Optical Burst-Mode Wavelength Conversion for 10Gb/s NRZ Optical Signals

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ABSTRACT
The 5G-induced paradigm shift from traditional macro-cell networks towards ultra-dense deployment of small cells, imposes stringent bandwidth and latency requirements in the underlying network infrastructure. While state of the art TDM-PON e.g. 10G-EPON, have already transformed the fronthaul networks from circuit switched point-to-point links into packet based architectures of shared point-to-multipoint links, the 5G Ethernet-based fronthaul brings new requirements in terms of latency for an inherently bursty traffic. This is expected to promote the deployment of a whole new class of optical devices that can perform with burst-mode traffic while realizing routing functionalities at a low-latency and energy envelope, avoiding in this way the latency burden associated with a complete optoelectronic Ethernet routing process and acting as a fast optical gateway for ultra-low latency requiring signals. Wavelength conversion can offer a reliable option for ultra-fast routing in access and fronthaul networks, provided, however, that it can at the same time offer both packet power-level equalization to account for differences in optical path losses and comply with the typical, in optical fronthauling, NRZ format. In this paper, we demonstrate an optical Burst-Mode Wavelength Converter using a Differentially-Biased SOA-MZI that operates in the deeply saturated regime to provide optical output power equalization for different input signal powers. The device has been experimentally validated for 10Gb/s NRZ optical packets, providing error-free operation for an input packet peak-power dynamic range of more than 9dB.

Keywords: Wavelength routing, Wavelength Conversion, Power equalization, strongly saturated conditions, PONs, BMWC, SOA-MZI.

1. INTRODUCTION
The rise of 5G networks has been driving an explosive 1000x increase of mobile data traffic, forecasting peak user rates up to 20Gb/s and low latencies down to 1ms۱. While Centralized Radio Access Network (C-RAN) currently promises ultra-network densification with centralization of network resources۲, it also places tremendous load on the fronthaul network for efficient RAN transportation۳. Existing Passive Optical Networks (PONs) stand out as a promising candidate network, benefitting from wide deployment, point-to-multipoint topology and efficient use of fiber, targeting Fixed-Mobile Convergence with co-existing xhaul and fixed residential traffic۴. Yet PONs have been traditionally designed for bursty traffic with the Optical Line Terminal (OLT) placed at the metro ring network, providing access to several Optical Network Units (ONUs) through a 1:256 splitter, as shown in Fig. 1(a)۵.

Towards reaping the benefits of centralization of network resources, it becomes increasingly required to develop metro-access nodes capable of redirecting xhaul traffic from the Remote Antenna Units (RU) at a single Centralized Unit (CU) node with an attached pool of baseband processing units۲. With xhaul mainly relying on low-layer functional splits between the CU-RU, it requires the development of new optical fast gateways that simultaneously handle the fronthaul Non Return to Zero (NRZ) traffic even beyond 10Gb/s, compensate the near/far losses of uneven network topologies with typical distances of up to 10-20km, and offer low round-trip latencies below the 250 μs۱-۶. A recent Ethernet encapsulation demonstration of 2.5Gb/s CPRI-traffic revealed the processing latencies of 115μs for up to 6km distances۷, while an xhaul cross-connect exploited multiple wavelength tuned 10Gb/s SFPs for wavelength re-assignment and data re-transmission at lower-latency forwarding that overcomes time-consuming Ethernet processing۸. This transparent on-the-fly wavelength conversion has long been successfully demonstrated by all optical Burst-Mode Wavelength Converters (BMWCs), simultaneously supporting burst-mode equalization capabilities at high-bitrates۹۱۰, extending also the reach of traditional PONs۱۱-۱۳, suggesting similar benefits for fronthaul uplink scenarios. However, high bitrates beyond 10 Gb/s have been
demonstrated mainly for RZ pulses\textsuperscript{9,10}, either using challenging Manchester encoding with doubled bandwidth requirements for the driving electronics\textsuperscript{9} or complex unbalanced SOA-MZI structures\textsuperscript{10}. In the case of NRZ pulses for PONs, gain clamping of two cascaded SOAs initially achieved speeds of only 2.5Gb/s\textsuperscript{11} and later extended to 10Gb/s by inserting a third cascade of a SOA-MZI\textsuperscript{12}, doubling the number of SOA-elements and energy-consumption.

In this paper, we demonstrate a novel simplified all optical BMWC, relying only on a single balanced SOA-MZI device, operating in a differentially biased deeply saturated SOA-gain scheme\textsuperscript{14}. The proposed BMWC scheme offers a non-linear transfer function that simultaneously facilitates both power-equalization and wavelength conversion functionalities through a single device, yielding 50\% reduction in the number of active components and energy consumption of BMWCs for PONs\textsuperscript{12}. Error-free operation is demonstrated for bursty traffic with up to 9dB loud/soft ratio at 10 Gb/s NRZ data, while its performance is evaluated under realistic, non-dispersion compensated, transmission links up to 14km. A BER improvement up to 6.1 dB is reported for 10 Gb/s operation and up to 9dB loud/soft ratio, while its successful operation over 14km differential fiber length validate its credentials to operate in 5G mobile fronthaul and PON networks.

2. DEVICE AND EXPERIMENTAL SETUP

Figure 1(b) shows the proposed architecture, with antenna-RU being first connected to ONUs before transmitting the loud/soft bursts towards the BMWC and in turn to OLT. The operation of the BMWC is to equalize the loud/soft packet bursts due to different optical path losses of near/far ONUs, and perform wavelength conversion for backhaul transmission. The experimental setup used for the evaluation of the BMWC is shown in Fig. 2, with the BMWC labeled with a green marker and two packet-generation stages with and without 14km-long fiber (Transmission stage I and II).

The BMWC comprises a SOA-MZI at a differentially biased scheme with SOAs operated in the deeply saturated regime at 268mA, 330mA respectively, to realize a non-linear SOA-MZI transfer function with clipping properties for different control power levels \cite{14}. A CW beam at $\lambda_2=1549.3$nm of 6.95dBm is injected, as the SOA-MZI input, in port B. The control signal, originating from the Transmission stage, is split into two identical signals in a 50:50 coupler that are injected in SOA-MZI ports A and H, acting as the push and pull signals with power levels of 9.8dBm and -1.5dBm respectively. Finally, two additional CW assist-light beams at $\lambda_{as1}=\lambda_{as2}=1548$nm of 7.13dBm and -11.93dBm were fed to the ports D and E, to ensure SOA operation in the deeply saturation regime. For the transmission stage, two separate layout-configurations have been implemented and used inter-changeably in the setup, without any fiber propagation (stage I) and with 14km fiber-spool (stage II), as marked with purple markers in Fig. 2, to evaluate two different scenarios. In stage I, a CW at $\lambda_1=1550.4$nm is injected into two cascaded LiNbO$_3$ modulators driven by Programmable Pattern Generators (PPGs), with the first producing two sequential 10Gb/s 2$^7$-1 PRBS packets and the second imprinting different power-level variations to the two packets, by changing its driver’s gain. In stage II, two separate signals at $\lambda_1=1550.4$nm and

![Fig. 1 (a) Traditional PON architecture, (b) Proposed architecture with the Burst Mode Wavelength Converters (BMWC)](image-url)
\( \lambda = 1551.1 \text{nm} \) are combined in a 50:50 coupler and injected into a PPG-driven LiNbO\(_3\) modulator to produce a 284-bit pattern consisting of a packet of 10Gb/s 2\(^{-1}\) PRBS, with the rest of the pattern comprising zeros.

The resulting signal was demultiplexed by an Arrayed Waveguide Grating (AWG), and transmitted through two different optical paths with 14km difference. An Optical Delay Line (ODL) in conjunction with a 50:50 coupler, are utilized to merge the incoming optical signals, into a single packet stream comprising sequential loud/soft packets with an intermediate guardband of 15 bits, to emulate a PON link between two ONUs and the BMWC. The signal was finally amplified in an EDFA and filtered in a 3nm Optical Bandpass Filter (OBPF), before being injected as input to the BMWC. The final BMWC output, is filtered and launched to an oscilloscope (OSC) and a Bit-Error-Rate Tester (BERT) for monitoring purposes, while OBPF, Isolators (ISO), Polarization Controllers (PC), Variable Optical Attenuators (VOA), ODL and 99:1 monitoring couplers are used throughout the setup to control and optimize the operational settings of the experiment.

### 3. EXPERIMENTAL RESULTS

In order to demonstrate the power-equalization and wavelength switching capabilities of the proposed BMWC and evaluate the maximum supported dynamic range of the input packets, the BMWC was characterized at 10 Gb/s with packets of loud/soft peak-power ratios of 4dB, 6dB, and 8dB using Transmission stage I. The input traces of the incoming packets at \( \lambda_1 = 1550.4 \text{nm} \) are shown in Fig. 3(a), (b) and (c) featuring two loud and three soft packets interleaved, while Fig. 3(d), (e) and (f) depict the respective output traces of two consecutive packets at \( \lambda_2 = 1549.3 \text{nm} \) for comparison purposes. As can be observed, all output traces exhibit flat and equalized peak-power levels for all bits, demonstrating both power-equalization and wavelength conversion, while the respective equalized output eye diagrams illustrated in Fig. 3(g), (h) and (i), exhibit similar wide open eye diagrams with peak-power variation less than 0.5dB, measured by means of the Amplitude Modulation (AM) at the center of the eye diagram. The performance of the BMWC was also evaluated with the aid of BER measurements for loud/soft ratios ranging from 4dB up to 9dB and the BER curves are plotted in Fig. 4(a), using solid lines for the output signals and transparent-dashed lines for the input signals, while a quantitative representation of the BER improvement between the input and output is shown in Fig. 4(b), with error free operation at 10\(^{-9}\) achieved at the output for all loud/soft ratio values up to 9dB. On the contrary, error free operation for the input signal was obtained only for loud/soft ratios up to 7dB at the 10\(^{-9}\) condition, up to 8dB for the 10\(^{-4}\) condition and could not be achieved for the 9dB ratio, as shown in Fig. 4(b). This is attributed to the high loud/soft ratios that heavily degraded the BER measurements.
to the requirement for a low threshold value in the BER-tester to detect the pattern of the soft packets.

The operation of the proposed BMWC, was also evaluated using Transmission stage II in Fig. 2 to emulate a realistic PON scenario, utilizing a packet stream comprising optical packets traversing through optical fibers with 14-km differential length, and as such arriving in the BMWC with different power and dispersion characteristics. The time traces and eye diagrams of the incoming packet bursts are shown in Fig. 5(a) and (b), exhibiting 3.5dB loud/soft ratio due to the propagation losses and broadened pulses for the soft burst due to the chirping effects of chromatic dispersion. The BMWC’s output signal, shown in Fig. 5(c) and (d), features a flat power level and a wide open eye diagram with an Extinction Ratio.

Fig. 3 Experimental results for 10Gb/s for 4dB loud/soft ratio (a) input trace (5μs/div), (d) output trace (2μs/div), (g) eye diagram (50ps/div). For 6dB (b) input trace, (e) output trace, (h) eye diagram. For 8dB (c) input trace, (f) output trace, (i) output eye diagram

Fig. 4 (a) BER measurements for input and output signals and (b) BER improvement of input-output signals at different loud/soft ratios
ER) of 6.5dB and a peak-power variation, measured as AM, of only 1.5dB, revealing the device’s capability to equalize and wavelength switch 10Gb/s NRZ data stemming from typical fronthaul distances up to 14km. Fig. 5(e) compares the BER measurements for the 14km fiber transmission with and without the BMWC, revealing error free operation with 3.8dB power improvement for the case of the BMWC.

4. CONCLUSION

An all optical Burst Mode Wavelength Converter relying on a differentially biased SOA-MZI scheme was demonstrated achieving error-free operation for a loud/soft ratio of 9dB at 10 Gb/s, with a BER improvement up to 6.1 dB. The device’s operation was also evaluated, in a 14km long fiber transmission scenario, validating its functionality in realistic non-dispersion compensated PON optical links, while finally the routing and equalizing features of the proposed device could potentially be employed on SOA-MZI based optical switching architectures15-17, providing increased receiver sensitivity and flexible optical power budget allocation.

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REFERENCES