40 Gb/s NRZ-to-RZ and OOK-to-BPSK Format and Wavelength Conversion on a Single SOA-MZI for Gridless Networking Operations

F. Fresi, M. Scaffardi, N. Amaya, R. Nejabati, D. Simeonidou, A. Bogoni

***Abstract*— We propose and experimentally demonstrate simultaneous format and wavelength conversion at 40 Gb/s exploiting a single commercial SOA-MZI. Conversion from NRZ to a 2 ps RZ-OOK format suitable for grooming onto a 160 Gb/s OTDM frame is achieved. Furthermore, for the first time to the best of our knowledge, 40 Gb/s conversion from RZ-OOK to RZ-BPSK is achieved. The effectiveness of the proposed scheme is demonstrated by means of BER measurements. Error free operations are reported, with a power penalty of 0.5 dB for the case of NRZ-to-RZ OOK conversion and of 3 dB (comprehensive of the degradation due to the wavelength conversion used to generate the probe signal) for the case of OOK-to-BPSK conversion.**

***Index Terms*— Advanced modulation format, all-optical signal processing, format conversion, gridless networks, semiconductor optical amplifier Mach-Zehnder interferometer (SOA-MZI).**

I. Introduction

THE increasing demand for capacity and bandwidth flexibility both in the wide-area and local-area network has recently triggered new research initiatives, where a more flexible spectrum allocation approach than the standard International Telecommunication Union (ITU) grid is proposed [1]. Moreover, modulation format adaptation represents a valid method for overcoming transmission impairments and increase reach or transmission speed [2]. Hence, there is the requirement for new optical switching nodes capable of supporting traffic with different bit-rates and modulation formats and networks where spectrum is allocated depending on specific signal requirements. However, the segmented use of spectrum may result in the lack of availability of sufficiently wide spectrum slots for long-reach signals, which would lead to blocking. One way of overcoming this limitation is to carry out simultaneous wavelength and format conversion either to accommodate a particular signal in an available spectrum slot or to switch back to a more robust modulation format when sufficient spectrum is available. Therefore, a key technology enabler for these types of optical switching nodes and networks is a modulation format converter capable of supporting simultaneous wavelength and format conversion from Non-Return to Zero (NRZ) to Return to Zero (RZ) and from On-Off keying (OOK) to Binary Phase Shift Keying (BPSK) and vice versa.

NRZ-to-RZ OOK format conversion is necessary to groom a low bit-rate Wavelength Division Multiplexing (WDM) channel into a high bit-rate Optical Time Division Multiplexing (OTDM) frame. This operation would require likely simultaneous wavelength and format conversion. The resultant RZ signal pulsewidth must fit within the OTDM time-slot. NRZ-to-RZ OOK conversion has been demonstrated at 40 Gb/s using techniques based on Semiconductor Optical Amplifiers (SOAs) [3] and periodic poled lithium niobate (PPLN) [4]. The SOA-based techniques do not allow for simultaneous wavelength and format conversion whereas PPLN-based techniques are limited to wide output pulsewidths.

OOK-to-BPSK format conversion is needed when the information carried on a short-range OOK signal has to be transferred to a long-range BPSK signal. OOK-to-BPSK conversion up to 10 Gb/s has been demonstrated based on SOA Mach Zehnder Interferometer (SOA-MZI) [5] and on a single SOA [6]. In [7] 40 Gb/s DPSK wavelength conversion is demonstrated using a SOA-MZI, where the signal and its inverted replica are necessary. However, in a networking scenario the need of an inverted replica of the incoming data signal would require an additional functional block. Format conversion at higher bit rate by exploiting Cross-Phase Modulation (XPM) in highly nonlinear fiber is demonstrated in [8].

In this paper, we propose and experimentally demonstrate simultaneous format and wavelength conversion from NRZ to RZ-OOK and from RZ-OOK to RZ-BPSK at 40 Gb/s which can be used in a gridless networking environment to overcome transmission impairments or to reduce blocking. Each format converter utilizes a commercial SOA-MZI to transfer the information from the incoming signal to a local clock with RZ pulses. Furthermore, the NRZ to RZ-OOK conversion is successfully demonstrated to generate 2 ps output pulses

Manuscript received August 19, 2011. This work was partially supported by the European Commission through projects ACEPLAN and FP7 ICT-EURO-FOS Network of Excellence.

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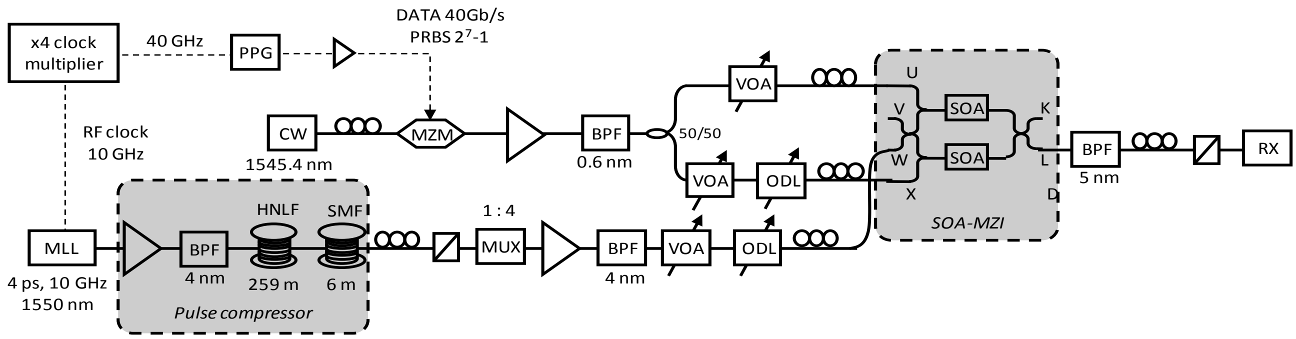

Fig. 1. Experimental setup for the 40 Gb/s NRZ-to-RZ OOK format and wavelength converter.

suitable for multiplexing into a 160 Gb/s OTDM frame. The OOK-to-BPSK conversion is obtained for the first time, to the best of our knowledge, at 40 Gb/s utilizing SOA-based devices without the need of the inverted signal replica.

II. Experimental Setup and Results

A. 40 Gb/s NRZ-to-RZ OOK Converter for 160 Gb/s OTDM

In the proposed scheme, information from a 40 Gb/s NRZ-OOK modulated signal is copied onto a 2 ps FWHM 40 GHz pulse train, resulting in a 40 Gb/s RZ-OOK output suitable for aggregation onto a 160 Gb/s OTDM signal. The experimental setup is shown in Fig. 1. The NRZ input signal, a 40 Gb/s PRBS 2^7-1 at 1545.4 nm, is split and fed to the SOA-MZI working in a push-pull differential configuration. This configuration provides an improved equalization of the converted pulses thereby overcoming the speed limit of the SOA carrier dynamics. The power of the push and pull signals is -0.3 dBm and -2.5 dBm respectively and 1 bit relative delay is set. Both SOAs are biased at 350 mA and the phase shifters

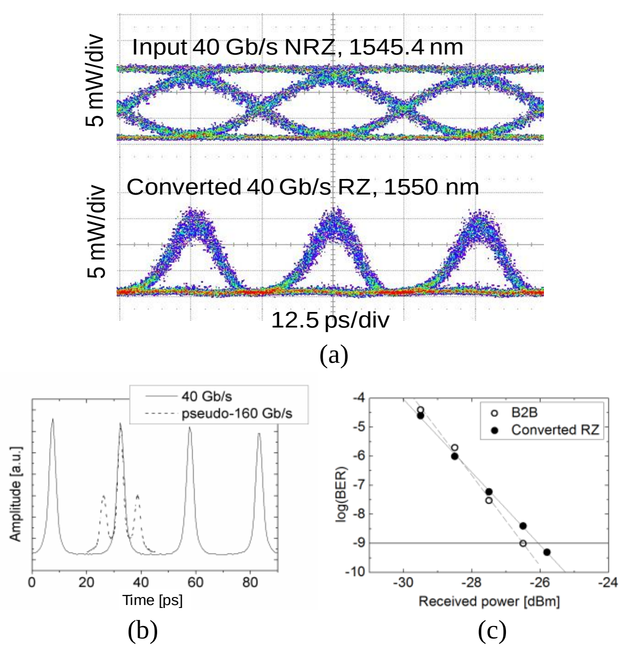

Fig. 2. (a) Eye diagrams for the input 40 Gb/s NRZ (top) and converted 40 Gb/s RZ (bottom), visualized on a 50 GHz bandwidth oscilloscope. (b) Autocorrelation traces of the converted 40 Gb/s RZ (line) and of the converted 40 Gb/s RZ after multiplexing to a pseudo-160 Gb/s OTDM frame (dashed). (c) BER measurements of the back-to-back and of the converted RZ signal.

inside the SOA-MZI are optimized for proper operation. The 40 GHz pulse train is generated by a 10 GHz fiber-ring mode-locked laser (MLL) at 1550 nm followed by a compressor to reduce pulsewidth from 4 ps FWHM down to 2 ps and a 1:4 split-and-delay multiplexer. The 40 GHz pulse train enters the SOA-MZI with 4 dBm power, and the 40 Gb/s RZ converted signal is filtered with a 5 nm optical band-pass filter (BPF). Fig. 2 (a) shows the eye diagrams of the input 40 Gb/s NRZ signal (top) and of the converted RZ one (bottom), visualized on a 50 GHz bandwidth limited oscilloscope. The output eye opening and the pulse equalization look good.

In order to measure the actual pulsewidth of the output RZ-OOK signal and to evaluate the suitability as a 160 Gb/s OTDM tributary, a 1 stage split-and-delay multiplexer is deployed at the converter output. The relative delay is set to 6.25 ps to form a pseudo-160 Gb/s OTDM signal. Fig. 2 (b) shows the autocorrelation traces of the 40 Gb/s RZ converted signal (line) compared to the autocorrelation of the pseudo-160 Gb/s (dashed). The autocorrelation confirms a 2 ps FWHM and the absence of pedestal on the output signal, that make it suitable for multiplexing onto a 160 Gb/s OTDM signal. The performance of the format and wavelength converter is also evaluated in terms of bit error rate (BER) using a pre-amplified receiver. The power penalty at BER = 10^{-9} due to the SOA-MZI converter is about 0.5 dB, as shown in Fig. 2 (c).

B. 40 Gb/s RZ-OOK to RZ-BPSK Converter

The proposed scheme provides format and wavelength conversion from 40 Gb/s RZ-OOK to 40 Gb/s RZ BPSK in a single SOA-MZI as shown in Fig. 3. A 10 GHz MLL source, followed by a 1:4 split-and-delay multiplexer, generates a 4 ps FWHM, 40 GHz optical pulse train at 1550 nm, subsequently modulated with a 2^7-1 PRBS. Information is transferred from the amplitude of the RZ-OOK signal to the phase of a 40 GHz RZ optical clock at 1544 nm (FWHM = 10 ps) acting as a probe, generated by wavelength conversion in a SOA (XPM-based wavelength converter) of the signal provided by the cascade of the MLL and the 1:4 multiplexer. The SOA-MZI operates in push-pull configuration with the input RZ-OOK signal used as pump and is biased so to provide constructive interference for the probe. Push and pull pumps are synchronous and they induce the same phase shift over the probe in both the SOAs, so to preserve the condition of

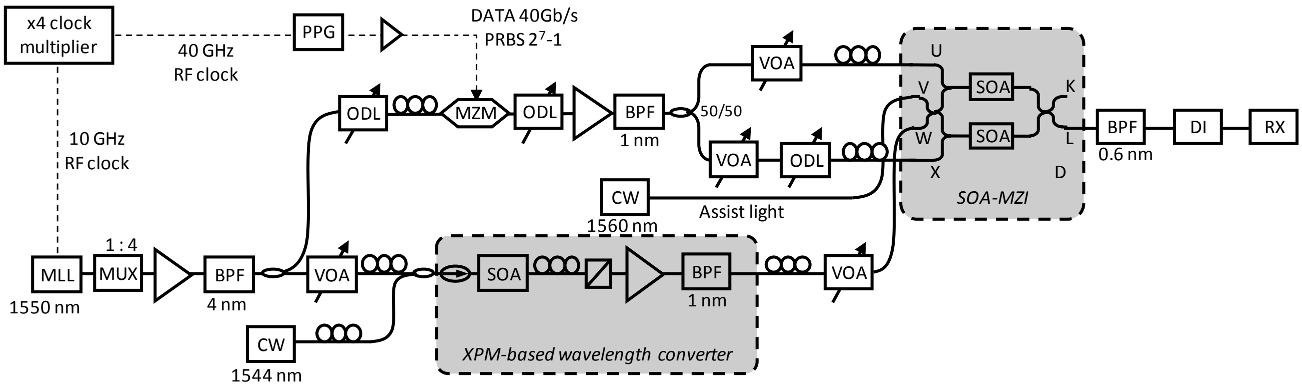

Fig. 3. Experimental setup for the 40 Gb/s RZ-OOK to RZ-BPSK format and wavelength converter.

constructive interference and avoid intensity modulation. Nevertheless, the phase of the probe pulses is changed corresponding to the intensity of the pumps, thus transferring the information from the intensity of the input signal to the phase of the output one. System parameters are optimized to achieve good conversion inducing a phase shift of ~π radians. The use of an assist light help overcoming the speed limit of the SOA carrier dynamics by reducing amplitude fluctuations and pattern effects. Average power for the “push” and “pull” pumps are 7 dBm and 5 dBm, respectively, while the bias current is 390 mA for the upper SOA (port U), and 210 mA for the bottom SOA (port X). The average power for the probe and the assist light is 13 dBm and 4 dBm, respectively. Phase shifters are optimized for proper operation, and the variable optical delay line (ODL) in the lower arm is used to finely synchronize the two pumps. A one-bit delay interferometer (DI) followed by a conventional pre-amplified receiver is used to photodetect the converted signal. Fig. 4 (a) shows the pump and probe signals at the input of the SOA MZI, while Fig. 4 (b) shows the BPSK converted signal before (top) and

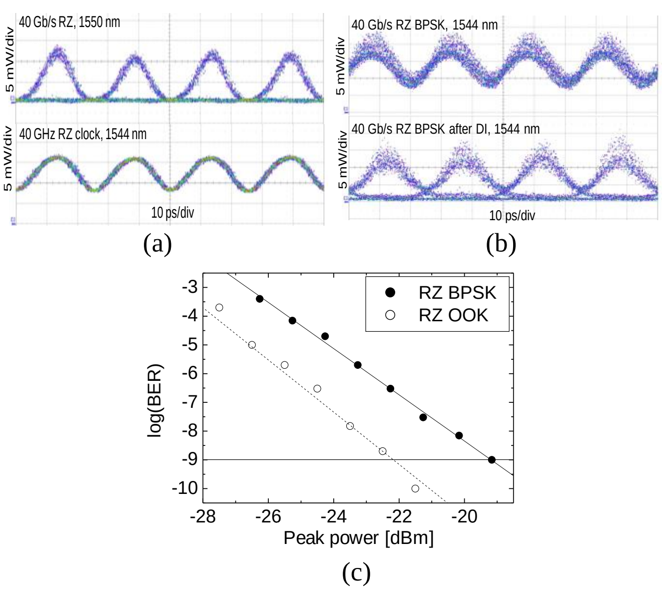

Fig. 4. (a) 40 Gb/s RZ-OOK input signal (top) and 40 GHz RZ probe clock (bottom). (b) 40 Gb/s RZ-BPSK converted signal at SOA-MZI output before (top) and after (bottom) the delay interferometer, evaluated on a 50 GHz bandwidth limited oscilloscope; (c) BER measurements for back-to-back and for the BPSK converted signal.

after (bottom) the delay interferometer. Amplitude fluctuations due to residual pattern effect are visible.

The performance of the format converter is evaluated in terms of BER. A power penalty of 3 dB for the receiver sensitivity is measured for a BER = 10^{-9}, as shown in Fig. 4 (c). The measured power penalty also includes the degradation due to the wavelength converter used to generate the probe signal.

Conclusion

We have proposed and experimentally demonstrated simultaneous format and wavelength conversion at 40 Gb/s using a single commercial SOA-MZI. The proposed NRZ-to-RZ OOK and RZ OOK-to-BPSK format and wavelength converters can be used in a gridless networking environment to accommodate signals in available spectrum slots or to overcome transmission impairments, enabling flexible bandwidth reallocation at each node. The output RZ-OOK signal is suitable for tributary multiplexing onto a 160 Gb/s OTDM stream.

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