Single and Multicast Wavelength Conversion at 40 Gb/s by Means of Fast Nonlinear Polarization Switching in an SOA

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***Abstract*—We experimentally demonstrate all-optical wavelength conversion of a 40-Gb/s nonreturn-to-zero signal by means of nonlinear polarization switching in a single semiconductor optical amplifier (SOA). Using a highly nonlinear SOA optimized for very fast gain recovery time, we observe no appreciable penalty for the conventional (single) wavelength conversion. We also obtain, for the first time by using this technique, the simultaneous multiconversion to different wavelengths (four on a 200-GHz frequency grid) of an input signal.**

***Index Terms*—All-optical wavelength conversion, multicasting, nonlinear polarization switching (NPS), semiconductor optical amplifier (SOA), wavelength-division-multiplexing (WDM).**

I. INTRODUCTION

ALL-OPTICAL processing of signals in the gigabit/second range using the fast optical nonlinearities of the semiconductor optical amplifiers (SOAs) has been extensively investigated in the last years. Compact and integrated devices based on this technology seem to be the most promising way to support migration of optics from the pure point-to-point transport applications to more advanced node functionalities [1], [2]. Among the various techniques based on SOA dynamics, an attractive option is to use the nonlinear optically induced birefringence to obtain signal switching via polarization switching [3]. The structure of an SOA-based nonlinear polarization switch (NPS) is quite simple. It requires local polarization-controlled continuous-wave (CW) signals, an SOA, and a polarization-controlled output to a polarization-beam splitter (PBS). Moreover, the working principle of the NPS is somewhat similar to that of a nonlinear interferometer. A driving signal produces a change of the effective refraction indexes of the two orthogonal modes of the SOA, and for this reason the transverse electric and transverse magnetic modes of a copropagating signal experience a net phase difference and finally interfere in the PBS. Hence, potentially high-speed operation with regenerative property and two different working modes for switching (logically inverted and noninverted) are possible.

Based on this basic principle for nonlinear polarization switching, various optical functions were demonstrated up to now. Logical gates [4], [5], optical demultiplexing devices [6], [7], and wavelength converters [8], [9] have been reported in literature. Optical signal processing for application in an optical packet switching environment is also possible using self-induced polarization rotation with a similar scheme [10]. In addition, NPS in linear optical amplifiers has been proposed also for 2R regeneration purposes [11].

However, in all cases, the main drawback was in terms of operating bit rate, as the maximum bit rate was quite limited, e.g., 5 Gb/s for the logical gates and 10 Gb/s for the wavelength converters. In the last case, a significant penalty (3 dB) was also reported. Only using more involved setups exploiting a differential scheme, 40-Gb/s operation has been reported [12].

In this letter, we experimentally assess the potential of NPS in the usual (not differential) configuration at 40 Gb/s for the first time. The key element for enhancing the speed of the NPS is the use of an SOA optimized for high gain figure and very fast saturated gain recovery time. First, conventional wavelength conversion is obtained for a 40-Gb/s nonreturn-to-zero (NRZ) signal with no penalty. Furthermore, the NPS also produces multiple simultaneous conversion to different destination wavelengths. This last feature could be useful both for obtaining wavelength-division-multiplexing broadcast or multicast of an incoming data signal to different output fibers [13] and for optical signal processing in optical packet switched networks. Indeed, this function has been used in all-optical header recognition to realize time to wavelength conversion of the header address [14].

II. EXPERIMENT

The experimental setup is shown in Fig. 1. First, we generate the 40-Gb/s data signal by externally modulating a CW distributed feedback laser at $\lambda = 1556.5$ nm, with a low-chirp electroabsorption modulator (EAM). The EAM is driven by a 39.813-Gb/s, $2^{23} - 1$ long, pseudorandom bit sequence NRZ electrical data generated by a 40-Gb/s bit-error-rate tester (BERT). This optical signal is injected in the SOA together with four local, 200-GHz-spaced CW signals. The CW lightwaves have parallel polarization and are combined by an arrayed waveguide grating (AWG). At the SOA input, the power level is 13 dBm for the modulated pump and 6.5 dBm for each of the CW channels.

The multiple quantum-well SOA is a pigtailed, mode expanded, high confinement factor (20%) device, with 31-dB small-signal gain, 10-dBm output saturation power, and 1.5-dB

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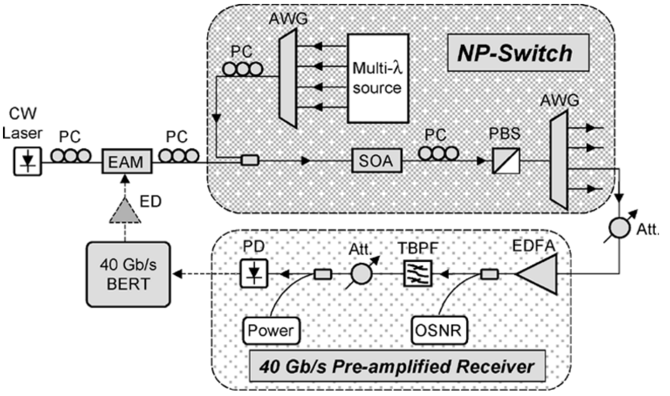

Fig. 1. Experimental setup. ED: electrical driver. PC: polarization controller. TBPF: tunable bandpass filter. PD: 40-GHz photodiode.

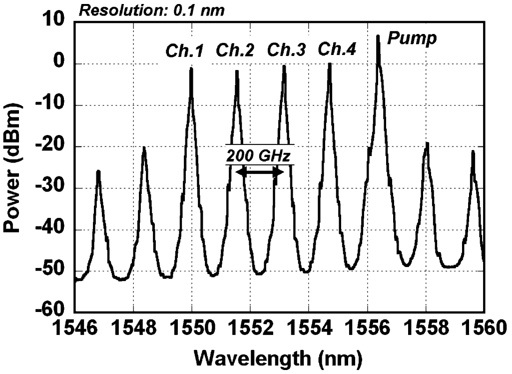

Fig. 2. Optical spectrum at the SOA output, when the pump and the four CW channels are on a 200-GHz frequency grid.

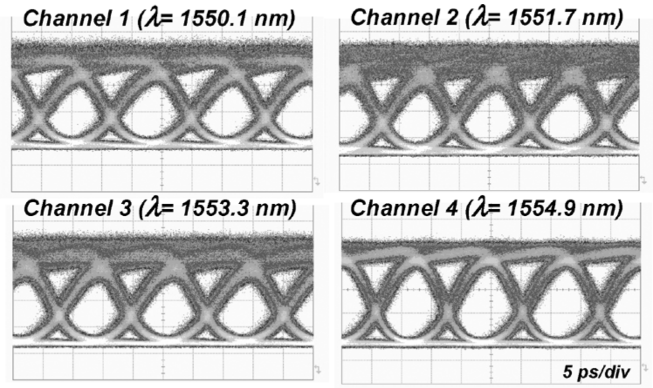

Fig. 3. Eye diagrams of the four simultaneously converted 40-Gb/s copies.

residual polarization-dependent gain (PDG). The device is optimized to have 60% gain recovery time around 12 ps at a drive current of 300 mA. The amplified spontaneous emission (ASE) ripple is 0.2 dB. The output from the SOA is polarization controlled and sent to a PBS with around 30-dB polarization extinction ratio. One of the two PBS outputs is sent to the second AWG, which has the same channel allocation as the first one. This AWG separates the four wavelength-converted signals to different output fibers, removing the other spurious signals. Those signals are separately analyzed using a preamplified receiver connected to the 40-Gb/s BERT. This receiver is made of an high gain erbium-doped fiber amplifier (EDFA), a 1.2-nm tunable bandpass filter for ASE rejection, and a fast photodiode [(PD) bandwidth $= 40$ GHz]. The optical signal-to-noise ratio (OSNR) is taken after the EDFA and all measurements are performed at constant power (-2 dBm) on the PD.

The states of polarization (SOPs) of the various signals are carefully optimized. Particularly, in order to have the maximum polarization modulation efficiency, the SOP of all four local CW signals is at 45° angle with respect to the axis of the SOA [15]. At the SOA output, using a polarization controller, all those signals are rotated so that they have minimum power at the PBS output when the coinjected pump is zero. Hence, this setup is working in the noninverted logic mode. Therefore, when logical ones of the pump signal pass through the SOA, the resulting polarization rotation of the signals is converted into an increased intensity at the PBS output. In the following, we will see that this process is effective either for a single channel and for all the CW channels at the same time.

III. RESULTS AND DISCUSSION

In Fig. 2, we report the optical spectrum taken at the SOA output. All signals are on a 200-GHz grid. The pump is the 40-Gb/s intensity modulated signal and the four CW channels are polarization modulated at this point.

Significant four-wave mixing (FWM) contributions can be seen aside the input signals, because of the deep saturation and high nonlinearity of the device. Nevertheless, this effect is not a major limiting factor of the quality of the converted signals. The eye diagrams taken after the PBS and the AWG demultiplexer of all the four converted channels are indeed shown in Fig. 3. Despite some noise on the one level, all the channels show a clear eye opening. The intensity noise is probably due to the beating of the different FWM components that arise in the multimixing process in the SOA. Several FWM tones are generated between the four copolarized channels. Moreover, internal channels (two and three), jammed by more FWM components show higher intensity noise than aside channels (one and four).

While the maximum conversion efficiency is obtained for the CW signals at 45° with respect to SOA, the switching process has a noncritical dependence on the SOP of the pump signal. This can be understood by noticing that the phase difference between the copropagating modes in the SOA is proportional to differential gain between the two modes. In case of polarization insensitive devices, the differential saturated gain has only a slight dependence from the SOP of the saturating signal. Indeed we find limited variations at the output in the case of limited changes of the incoming signal SOP. On the other hand, when we perform abrupt changes of the input signal SOP, a slight reoptimization of the polarization controller at the SOA output is required. This behavior is likely due to the residual PDG of the device. The intensity of the four converted channels at the AWG output is between -2 and -4 dBm, hence conversion efficiency of the switch for all the channels is in the range between -8.5 and -10.5 dB.

A quantitative evaluation of the quality of the converted signals is obtained by the BER measurements that are reported in

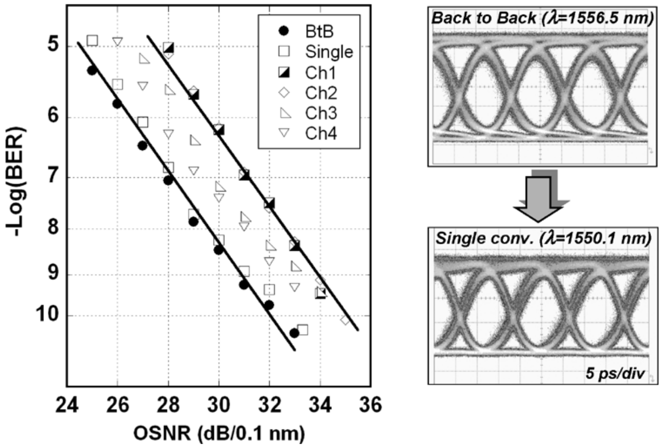

Fig. 4. On the left, BER measurements for the back-to-back 40-Gb/s signal (dots) and for the single (squares) and multiple wavelength converted channels. On the right, the eye diagrams of the incoming and of the 800-GHz wavelength converted 40-Gb/s signal in the case of single conversion.

Fig. 4. First, we test the switch for usual conversion to a single wavelength.

In this case, we have only one CW laser at 1550.1 nm with the input power increased to 9 dBm to optimize the quality of the converted signal. In this configuration, the input signal is 800-GHz wavelength down converted.

The eye diagrams of the converted signal and, for comparison, of the original 40-Gb/s signal, are reported in the right insets of Fig. 3. As can be seen, the quality of the converted signal is high and the BER measurements confirm that there is no significant OSNR penalty (at 10^{-9} BER) and no evidence of BER floor. We outline that the best reported result taken by NPS [10] showed a quite high power penalty (3 dB) at the lower bit rate of 10 Gb/s.

We then analyze the BER values in the case of multiwavelength conversion. In this case, all the four CW channels are turned on (see spectrum in Fig. 2). From Fig. 4, we see that the maximum OSNR penalty is around 3.2 dB for Channels 1 and 2. This penalty is related to the distortions in the mark level that are shown in Fig. 2. Nevertheless, those penalty levels are significantly lower than those previously obtained at 40 Gb/s using an alternative technique [16].

IV. CONCLUSION

We experimentally demonstrated that a wavelength converter based on optically induced birefringence polarization switching in an SOA can properly work at 40 Gb/s. By exploiting a highly nonlinear SOA with very short gain recovery time, we obtain 800-GHz wavelength conversion without appreciable penalty. Using the same technique, we also obtained the simultaneous conversion of an incoming 40-Gb/s NRZ data signal to four 200-GHz-spaced channels. In this case, the maximum measured OSNR penalty is 3.2 dB and the conversion efficiency is in the range between −8.5 and −10.5 dB. Considering those values, we may expect that a higher number of converted channels may be obtained using additional CW lasers.

Moreover, we believe that the results presented in this letter can pave the way to the use of the NPS for ultrafast optical processing (as an example, for logical optical gates or optical header processing working at 40 Gb/s).

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