Raman Amplifier-Soliton Compressor and Its Application to All-Channel Hybrid OTDM Demultiplexing

Irneza Ismail[1,2], Motoharu Matsuura[1], Naoto Kishi[1]
[1]Dept. of Communication Engineering and Informatics
The University of Electro-Communications, Japan
[2]Faculty of Science and Technology
Islamic Science University of Malaysia, Malaysia
Email: irneza@uec.ac.jp

Quang Nguyen-The
Faculty of Radio-Electronics
Le Quy Don Technical University, Vietnam

***Abstract*—An all-optical demultiplexing of 40-Gb/s hybrid OTDM channels by using Raman-amplifier-soliton-compressor-flexible control-window is demonstrated. Error-free operations with less than 1.3-dB power penalties were obtained and this scheme is expected to be scalable toward higher bit-rates.**

I. Introduction

Bit-rate transparency and various format adaptations have become an essential requirement to achieve future high speed operation in optical time division multiplexing (OTDM) and optical networks. In the future optical network, the combination between different format and bit-rate may co-exist in the same transmission lines or even in the same carrier wavelength [1–3]. In the past, various demultiplexing techniques have been proposed and demonstrated [4–8]. However, the demultiplexing schemes so far are limited in terms of bit-rate and modulation format flexibility. Four-wave mixing (FWM) in highly-nonlinear fiber (HNLF) holds a great interest in demultiplexing due to its fast nonlinear response and transparency to modulation format and bit-rate [9]. Furthermore, an important issue for OTDM is the ability of the converter for selecting one or more tributary channel regardless of different line rates and format for further signal processing. Reference in [8] has successfully demonstrated a hybrid OTDM demultiplexing using electro-absorbtion modulator (EAM). However, the demultiplexer has a wider switching window which may degrade the quality performance of the target channel as part of an adjacent data may still include in the switching window. The intention of the present study is to provide the converter with abilities to deal with ultra-short pulses with various signal durations and format.

Optical short pulse generation with high repetition rate has attracted a lot of interest for various applications in today's dynamic networks. A demonstration of such signal with different applications in OTDM and return-to-zero (RZ) signal regeneration at high bit rate have been reported in [4, 7]. This scheme is a gainful technique that can produce a pulsed idler with identical repetition rate as the pump and potentiality can demultiplex the OTDM signals while offering power amplification in the FWM process. It is also found that the generated gating window pulse requires a spectral broadening of the higher pump power in order to increase the threshold for Stimulated brillioun scattering (SBS) and the temporal gating window duration is always fixed. The adiabatic soliton compression techniques have attracted much attention to generate high-quality short-duration pulse trains in the order picoseconds [10]. This useful approach can be extended by using a high quality tunable ultra-short duration of the RZ clock pulse introduced in our experiment, which has benefited over continuous wave (CW) due to flexible spectral width. It can also provide energy in the fiber parametric gate without the use of extra erbium-doped fiber amplifier (EDFA) compared to other schemes. However, signal processing for OTDM hybrid format is difficult to be implemented, and there has been no report using the adiabatic soliton compression in distributed Raman amplification for hybrid signals demultiplexing. It would be more attractive to offer some more advantages, such as simultaneous dual-format demultiplexing with high quality picosecond input-output pulse width signal.

In this paper, we demonstrate a proof concept for demultiplexing of arbitrary lower rate 10 Gb/s tributary channels from a 40 Gb/s hybrid amplitude and phase format data signals with the advantageous use of Raman amplifier-soliton compressor (RASC) as a higher power output of the fiber-based FWM gate. It would also be useful to be able to demultiplex a single OTDM channel with different formats to reduce complexity and cost at the system level. Thus, the scalability for flexible higher bit-rate demultiplexing and different granulaties for tributary channels by using our proposed system is evident and further discussed.

II. Operation principle and setup

The demultiplexing scheme is realized using a fiber-based single-parametric-gate HNLF and an RASC. For the control sampling gate, tunable width RZ clock pulse from the RASC is set as a control signal corresponding to various Raman pump power settings. When OTDM data as the input probe

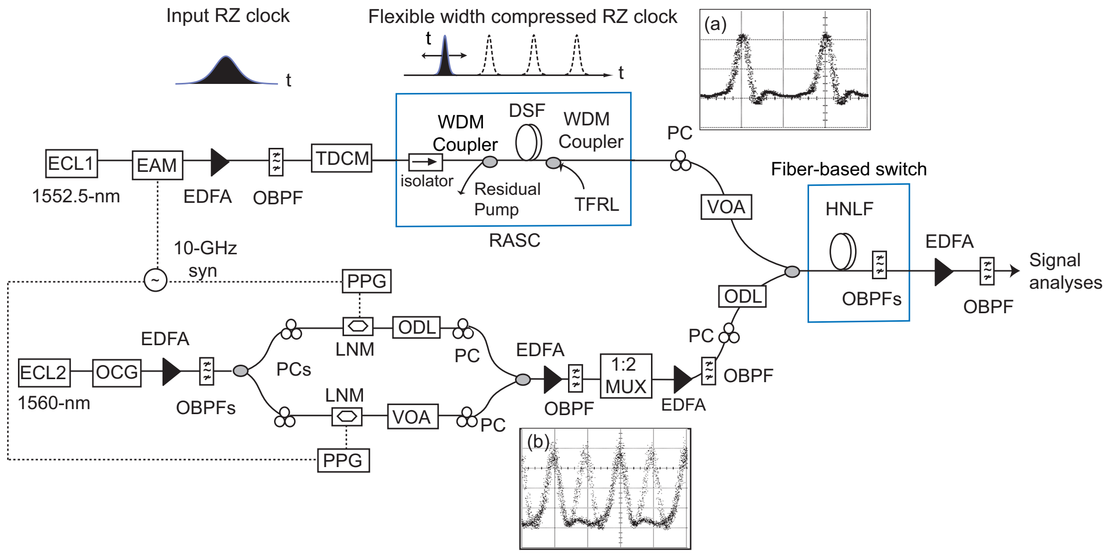

Fig. 1. Experimental setup of the proposed scheme and insets for (a) waveform of the compressed RZ clock from RASC and (b) eye patterns of 20 Gb/s mixed hybrid OTDM signal (50 ps/div).

signals, the control gate RZ clock with different pulse width can be converted into pulse durations with higher quality performance. The experimental setup is illustrated in Fig. 1. A CW light generated from an external-cavity-laser (ECL) at 1552.5 nm was modulated by using an EAM to generate a 10 GHz RZ clock signal. An EDFA and an optical band-pass filter (OBPF) were used to compensate the EAM insertion loss. A tunable dispersion-compensating module (TDCM) was employed to suppress the frequency chirping induced by the EAM. The RASC was based on adiabatic soliton compression operation consisted with 17 km dispersion-shifted-fiber (DSF) and a wavelength tunable Raman fiber laser (TFRL). The second- and third-order dispersion of the DSF are 3.8 ps/nm/km and 0.059 $ps/nm^2/km$, respectively. Inset in Fig. 1 (a) shows the waveform of compressed RZ clock from RASC. At the output of RASC, a variable optical attenuator (VOA) was employed to control the input power before sent to HNLF. On the other hand, a 10 GHz ultra short pulse train was generated in an optical comb generator (OCG). The generated pulse was filtered by two 1.0 nm OBPFs to obtain the pulse duration around 3.7 ps at the centered wavelength of 1558 nm. The pulse train was modulated simultaneously using a $LiNbO_3$modulators (LNM) by a 10 Gb/s data with a pseudorandom bit sequence (PRBS) of 2^{31}-1 data generated from a pulse pattern generator (PPG). A polarization controller (PC) and a VOA were used to adjust both signals having the same peak power and polarization. After passing through the coupler, the 20 Gb/s signals were multiplexed to form a 40 Gb/s signal. Inset in Fig. 1 (b) shows an eye pattern of the 20 Gb/s on-off keying (OOK) and differential-phase shift keying (DPSK) tributaries. Both control and probe data were inserted into HNLF. The HNLF had a zero dispersion wavelength of 1552 nm, a dispersion slope of 0.032 $ps/nm^2/km$, and a nonlinear coefficient of 12.6 $W^{-1}km^{-1}$. After HNLF, the OTDM signal was demultiplexed. The bit-error-rate (BER) characteristics and pulse width of the demultiplexed channels were measured by an error detector (ED) and an autocorrelator, respectively.

III. Result and Discussion

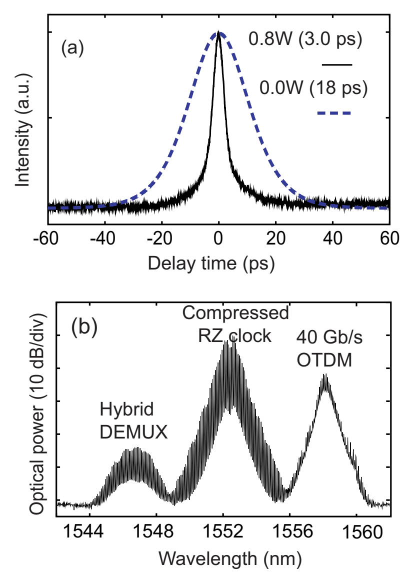

Fig. 2. (a) Autocorrelation traces sampling gate of compressed RZ clock at the Raman pump power 0.0 and 0.80W and (b) FWM spectra after demultiplexing of hybrid signals.

In this experiment, the Raman-pump power can flexibly be tuned to enable the converter functions to deal with ultra-short pulses with different input OTDM data pulse widths. Thus, the characteristics of the control pump signal play an essential role of the smooth, short pulse width with pedestal-free channels after FWM process. Figure 2 (a) provides the autocorrelation trace function of the tunable-width Rz clcok pulse. The initial input of RZ clock pulse with 18 ps long was considerably compressed down to 3.0 ps as the Raman pump power was controlled up to 0.80 W. The output compressed pulse were well fitted to $sech^2$ functions and the time-bandwidth product of 0.37 estimated at 0.80 W showed that transform-limited pulses were attained. It should be noted that the use of soliton pulse with an ideal $sech^2$ profile will be expected to obtain better demultiplexing performance. With the RZ control gating window around 3.0 ps, it is possible to demultiplex 40 Gb/s hybrid OTDM signal to 10 Gb/s tributaries channels. The measured pulse widths of 10 Gb/s RZ-OOK and RZ-DPSK were around 3.7 ps. Figure 2 (b) shows the spectra at the output of the HNLF. The tunable RZ clock pulse was fed into the HNLF experiences either pulse compression or broadening, depending on whether its amplitude was larger or smaller than that of the fundamental soliton. The demultiplexing performance was further investigated by measuring the bit error rate (BER) of the output signals by setting the Raman pump power for the RZ clock pulse.

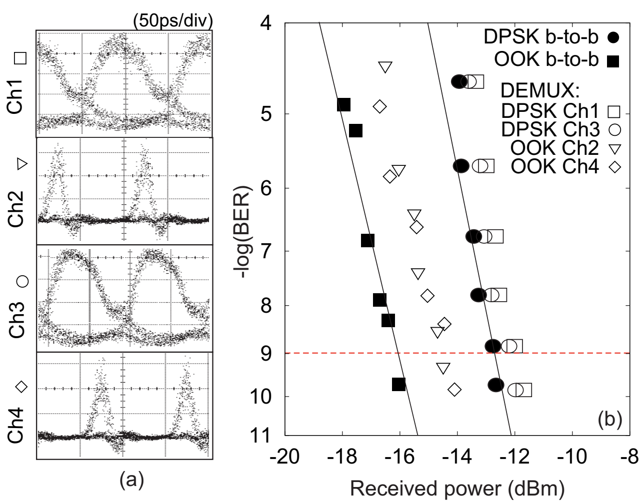

Fig. 3. All demultiplexing channel during Raman pump power 0.80 W for (a) demodulated eye patterns (50 ps/div.) and (b) BER measurements.

The demodulated eye patterns of 4 x 10 Gb/s demultiplexed hybrid tributary channels are shown in Fig. 3 (a). It can be seen that the eye patterns are well preserved with less deterioration. In Fig. 3 (b) shows that all demultiplexed channels can be achieved with power penalties smaller than 1.3 dB, which was mainly attributed by the amplified spontaneous emission (ASE) noise and filtering effect. The superior performance of RZ-DPSK tributary channel was observed in Fig. 3 (b) in comparison with RZ-OOK channel due to its constant intensity profile characteristic. On the other hand, the converted signals also followed the pulse width of the compressed RZ clock. This compression and pedestal removal of the pulse was predicted since the intensity of the demultiplexed signal was proportional to the intensity of the compressed RZ clock [11]. The measured demultiplexed pulse widths for Ch1 and Ch2 were 2.60 ps, and 2.62 ps as shown in Fig. 4. The calculated time-bandwidth-product was 0.37 at the worst channel. Potential flexible higher bit-rate can be achieved by optimization for shorter pulse operations of the RASC compression process, and increment time slot of dual-format channels.

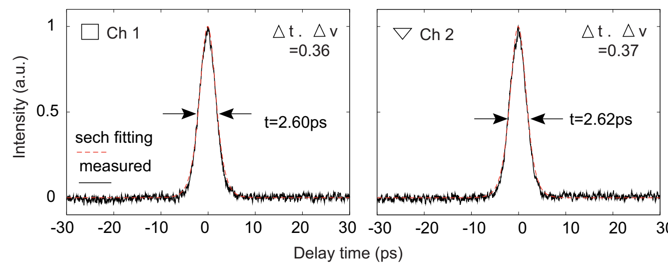

Fig. 4. Measured autocorrelation traces of all demultiplexed channels at the Raman pump power of 0.80 W.

IV. Conclusion

We have demonstrated a 40 Gb/s hybrid format demultiplexing using a tunable pulse source based on RASC. The results show the superior performance of all demultiplexed channels with less than 1.3 dB power penalties. This experiment shows the potential of using an OTDM hybrid data stream that can be upgraded to higher bit rates gained from RASC component employed in our system.

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