WDM-to-OTDM Conversion in a Highly Nonlinear Fiber

Srujith Poondla [1],Charllo Bala Vignesh [2] ,V Anoosh Kumar Reddy [3]

[1,2,3,] **VIT University ,Vellore , India**

Abstract— **In this article we demonstrated an all-optical wavelength-division-multiplexing (WDM)-to-optical-time-division-multiplex-ing (OTDM) conversion using spectral broadening of super continuum (SC) generation in a highly nonlinear fiber. Four 10-Gb/s WDM channels were injected into time delay blocks for controlling the timing among them, and converted to OTDM channel by the SC-based multiplexing. The SC generation had advantages of eliminated the use of any pump in the WDM-to-OTDM conversion.**

Key words— **Optical fiber communication, wavelength-division multiplexing, optical time division multiplexing, optical signal processing, optical Kerr effect.**

I. Introduction

Optical fiber communication systems are characterized by their extremely high transmission capacity, which are based on optical time-division-multiplexing (OTDM) and wavelength-division-multiplexing (WDM) with their own advantages [1]–[3]. In addition, it is necessary to develop all-optical signal processing, which replaces optical-electrical-optical (OEO) conversion with the electronic speed bottleneck in high-speed WDM and OTDM networks. To provide such a WDM/OTDM network, the all-optical conversion between WDM and OTDM signal formats become an important trans-multiplexing operation at photonic gateways of that networks [4]–[6]. In all-optical WDM-to-OTDM conversion, lower data rate signals at different wavelengths from the end users of access would be aggregated into high speed OTDM data stream for the backbone or core networks [7]. In combination with all-optical OTDM-to-WDM conversion [8], [9], a solution of all-optical processing for interconnection at the photonic gateway nodes of the WDM/OTDM networks would be com-pletely provided.So far, there have been many reports demonstrating all-optical WDM-to-OTDM conversion using an electro ab-sorption modulator (EAM) [10], cross-gain modulation (XGM) effect in semiconductor optical amplifiers (SOAs) [11], a Mach-Zehnder interferometer wavelength converter based on SOAs (MZI-SOAs) [12] with the advantage of small device size as well as the possibility of integration with the other devices. However, the conversion using EAM or SOA technology has a limited frequency response. Recently, highly nonlinear fiber (HNLF) has attracted much attention for performing optical signal processing [13]. Therefore, another approach is to use the different nonlinearities in the HNLF such as four-wave mixing (FWM) [14], and cross-phase mod-ulation (XPM) [15] for WDM-to-OTDM conversion. The use of nonlinear optical loop mirror (NOLM) in conjunction with a hybrid mode-locked laser (HML) [16], time-domain optical Fourier transformation (OFT) [17] for WDM-to-OTDM con-version has also been reported. Recently, we have successfully achieved the conversion of 4 × 10 Gb/s WDM channels to one 40 Gb/s OTDM channel by using Raman compression [18]. However, due to the nature of the techniques in the previous demonstrations, additional pump signal was required for the conversion.

In this letter, we proposed and experimentally demonstrated the conversion of 4 × 10 Gb/s WDM channels to one 40 Gb/s OTDM channel by using supercontinuum (SC) generation in a HNLF. The SC generation had advantages of eliminated the use of any pump in the WDM-to-OTDM conversion. There-fore, the straightforward techniques by using SC generation for WDM-to-OTDM conversions would decrease cost, size of the WDM/OTDM network. Four WDM channels were time interleaved in the delay blocks with appropriate time delays between each channel before injecting into the HNLF for the multiplexing process by using SC generation and filtering. The converted 40 Gb/s signal was demultiplexed to 10 Gb/s for bit error rate (BER) measurement. Less than 2-dB power penalty at BER = 10^{-9} from the back-to-back was obtained for all demultiplexed channels.

II. Operation Principle

The operation principle of the proposed all-optical WDM-to-OTDM conversion using the SC generation is shown in Fig. 1. WDM return-to-zero (RZ) data signals at rate $B = N \times R$ (N channels at base rate R) configured with N channels of wavelengths $\lambda_1, \lambda_2, \ldots, \lambda_N$ are generated by using conventional amplitude modulators such as EAM and $LiNbO_3$ modulators. However, those modulators generate around 20 ps for 10 GHz amplitude modulators, which are not short enough

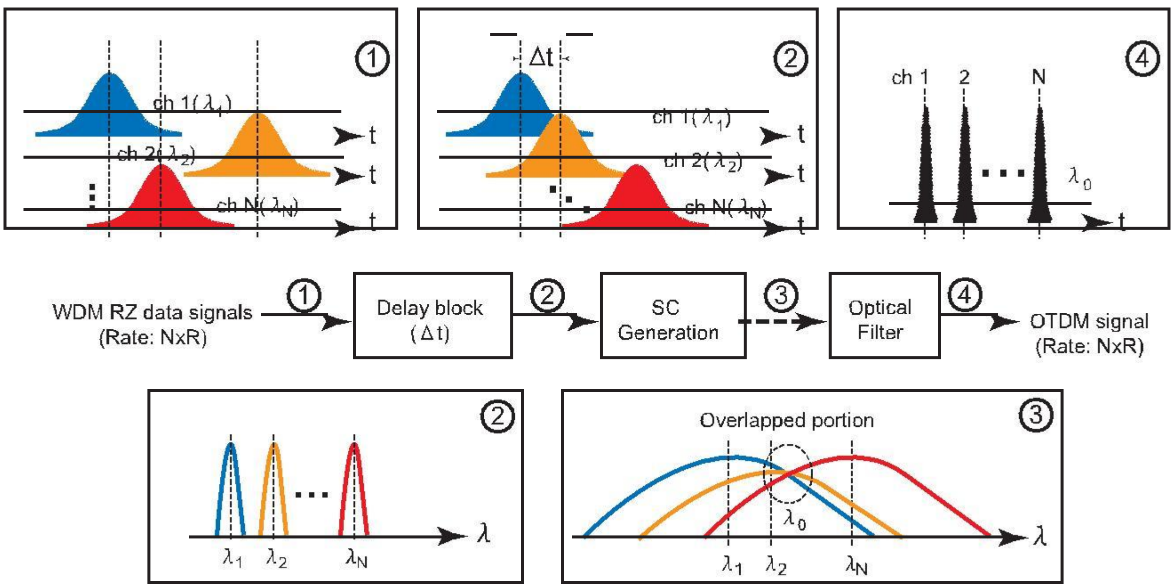

Fig. 1. Operation principle of the proposed scheme.

for the formation of ultrahigh-speed OTDM data streams. WDM RZ data signals are sent to a delay block to control the delay of each channel by _t for WDM-to-OTDM conversion. The delay block is built by means of tunable optical delays and coupled into one output fiber. Insets 1 and 2 in Fig. 1 describe the formation of the WDM RZ data signals that are temporary shifted relative to each other by the delay block. These WDM RZ data signals are sent to the SC generation for broadening their spectra due to self-phase modulation (SPM). In a medium with Kerr nonlinearity, after propagation over the distance z, the maximum SPM-induced spectral broadening of the signal pulse can then be estimated as [19]

$$\Delta\omega = \frac{\omega}{c} n_2 z \frac{I_0}{\tau}$$

where n_2 is the nonlinear refractive-index coefficient at the frequency ω, I_0 is the peak intensity of the input signal pulse, and τ is the pulse width. It can be seen from expression (1) that the maximum SPM-induced spectral broadening depends on the peak intensity of the pulse I_0 and the pulse width τ. When the WDM RZ data signals are injected into the SC gen-eration, each of them gets spectrally broadened. Therefore, the overlapped portion of all WDM RZ data signals can be achieved by adjusting the power levels of the data signals. Inset 3 in Fig. 1 shows conceptual overlapped spectra after the SC generation. These overlapped spectra then are filtered by the optical filters. In this way, a converted OTDM data signal at rate $B = N \times R$ with wavelength of λ_0, as shown in inset 4 in Fig.1, can be achieved at the output of the optical filters.

III. Experimental Setup

Figure 2 shows the experimental setup of 4×10 Gb/s WDM channels to one 40 Gb/s OTDM channel conversion using SC generation. A combined four 10 Gb/s WDM nonreturn-to-zero (NRZ) data signals at wavelength of 1554.94 nm (ch1), 1556.55 nm (ch2), 1558.17 nm (ch3), and 1559.79 nm (ch4) with channel spacing of 1.6 nm (200 GHz) were produced by using four external cavity laser diodes (ECLs) and a $LiNbO_3$

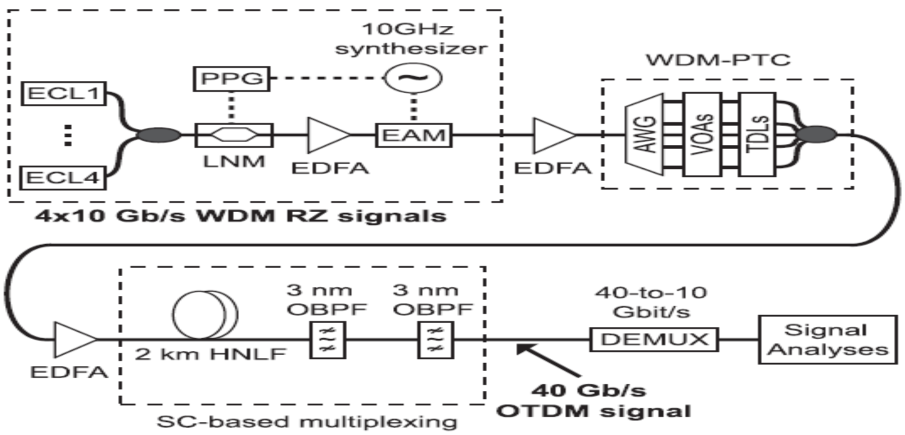

Fig. 2. Experimental setup for 4 × 10 Gb/s WDM channels to one 40 Gb/s OTDM channel conversion. ECL: external-cavity laser-diode, LNM: $LiNbO_3$ modulator, EAM: electroabsorption modulation, PPG: pulse pattern generator, EDFA: erbium-doped fiber amplifier, WDM-PTC: WDM power and time controller, AWG: array waveguide grating, VOA: variable optical attenuator, TDL: tunable delay line, HNLF: highly nonlinear fiber, OBPF: optical bandpass filter, DEMUX: demultiplexing.

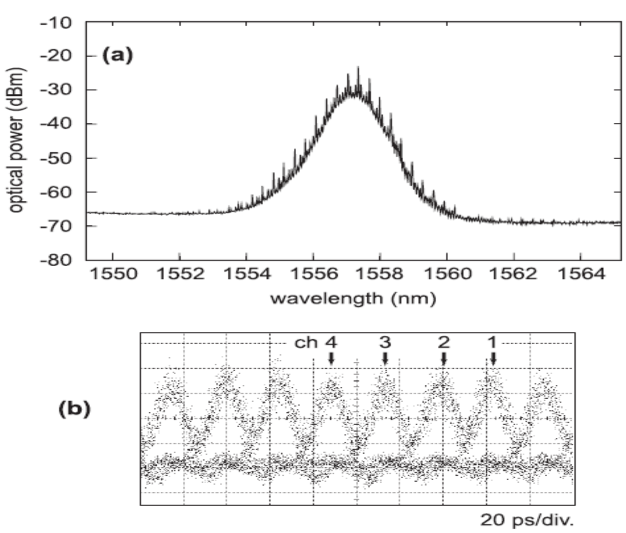

Fig. 4. (a) Output spectra of the converted 40 Gb/s OTDM data signal at the output of SC-based multiplexing and (b) corresponding eye pattern captured by a 30 GHz-bandwidth digital sampling oscilloscope (20 ps/div.).

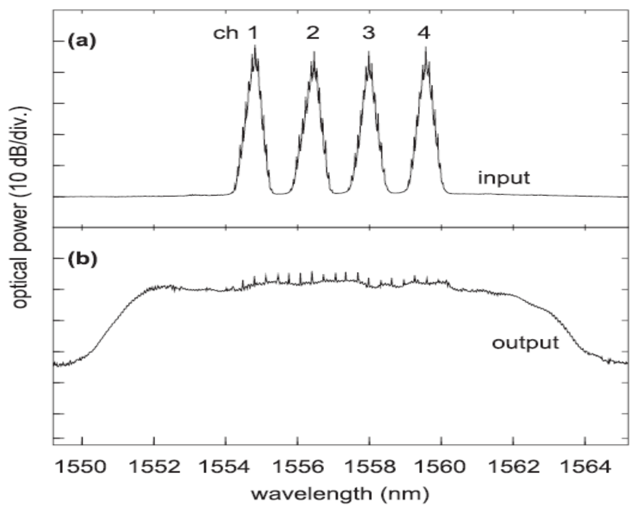

Fig. 3. Optical spectra of the 4 × 10 Gb/s WDM RZ data signals at the (a) input and (b) output of the HNLF.

pattern generator (PPG). These WDM NRZ data signals were amplified by an erbium-doped fiber amplifier (EDFA), and converted to a combined four 10 Gb/s WDM return-to-zero (RZ) data signals by utilizing an EAM. An EDFA was used at the output of the EAM to compensate for the EAM insertion loss. The WDM channels were manually synchronized. Before injecting into a SC-based multiplexing, it is important to adjust the power levels of the WDM RZ data signals for getting the overlapped spectra of all data signals in the frequency. In addition, delay blocks are also required to control the timing among the WDM RZ data signals. To fulfil these two requirements, we constructed a WDM power and time controller (WDM-PTC), which consisted of an arrayed waveguide grating (AWG), variable optical attenuators (VOAs) in series with tunable delay lines (TDLs), and a coupler. At the output of the WDM-PTC, the pulsewidth of the combined four 10 Gb/s WDM RZ data signal was approximately 20 ps. These WDM RZ data signals, which are temporary shifted relative to each other by the WDM-PTC were amplified by an EDFA, then injected into the SC-based multiplexing for WDM-to-OTDM conversion. The total power of the combined four 10 Gb/s WDM RZ data signals before injecting into the SC-based multiplexing was set to 21.5 dBm.

The SC-based multiplexing was based on SC generation, which contained 2 km of HNLF and optical bandpass filters (OBPFs). The HNLF had the second-order dispersion of −2.2 ps/nm/km and third-order dispersion of 0.032 ps/nm^2/km at 1550 nm, loss of 0.55 dB/km, nonlinear coefficient of 12.6 W^{-1} · km^{-1}, effective area of 11 μm^2. The spectra of the all four data channels at the output of HNLF were broadened over the SC generation. By adjusting the power levels of the WDM RZ data signals, the overlapped spectra of all data signals in the frequency could be achieved. These overlapped spectra were filtered by two 3-nm OBPFs. In this way, conversion to a 40 Gb/s OTDM data signal was achieved at the output of the SC-based multiplexing. The converted 40 Gb/s OTDM data signal was demultiplexed to 10 Gb/s base rate by using a FWM-based demultiplexing. A spectrum analyzer and 30 GHz-bandwidth digital sampling oscilloscope were used to observe the spectrum and eye pattern of the signals, respectively. The demultiplexed signals were also sent to a 10 Gb/s receiver for BER measurement.

IV. Experimental Results and Discussion

Figure 3(a) and (b) show optical spectra of 4×10 Gb/s WDM RZ data signals at the input and output of the HNLF, respectively. Compared to the input signals, the spectra of the all data channels at the output were broadened over the SC generation. Therefore, the overlapped portion of the spectra of all data channels can be obtained. The 40 GHz tones in the spectra after the SC generation at the output of the HNLF show the successful converting to 40 Gb/s OTDM data signal.

The output spectra and eye pattern of 40 Gb/s OTDM data signal at the output of SC-based multiplexing stage after filtering at ~1557.3 nm are shown in Fig. 4(a) and (b), respectively. Clear eye-opening in Fig. 4(b) shows that the present system successfully performs the conversion of 4 × 10 Gb/s WDM channels to one 40 Gb/s.

Figure 5(a) shows the BER performance of all demulti-plexed channels. We obtained the error free operation for all channels.

Compared to the back-to-back signal, less than 2-dB power penalty at BER = 10^{-9} was obtained for all demultiplexed channels. The penalty variation among all channels was obtained to be less than 1-dB. Here the input WDM channels overlapped each others in the time, causing crosstalk effects between adjacent channels and increasing signal distortions. However, the 2R Mamyshev regenerator [20] can improve the degraded signals significantly. The inset in Fig. 5(a) shows the eye pattern of 10 Gb/s back-to-back signal for one of the original 10 Gb/s RZ channels. The eye patterns of all demultiplexed channels are shown in Fig. 5(b). All eye patterns show clear and open eyes, which indicates

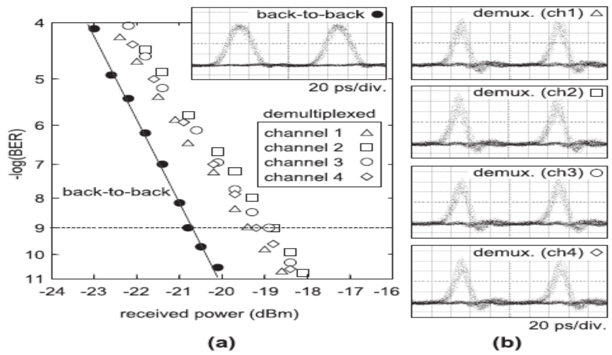

Fig. 5. (a) Bit-error rate (BER) measurements of demultiplexed channels; inset is eye pattern of 10 Gb/s back-to-back signal for one of the original 10 Gb/s RZ channels, and (b) eye patterns of all demultiplexed channels (20 ps/div.).

In this work, input WDM channels with pulsewidth of 20 ps were converted to 6 ps OTDM channel. Therefore, the obtained pulsewidth is suitable for 40 Gb/s OTDM transmission. Two and four channels could be used for conversion of 2 × 20 Gb/s WDM channels and 4 × 10 Gb/s WDM channels to a 40 Gb/s OTDM channel, respectively. Due to the limited of charac-teristics of the HNLF with small nonlinear coefficient and high third-order dispersion, the current demonstration faces a challenge to be functional for higher OTDM bit-rates over 40 Gb/s. One possible solution is the use of the Raman compression [18] or a suitable HNFL.

V. CONCLUSION

We have proposed and experimentally demonstrated all-optical format conversion scheme from 4 × 10 Gb/s WDM channels to one 40 Gb/s OTDM channel by using SC-based multiplexing. Less than 2-dB power penalty at BER = 10^{-9} was obtained all channels after the OTDM demultiplexing in comparison with the 10 Gb/s back-to-back signal. Small penalty variation among all demultiplexed channels was achieved with less than 1-dB. The straightfor-ward technique by using SC generation made our proposed technique distinguished from the previous WDM-to-OTDM conversion.In combination between the demonstrations in OTDM-WDM conversion in Ref. [9] and WDM-to-OTDM conversion in this letter can be done in transmultiplexer at the photonic gateway nodes of the WDM/OTDM networks.

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