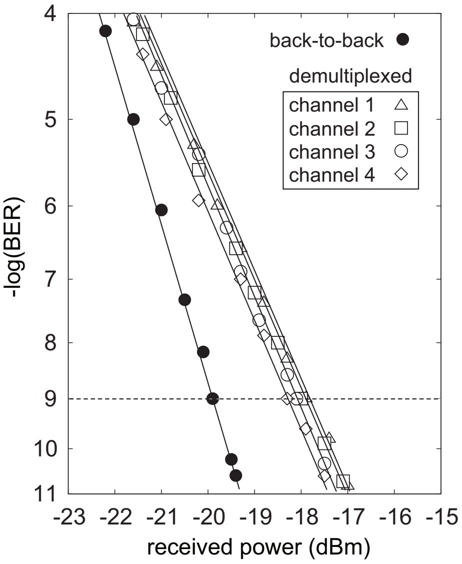

Figure 6. Bit-error rate (BER) measurements of back-to-back and demultiplexed channels.

serial signal pulse would exhibit the same pulsewidth as the compressed 4×10 Gb/s clock pulse train from the RA-ASC, which is around 2.5 ps.

After the parallel-to-serial conversion, the OTDM serial signal was demultiplexed and then sent to an optical receiver for BER measurement to evaluate the quality of the signal. Figure 6 shows the BER performance of the back-to-back signal for one of the 10 Gb/s channel and all demultiplexed channels. We obtained the error-free operation for all channels. All channels performed almost the same, and less than 2-dB power penalty at BER=10^{-9} was achieved for all demultiplexed channels compared to the back-to-back signal. The results show that the multiwavelength pulse compression using RA-ASC is applicable for the conversion of 4×10 Gb/s parallel channels to one 40 Gb/s serial channel.

4 All-Optical Serial-to-Parallel Data Conversion

Together with the parallel-to-serial converter, all-optical serial-to-parallel data converter forms a complete functionality for the all-optical wavelength/time-division trans-multiplexing. So far, extensive techniques have been proposed to convert a high-speed aggregated channel to one lower data-rate channel by using a single SOA assisted by an optical filter [23], a NOLM [24], a fiber optical parametric amplifier (FOPA) [25], cascaded wavelength conversion in quasi-phase-matched (QPM) periodically poled lithium niobate (PPLN) waveguides [26]. To use these techniques for the serial-to-parallel conversion, replication of such devices is necessary because they focus on processing individual channel at a time, hence increasing the complexity and cost of the configuration. Therefore, the single serial-to-parallel conversion device which is capable of producing all parallel data pipelines from a single gate

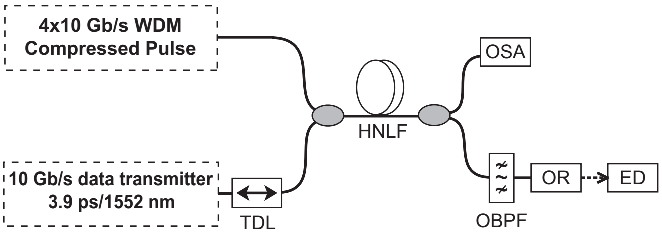

Figure 7. Experimental setup of all channel OTDM demultiplexing. TDL: time delay line, HNLF: highly nonlinear fiber, OBPF: optical bandpass filter, OSA: optical spectrum analyzer, OR: optical receiver, ED: error detector.

is desirable. Such a device often accompanies with multiwavelength synchronous ultrashort pulses [27] or to replicate OTDM data stream using signal multicasting technique [28] to recover all the subrate tributaries from the serial data stream. Here, we use a much simpler approach by using multi-wavelength picosecond pulse source generated from the RA-ASC as a synchronous sampling clocks for the serial-to-parallel data conversion.

4.1 Experiment Setup

The experimental setup for the single-gate serial-to-parallel data converter is shown in Figure 7. A combined four 10 GHz multiwavelength pulse streams at different wavelength were compressed by the RA-ASC as decribed in Section 2. Four compressed pulse streams were shifted relative to each other by 25 ps to form four synchronous sampling clocks with a total repetition rate at 40 GHz. As shown in Section 2, the RA-ASC produces approximately the same compressed pulse quality for all WDM pulse streams, which is essential for the subsequent all-optical gating. To generate a high-quality pulse train which is applicable for high-speed serial data systems, we used an optical comb generator which is a Fabry-Perot electro-optics (FP-EO) phase modulator. In this paper, an 10 Gb/s data signal with pulsewidth of 3.9 ps at wavelength of 1552 nm was generated for ultrahigh-speed serial OTDM data channel.

Due to the limited resources, we could not construct the 1:4 multiplexer to generate a 40 Gb/s serial data stream at the time of this experiment. Instead, to verify the possibility for the serial-to-parallel data conversion, we used a time delay line (TDL) to shift the 10 Gb/s data signal 25 ps for each time interacting with the four compressed synchronous pulses from the RA-ASC. The 10 Gb/s data signal and the compressed 4×10 Gb/s WDM pulse streams were then injected into a 500 m HNLF for parametric interaction in which the 10 Gb/s data signal was set as a pump. The FWM processes between the data channels with their corresponding synchronous pulses lead to simultaneous conversion to four 10 Gb/s tributaries at different wavelength. To characterize pulse quality of the demultiplexed channels, OBPFs were used after the HNLF to select the demultiplexed signals (idlers). For the BER measurements, a nonpreamplifier receiving scheme with a 10 Gb/s error detector (ED) was employed.

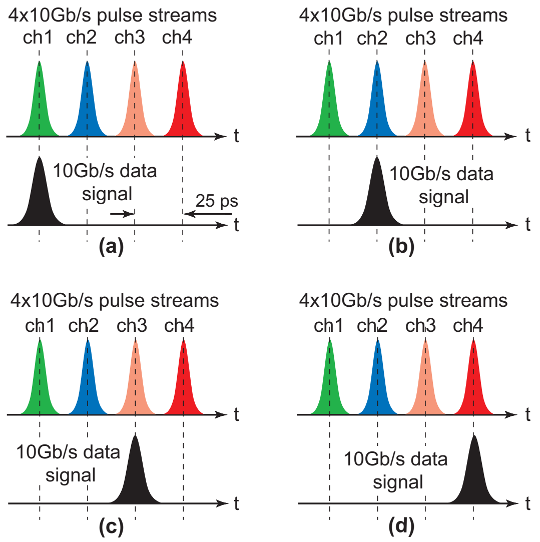

Figure 8. Shifting the 10 Gb/s data signal 25 ps for each time interacting with the compressed 4 × 10 Gb/s WDM pulse streams: (a) channel 1, (b) channel 2, (c) channel 3, and (d) channel 4.

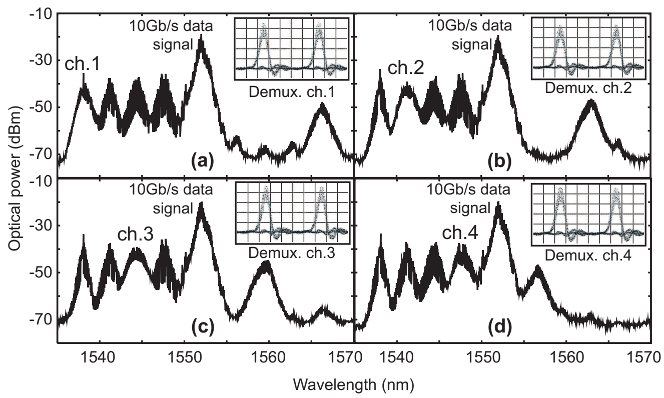

Figure 9. FWM spectra and demultiplexed eyes in four cases of 25-ps shifts at the 10 Gb/s data signal.

4.2 Results and Discussion

Figure 8 shows the temporal relation between the 10 Gb/s data signals with the compressed 4 × 10 Gb/s synchronous pulse streams (a) stream 1, (b) stream 2, (c) stream 3 and (d) stream 4. In addition, Figure 9 shows optical spectrum and the resulting eye patterns in four cases of FWM interactions between the 10 Gb/s data signals with the synchronous pulse (a) stream 1, (b) stream 2, (c) stream 3, and (d) stream 4. In each case, the 10 Gb/s data signal was interacted with only one designated synchronous pulse stream as can be seen in the spectrum. Clear eye patterns were observed in all cases. These results imply the capability for 40 Gb/s serial data channel of our proposed scheme.

Figure 10 shows the bit-error rate (BER) measurements of the converted data streams. The inset in Figure 10 shows the eye pattern of the back-to-back (B2B). We obtained the error-free operation at all channels, and the power penalty of 1.5 dB (BER=10^{-9}) at the worst channel are due to cross-talk by nonlinear effects among channels as shown in Figure 9. More importantly, only 0.2 dB variation of sensitivity among demultiplexed channels was achieved, which often widely fluctuates from channel to channel in previous demonstrations [29]. This is due to the advantage of RA-ASC in generating four WDM synchronous picosecond pulses with good quality at the same time. Note that the short pulsewidth tunability by controlling of the Raman pump power of RA-ASC makes our proposed system potential for bit-rate flexible serial-to-parallel data conversion for a serial data streams up to 160 Gb/s.

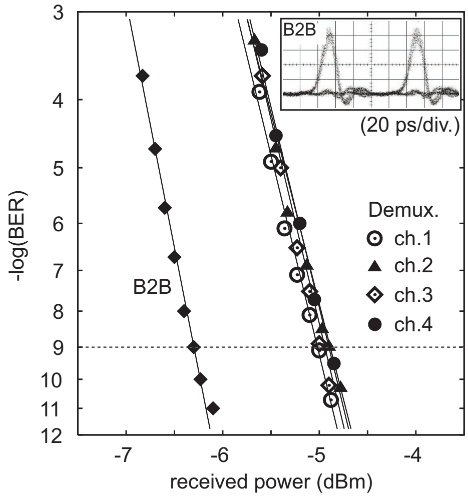

Figure 10. BER measurements of demultiplexed channels. Inset is eye pattern of 10 Gb/s back-to-back signal.

5 Conclusion

In this paper, we have presented and demonstrated multiwavelength picosecond pulse generation by taking advantage of adiabatic soliton compression in single distributed Raman amplifier. Pulsewidth tunability of the generated multiwavelength pulse can be achieved by changing the Raman pump power. We have then used such a multiwavelength pulse source to realize an all-optical serial/parallel data exchange through a single fiber nonlinear gate. The experimental demonstrations on parallel-to-serial and serial-to-parallel data conversions suggested a capability of our proposed schemes in realizing complete all-optical wavelength/time-division trans-multiplexer which is key functions to realize an photonic gateways for heterogeneous optical networks.

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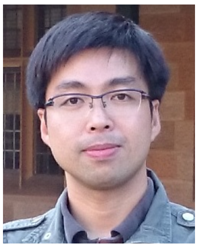

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