Cascadability Performance Evaluation of a New NRZ SOA-MZI Wavelength Converter

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***Abstract*—We evaluate the cascadability performance of a new semiconductor optical amplifier (SOA) Mach–Zehnder interferometer-based nonreturn-to-zero wavelength converter in a loop experiment. We use the bidirectional data injection control scheme with an additional continuous-wave signal to optimize the gains and phases imparted by the SOAs. The scheme has been shown to be capable of eight cascaded, error-free wavelength conversions at 10 Gb/s.**

***Index Terms*—All-optical wavelength conversion (WC), hybrid-integrated Mach–Zehnder interferometer (HMZI).**

I. Introduction

WAVELENGTH conversion (WC) is a key enabler of transparent all-optical networks. Besides wavelength changing, it has been used in all-optical switching and processing, regeneration, routing, and more recently in contention resolution [1]. One of the main devices used for wavelength conversion is the semiconductor optical amplifier, Mach–Zehnder interferometer (SOA-MZI). Depending on whether wavelength conversion is performed on an external continuous wave (CW) or a clock signal, SOA-MZIs possess either 2R (reamplifying, reshaping) or 3R (reamplifying, reshaping, and retiming) regenerative properties [2].

The SOA-MZI wavelength conversion on an external CW signal is significantly simpler to implement, as it does not require a high-speed short pulse laser or a clock recovery unit with their associated drivers. Unfortunately, this type of simpler wavelength converter with its 2R regenerative properties has also been shown to be capable of a very limited number of repeated cascades, significantly restricting its use in a high-speed fiber transmission line [3]. Moreover, signal degradation through repeated cascades also limits the number of consecutive SOA-MZI gates that may be used in optical signal processing circuits [4]. It would therefore be highly advantageous if the number of error free, successive cascades through SOA-MZI-based wavelength converters could be extended.

The simplest method to perform WC in an SOA-MZI is with single control, but this results in pulse broadening and patterning effects due to the unbalanced gain saturation in the two SOAs [5]. These are partly compensated in the bidirectional data injection scheme that uses countertraveling control signals in the two MZI branches [5]. We have observed that by using an additional external CW signal on one of the SOAs of the MZI, it is possible to differentially bias both the gains and the phases imparted on the signal in the two arms of the interferometer. This differentially biased bidirectional data injection control improves further on the performance of the bidirectional data injection arrangement. In this communication, we examine and compare in a recirculating loop experiment the cascade potential of the three control arrangements for wavelength conversion in an SOA-MZI. We show that the standard single control arrangement can only achieve two error-free cascades. The bidirectional data injection control scheme can achieve four cascades. The scheme proposed here extends the error-free cascades of SOA-MZIs to eight.

II. Experiment

Fig. 1(a)–(c) shows, respectively, SOA-MZI-based wavelength converters following the standard single control scheme, the bidirectional data injection control scheme and the differentially biased scheme proposed in this letter. The latter follows the layout of the bidirectional data injection scheme but employs an additional external CW signal into the lower arm SOA. The role of the external CW signal is to differentially bias the gains of the two SOAs so as to provide a phase shift $\Delta\varphi$ that equals π between the input signal components travelling in the two arms of the MZI, especially when there is no control pulse present. Whenever a control pulse enters the SOA-MZI, equal gains and phase shifts are experienced by the two CW input signal constituents resulting in optimized destructive interference at the MZI's S-output port and an ideal "0" wavelength converted level eliminating any undesirable pedestal. As in the case of the bidirectional data injection control scheme, the output signal of the differentially biased configuration is an inverted replica of the original data sequence.

The cascading performance of the three schemes was experimentally investigated with the use of the recirculating loop depicted in Fig. 1(d). The use of the loop allows for a large number

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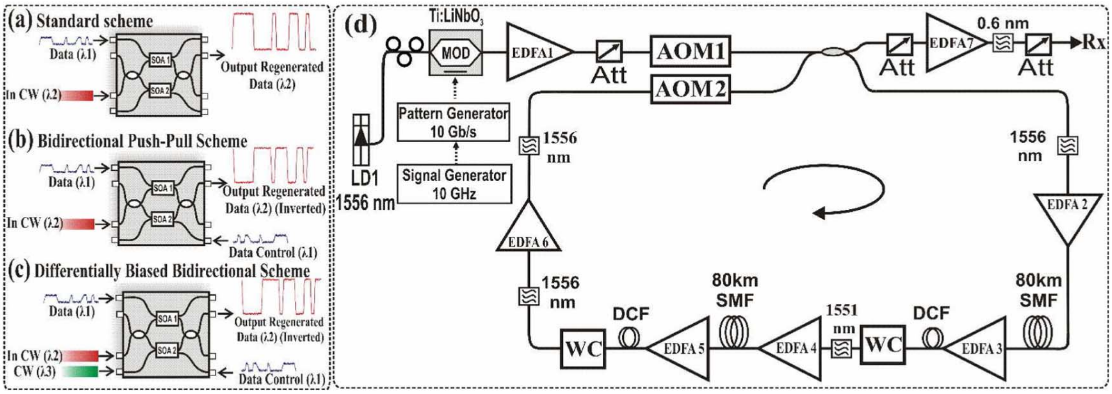

Fig. 1. Principle of operation of (a) standard WC scheme with one control signal, (b) bidirectional push–pull WC scheme, and (c) differentially biased bidirectional push–pull scheme with additional CW signal. (d) Experimental loop setup.

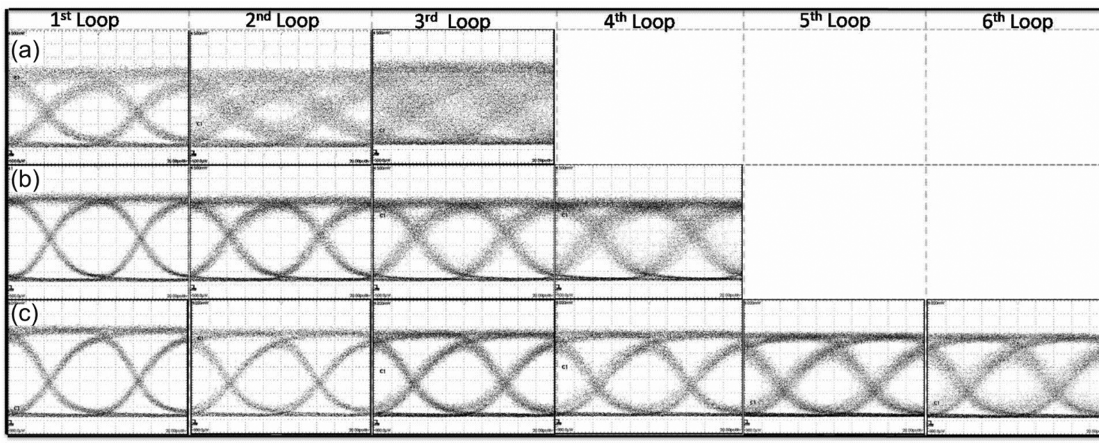

Fig. 2. Eye diagrams at the loop output for (a) standard WC scheme with one control signal, (b) bidirectional push–pull scheme, (c) differentially biased bidirectional push–pull scheme. Each loop employs two cascaded wavelength converters in sequence. Eye-diagram time scales are 20 ps/div.

of cascade stages to be studied with the use of a limited number of SOA-MZI switches. The loop input signal was generated from a 1556-nm CW laser diode modulated in a $Ti:LiNbO_3$ electrooptic modulator driven with a 10 Gb/s electrical NRZ signal to produce a $2^{31}-1$ pseudorandom bit sequence (PRBS). The recirculating loop consisted of two spans of 80-km single-mode fiber (SMF) fibers each followed by an erbium-doped fiber amplifier (EDFA) and the appropriate dispersion compensating fiber (DCF) (-1360 and -1190 ps/nm, respectively) to compensate for power loss and chromatic dispersion. The input signal power levels in the two SMF spans and DCFs are 3.2 and -4 dBm. Two SOA-MZI wavelength converters were used in each loop transit, one to convert the incoming signal from 1556 to 1551 nm after transmission in the first fiber span and the second to convert back from 1551 nm to the original wavelength 1556 nm. The SOA-MZIs are commercially available (by CIP Technologies), hybrid-integrated devices. They were operated with 300 mA current and required 1.7 dBm of CW signal at their input port. The powers of the control signals were 4 dBm for the standard scheme, 2 and -1.5 dBm for the co- and counterpropagating signals of the bidirectional scheme, and 2 and -0.5 dBm for the differentially biased data injection configuration. Finally, the power of the additional CW (1560 nm) signal in the differentially biased data injection scheme was 4 dBm. The throughput loss of the standard, bidirectional, and differentially biased schemes was 4, 3.1, and 4.22 dBm, respectively. Results have been obtained after optimization of the polarization states in the loop setup and without further adjustment during data collection.

III. Results and Discussion

Fig. 2 illustrates the change in the eye-diagrams after successive transits of the signal through the loop for the three wavelength conversion schemes. Each transit through the loop corresponds to a pair of consecutive wavelength conversions. Fig. 2(a) depicts the output of the loop for the standard single control scheme and shows an almost closed eye after the second transit through the loop. This figure corresponds to just four wavelength conversions and displays the rapid accumulation of amplitude and timing jitter. Fig. 2(b) shows the performance of the bidirectional data injection control scheme and displays a significant improvement, as the counterpropagating control suppresses the accumulation of jitter in amplitude and time. Two transits through the loop are error free, corresponding to four successive wavelength conversions. Finally, Fig. 3(c) shows the performance of the new, differentially biased, bidirectional data injection control scheme. It indicates that even after four loop transits that correspond to eight successive

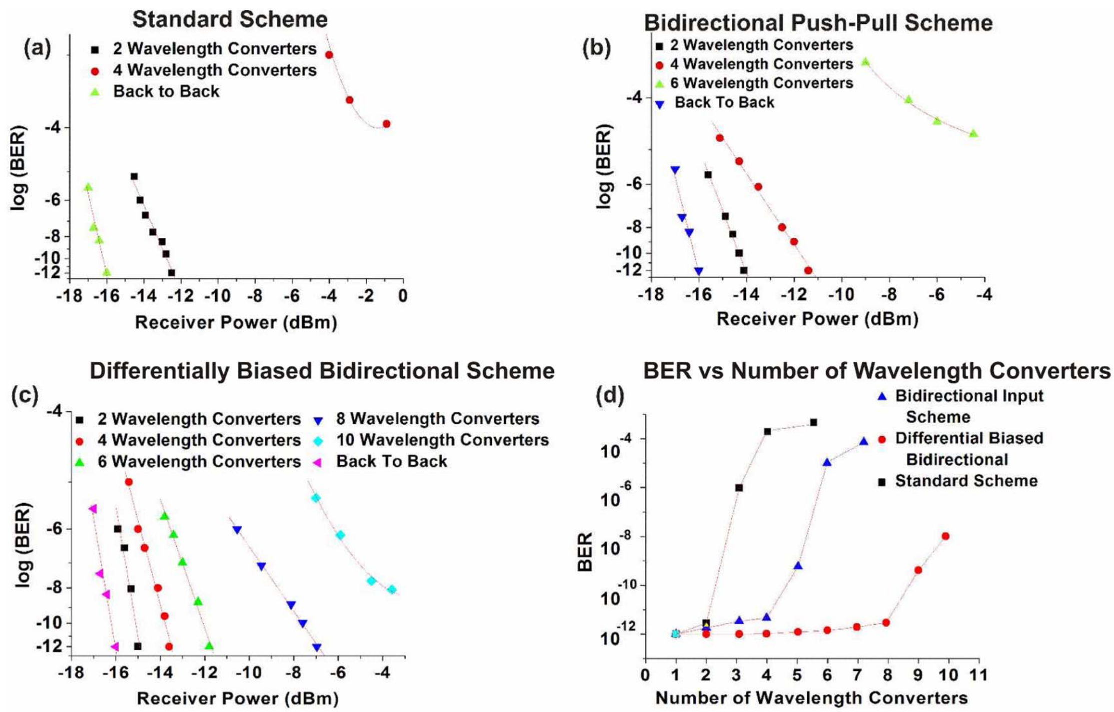

Fig. 3. BER measurements.

wavelength conversions, the eye diagram is wide open and error-free signal is obtained. Fig. 3(a)–(c) shows bit-error-rate (BER) measurements against received power for the single control, the bidirectional data injection, and the differentially biased bidirectional data injection control scheme, respectively.

Bit-error-rate measurements were performed at the same received optical signal-to-noise ratio (OSNR) value of 15 dB. Error-free operation for our scheme is verified even after eight MZI cascades compared to the two and four successful cascades for the single and bidirectional schemes. Fig. 3(d) displays the degradation in BERs for the three schemes against the number of cascades through the wavelength converters. The power of the received signal was -4 dBm and its OSNR 15 dB. The diagram shows that for the differentially biased bidirectional data injection scheme, the BER remains error free for up to eight cascades and that even after ten cascades it drops to 10^{-8}. By comparison an error floor at 10^{-4} was measured after four and six cascades for the standard and the bidirectional arrangements. Moreover, the abrupt increase in BER that can be seen in this figure is due to the additional degradation that the SOA-MZI introduces to the wavelength converted signal when the control data sequence is degraded beyond a certain point after a number of cascades, different for each wavelength conversion scheme. Furthermore, the four BER diagrams of Fig. 3, do not present BER curves for the recirculating loop without the wavelength converters. The reason for this is that the study presented in this manuscript focuses on the evaluation of the cascade potential of the new wavelength conversion scheme and the comparison of its performance to other NRZ SOA-MZI-based WC solutions. Studies that concern the performance evaluation of various SOA-MZI regenerator schemes in transmission links or their comparison to systems that do not use wavelength converters/regenerators, are out of the scope of this manuscript.

IV. Conclusion

We have examined the performance of a novel arrangement for NRZ wavelength conversion in an SOA-MZI in successive cascades in a loop experiment. The arrangement involves bidirectional data injection control with an additional CW signal to optimize gains and phases imparted by the SOAs. The scheme has been shown to be capable of eight cascaded, error-free wavelength conversions. By comparison, the standard single control scheme could achieve only two cascaded, error-free wavelength conversions, and the bidirectional data injection Scheme 4.

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