An SOA-MZI NRZ Wavelength Conversion Scheme With Enhanced 2R Regeneration Characteristics

Dimitrios Apostolopoulos, Konstantinos Vyrsokinos, Panagiotis Zakynthinos, Nikos Pleros, and Hercules Avramopoulos

***Abstract*—We present a novel scheme for all-optical nonreturn-to-zero (NRZ) wavelength conversion with enhanced 2R regenerative characteristics. It employs a hybridly integrated semiconductor optical amplifier Mach–Zehnder interferometer using bidirectional data injection and an additional external continuous-wave signal for differentially biasing the interferometer arms, optimizing gain and phase conditions during the switching functionality. Experimental verification of its superior 2R regenerative capabilities are demonstrated for 10-Gb/s NRZ data signals.**

***Index Terms*—Integrated Mach–Zehnder interferometer (MZI), optical regeneration, optical signal processing, semiconductor optical amplifier (SOA), wavelength conversion (WC).**

I. Introduction

SEMICONDUCTOR optical amplifier Mach–Zehnder interferometers (SOA-MZIs) have been widely used in the past years as all-optical high-speed switches for signal conditioning and signal processing purposes, taking advantage of their low switching power requirements and their potential for integration in single- or multi-element compact chip modules [1]. Wavelength conversion (WC) is one of their major application areas, since SOA-MZIs allow for 2R regeneration of the wavelength converted signal utilizing energy restoration and amplitude jitter suppression characteristics provided by the saturable amplification in the SOAs [2]. However, their regenerative properties are counteracted by severe patterning and pulse broadening effects that stem from the SOA's gain recovery time, being so far effectively mitigated mainly for return-to-zero data signals by exploiting push–pull switching arrangements [3]. Nevertheless, as optical networks penetrate deeper into metro- and access expanding both in size and in functional performance, enhanced 2R regenerative capabilities even for nonreturn-to-zero (NRZ) data signals will be required in order to increase the transmission potential and subsequently the data-format and bit-rate transparent network regions without employing retiming processes.

The standard approach to SOA-MZI-based WC of NRZ signals employs a single control (CTR) signal offering reduced complexity but enhanced susceptibility to pulse broadening and patterning effects due to the unbalanced gain saturation in the two SOAs [4]. These effects are partially compensated in the bidirectional push–pull scheme, which employs two control pulses travelling in opposite directions through the two MZI branches [4]. The two control signals cause the same gain modulation to the two SOAs but induce a differential phase shift to the continuous-wave (CW) input signal components. This leads to a continuously gain balanced MZI and to a fully intensity balanced WC operation with improved regenerative characteristics; however, it does not ensure a fully controllable phase-balance between the SOAs resulting in nonoptimized switching and a wavelength converted signal that is superimposed on a pedestal background.

In this letter, we present a novel NRZ WC scheme with enhanced regenerative capabilities, introducing differential biasing to the two SOAs of the MZI while retaining the bidirectional push–pull control arrangement. Differential bias of the two SOAs is achieved optically by means of an additional external CW signal and allows for the controllable balance of both gain and phase in the two SOAs. The scheme has been experimentally evaluated with different 10-Gb/s NRZ pseudorandom binary data sequences (PRBS) up to $2^{31}-1$, showing in all cases improved regenerative properties compared to the bidirectional push–pull and the standard WC configurations, yielding a negative power penalty of 1.2 dBm for a $2^{7}-1$ and of 0.5 dBm for a $2^{31}-1$ PRBS sequence with respect to the degraded data input signal.

II. Concept and Experimental Setup

Fig. 1 illustrates the block diagram layouts for the standard single CTR scheme, the bidirectional push–pull control scheme, and the proposed differentially biased bidirectional push–pull configuration. All three setups are using a CW signal at a new λ_2 wavelength to which the incoming data is wavelength-converted. This signal is split into two equal components that travel through the respective SOA-MZI branches and are forced to interfere at the output of the MZI. Fig. 1(a) depicts the standard WC layout that employs a single CTR being inserted into one of the two MZI arms and affecting the gain and phase of only one of the two CW signal components. Fig. 1(b) illustrates the bidirectional push–pull injection scheme with its two identical control pulses arriving simultaneously at the two SOAs and travelling through the respective MZI branches in counterpropagating directions [4], providing in this way an inverted replica of the incoming data at its output. Finally, Fig. 1(c) presents the differentially biased bidirectional push–pull configuration that follows the setup of the bidirectional data injection scheme, but employs additionally an

Manuscript received December 11, 2008; revised April 22, 2009. First published July 17, 2009; current version published September 11, 2009.

D. Apostolopoulos, K. Vyrsokinos, P. Zakynthinos, and H. Avramopoulos are with the School of Electrical and Computer Engineering, National Technical University of Athens, Zografou, GR 15773 Athens, Greece (e-mail: apostold@mail.ntua.gr; kvyrs@cc.ece.ntua.gr; zakynth@mail.ntua.gr; hav@mail.ntua.gr).

N. Pleros is with the Department of Informatics, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece (e-mail: npleros@csd.auth.gr).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2009.2026725

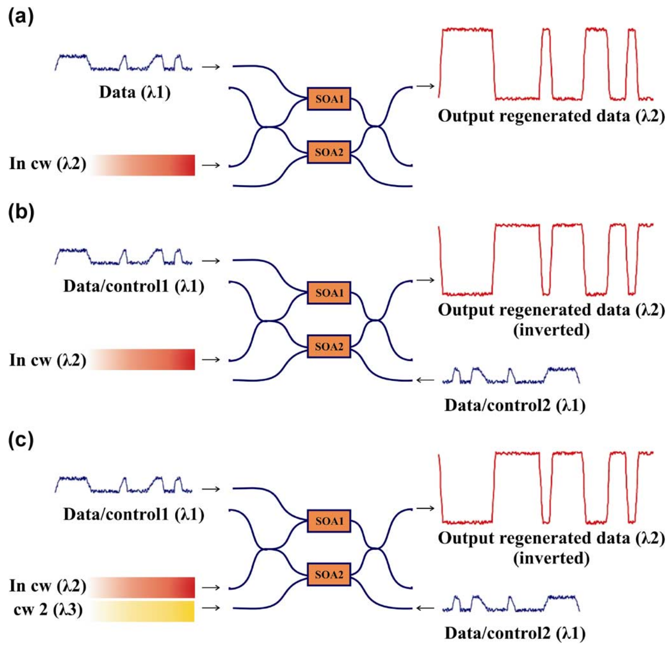

Fig. 1. Three WC configurations: (a) standard scheme, (b) bidirectional push–pull, and (c) differentially biased bidirectional scheme.

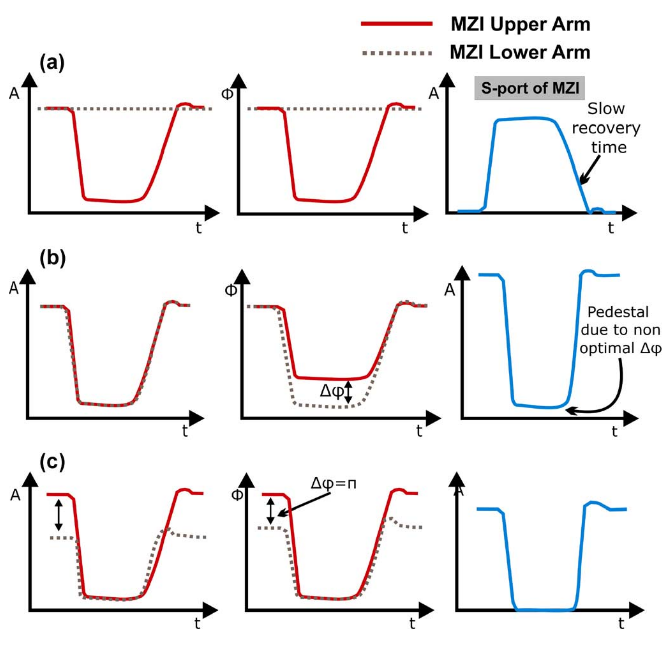

Fig. 2. Principle of operation for the: (a) standard scheme, (b) bidirectional push–pull scheme, and (c) differentially biased bidirectional scheme. The left and middle columns show the amplitude and the phase of the CW signal components at the output of the two SOAs, respectively. The right column illustrates the corresponding amplitude of the wavelength converted signal at the switched port of the MZI.

external CW signal into the lower arm SOA. Again, the inverted data waveform is obtained as the wavelength converted signal.

Fig. 2 provides a schematic representation of the principle of operation of the three WC schemes, with the left and middle figure column showing the amplitude and phase of the two CW signal components at the two SOAs, respectively, whereas the right column depicts the switched signal waveform obtained at the switched (S)-port of the MZI. Fig. 2(a) describes the

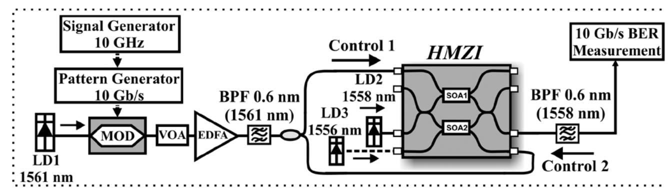

Fig. 3. Experimental setup for the WC.

standard WC functionality, where only a single CTR is used resulting to gain and phase variations to only one of the two CW signal components. In this case, interference at the output of the MZI occurs between two fields of unequal amplitude leading to incomplete and pattern-dependent switching. Moreover, the uncompensated SOA gain recovery results to a slow falling edge for the wavelength converted pulse and, subsequently, to pulse-broadening phenomena. Fig. 2(b) shows the respective amplitude and phase of the two CW signal components in the bidirectional push–pull injection scheme, where two identical control pulses travelling through the respective MZI branches in opposite directions are employed. The two control pulses induce the same gain modulation to both SOAs yielding a continuously gain balanced MZI and compensating for the noise-induced power fluctuations both during mark and space signal injection. Successful switching operation is achieved due to the differential, control pulse-direction-dependent phase change $\Delta\varphi$ experienced by the two CW components, providing an inverted replica of the control data signal at the MZI's S-port. This output signal has sharper pulse rising/falling edges and a nearly doubled eye height compared to the standard WC scheme. However, the SOA gain level optimization criterion and the absence of a phase-controlling oriented mechanism lead to a nonexact π phase shift value degrading the switching quality at space level and yielding a constant pedestal.

Fig. 1(c) illustrates the case of the differentially biased bidirectional push–pull configuration. Differentiation in biasing the gains of the two SOAs is achieved by means of an external CW signal inserted into the lower arm SOA, whose power is properly adjusted so that the lower arm input CW signal component perceives an additional π-phase shift compared to its respective component travelling through the upper MZI branch, when no control pulse is present. Whenever a control pulse enters the SOA-MZI, equal gains and phase shifts are experienced by the two input CW signal constituents resulting in optimized destructive interference at the MZI's S-port and to an ideal "0"-level for the wavelength converted signal, eliminating any undesirable pedestal. To this end, this scheme retains the improved noise reduction capabilities of the balanced configuration of the bidirectional WC scheme, while offering improved reshaping properties by suppressing the constant noise level appearing in the form of the pedestal.

Experimental evaluation of the proposed WC scheme and direct performance comparison between the three WC configurations was performed for different 10-Gb/s NRZ PRBS data sequences up to $2^{31}-1$. The experimental setup is shown in Fig. 3 and comprises the optical signal generator and a commercially available, hybridly integrated, SOA-MZI regenerator fabricated by CIP Technologies. The optical signal generator employs a CW signal at 1561 nm that was injected into a $Ti:LiNbO_3$ electrooptic modulator driven by a 10-Gb/s NRZ pulse pattern gen-

TABLE I
OPTICAL POWERS USED FOR THE THREE WC SCHEMES

WC scheme	Input CW @1558nm (dBm)	Co-propagating CTR (dBm)	Counter-propagating CTR (dBm)	external CW@1556 nm (dBm)
Standard	3.4	0		
Bid. push-pull	3.43	3.15	1.74	
Diff. biased	1.76	-0.7	-1.2	2.52

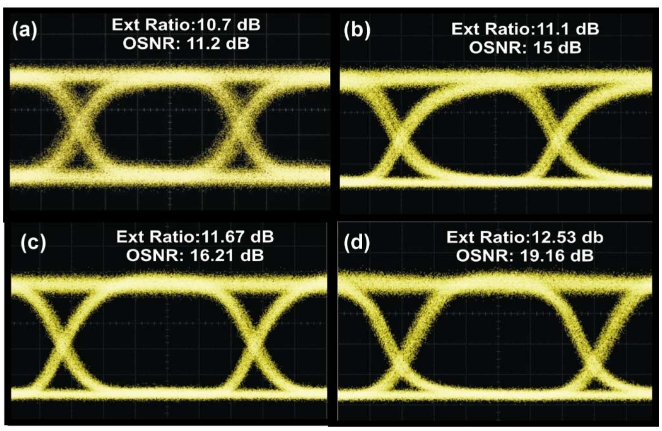

Fig. 4. Eye diagram of the: (a) degraded input signal, (b) standard single CTR scheme, (c) bidirectional push–pull scheme, and (d) differentially biased bidirectional scheme.

erator and producing a PRBS data stream. This pulse train was then inserted into a variable optical attenuator and an erbium-doped fiber amplifier (EDFA) to degrade its quality in terms of optical signal-to-noise ratio (OSNR) and extinction ratio prior to entering the MZI as the control signal. A 1558-nm laser diode was used as the input CW signal generating source, whereas a similar laser diode provided the external 1556-nm CW beam for the differentially biased scheme. The two SOAs are 1.6-μm -long multiquantum-well structures with 500-μm mode converters at both ends, having a small signal gain of 28 dB and 25 ps 1/e gain recovery-time under saturation. Table I shows the powers used for the three WC schemes.

III. RESULTS AND DISCUSSION

Fig. 4 shows the eye diagrams of the degraded input and the three wavelength converted signals for a $2^7 - 1$ PRBS data stream. OSNR and extinction ratio measurements reveal the increased signal quality improvement properties of the differentially biased approach. The degraded input stream exhibited an OSNR of 11.2 dB and extinction ratio of 10.7 dB, as shown in Fig. 4(a), whereas the respective values for the wavelength converted signal at the standard WC scheme were 15 and 11.1 dB [Fig. 4(b)], at the bidirectional push–pull scheme 16.21 and 11.67 dB [Fig. 4(c)], and at the differentially biased bidirectional scheme 19.16 and 12.53 dB [Fig. 4(d)]. The OSNR values for the incoming and the wavelength converted signals were calculated at the output of the 0.6-nm bandpass filters located next to EDFA1 and the SOA-MZI, respectively, by means of the polarization nulling method [5].

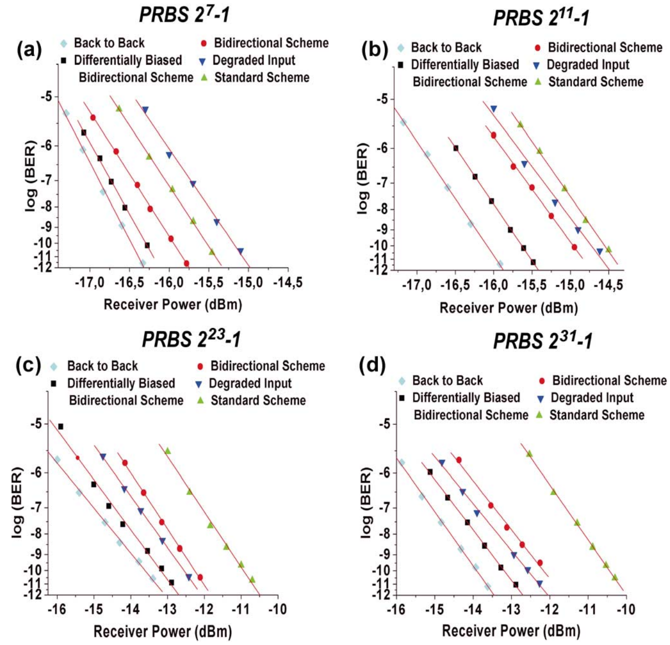

Fig. 5. BER measurements for various order PRBSes.

Fig. 5 shows the bit-error-rate (BER) curves for the wavelength converted signals of the three configurations. The highest negative power penalty among the three respective wavelength converted outputs was always obtained by means of the differentially biased WC configuration, ranging from 0.5 dBm in the case of $2^{31} - 1$ up to 1.2 dBm in the case of $2^7 - 1$ PRBS sequences used as the degraded input signal. It should be noted that the standard as well as the bidirectional push–pull WC schemes provided a positive power penalty when $2^{31} - 1$ PRBS data were used, verifying the superior regenerative characteristics of the differentially biased arrangement and its enhanced robustness to the inherent pattern-dependent operation of SOA-based WC structures.

IV. CONCLUSION

We have presented a novel scheme with improved 2R regeneration capabilities for all-optical NRZ signal WC. Our technique utilizes a differentially biased SOA-MZI switch operating in a bidirectional push–pull configuration.

REFERENCES

[1] L. Stampoulidis *et al.*, "Enabling Tb/s photonic routing: Development of advanced hybrid integrated photonic devices to realize high-speed, all-optical packet switching," *IEEE J. Sel. Topics Quantum Electron.*, vol. 14, no. 3, pp. 849–860, May/Jun. 2008.

[2] A. Poustie, R. Wyatt, R. McDougall, G. Maxwell, and B. R. Hemenway, "Optical timing jitter transfer characteristics of a 40 Gb/s hybrid integrated SOA-Mach-Zehnder interferometer all-optical regenerator," in *Proc. ECOC Conf.*, vol. 3, p. 413, Paper We 2.4.6.

[3] K. Tajima, "All-optical switch with switch-off time unrestricted by carrier lifetime," *Jpn. J. Appl. Phys.*, vol. 32, no. 12A, pt. 2, pp. L1746–L1749, Dec. 1993.

[4] M. Hattori, K. Nishimura, R. Inohara, and M. Usami, "Bidirectional data injection operation of hybrid integrated SOA-MZI all-optical wavelength converter," *J. Lightw. Technol.*, vol. 25, no. 2, pp. 512–519, Feb. 2007.

[5] J. H. Lee, J. H. Lee, D. K. Jung, C. H. Kim, and Y. C. Chung, "OSNR monitoring technique using polarization-nulling method," *IEEE Photon. Technol. Lett.*, vol. 13, no. 1, pp. 88–90, Jan. 2001.