Enhancing the Frequency Response of Cross-Polarization Wavelength Conversion

Chia Chien Wei, Ming Fang Huang, and Jason (Jyehong) Chen

Abstract—**This work presents a novel wavelength conversion scheme, differential cross-polarization modulation (DXPoM), using an extra birefringence delay to enhance the performance of the conventional cross-polarization modulation. Simulation and experimental results confirm that the predicted performance is enhanced. Using the proposed scheme improves rise time by over 300%, reduces timing jitter by 50%, and increases extinction ratio by 9%.**

Index Terms—**Birefringence, frequency conversion, semiconductor optical amplifiers (SOAs), wavelength-division multiplexing (WDM).**

I. Introduction

All-optical wavelength converters (AOWCs) are expected to become key components in future wavelength-division-multiplexing (WDM) networks [1]. Wavelength converters will increase the flexibility and the capacity of WDM networks, and could be used in wavelength routers that manage wavelength paths through optical networks based on complex meshes, rather than point-to-point architectures. However, optoelectronic conversion methods, due to their bit-rate dependence, dramatically increase costs when the system is upgraded and the costs increase as the bit rate rises. Several AOWCs based on semiconductor optical amplifiers (SOAs) have been proposed, such as cross-gain modulation (XGM) [2], cross-phase modulation (XPM) [2], four-wave mixing (FWM) [3], and cross-polarization modulation (XPoM) [4]. Each scheme has its own advantages and disadvantages. For example, FWM has low conversion efficiency, and the conversion speed of XGM, XPM, and XPoM are limited by the carrier's recovery time. Among these parameters, conversion speed is considered to be the most important factor; insufficient speed response causes larger timing jitter and, thus, limits cascadability [5].

This study presents a novel wavelength conversion scheme by adding an extra birefringence delay line in the standard XPoM method. While XPoM and XPM are both based on interferometric principle, time differential between two arms in XPM [6], [7] also works in XPoM. Therefore, with the extra delay line, the conversion speed of XPoM is enhanced significantly. Since the proposed approach adjusts the time differential of XPoM between transverse electronic (TE) and transverse magnetic (TM) modes, the new technique is referred to here as differential cross-polarization modulation (DXPoM). The new scheme functions as a 2R regenerator that provides both pulse reamplification and reshaping functions. Both simulation and experimental results corroborate that the predicted performance is enhanced. Compared to the conventional XPoM method, the experimental results for DXPoM improve rise time by over 300%, reduce timing jitter by 50%, and increase extinction ratio (ER) by 9%.

Manuscript received October 12, 2004; revised Febuary 25, 2005. This work was supported by the National Science Council of the Republic of China, Taiwan, under Contract NSC 93-2215-E-009-027.

The authors are with the Institute of Electro-Optical Engineering and Department of Photonics, National Chiao-Tung University, Hsin-Chu, Taiwan 300, R.O.C. (e-mail: mgyso.eo91g@nctu.edu.tw; mfhuang.eo90g@nctu.edu.tw; jchen@mail.nctu.edu.tw).

Digital Object Identifier 10.1109/LPT.2005.851049

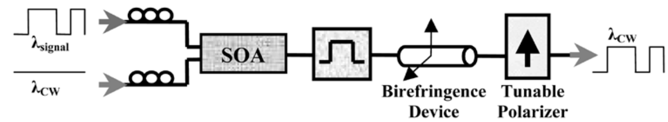

Fig. 1. Configuration of a DXPoM wavelength converter.

II. Operating Scheme and Simulation

Fig. 1 illustrates the configuration of DXPoM. As in a typical XPoM, a continuous-wave (CW) probe laser beam at wavelength λ_{CW} and a signal pump laser beam at wavelength $\lambda_{\mathrm{signal}}$ were fed into an SOA. Proper control of the polarization states of λ_{CW} and $\lambda_{\mathrm{signal}}$ allowed the injected pump light to introduce additional birefringence in the SOA, and resulted in a differential refractive index change between the TE and TM modes of the probe beam. At the polarizer, the two orthogonal modes are partially combined coherently. The proposed scheme and the conventional XPoM differ in that the proposed method adds an extra birefringence delay line in front of the polarizer. Based on the interferometric principle similar to the Mach–Zehnder interferometer, the XPoM exploits the phase difference between the TE and TM modes when passed through an SOA. By adding an extra delay between TE and TM modes, the polarization state of the output CW beam after passing the delay line was rotated more rapidly with the variation of the signal power and, therefore, overcome the speed limitation due to the carrier's recovery time. Consequently, DXPoM was expected to have a better ER, a higher conversion speed, and a lower timing jitter.

The large signal simulation is carried out to obtain details of DXPoM. In our simulation, the transfer matrix method is adopted and the basic rate equations are [8]

$$\frac{\partial E_i^k}{\partial z} + \frac{1}{\nu_g}\frac{\partial E_i^k}{\partial t} = -\frac{j}{2}\alpha\Gamma^k g_{m,i}E_i^k + \frac{1}{2}\Gamma^k g_i E_i^k$$

$$\frac{\partial N}{\partial t} = \frac{I}{qV} - \frac{N}{\tau_s} - \sum_i\sum_k \frac{\Gamma^k g_{m,i}\left|E_i^k\right|^2}{\hbar\omega_i A_{\mathrm{cross}}}$$

$$k = \mathrm{TE}, \mathrm{TM} \qquad (1)$$

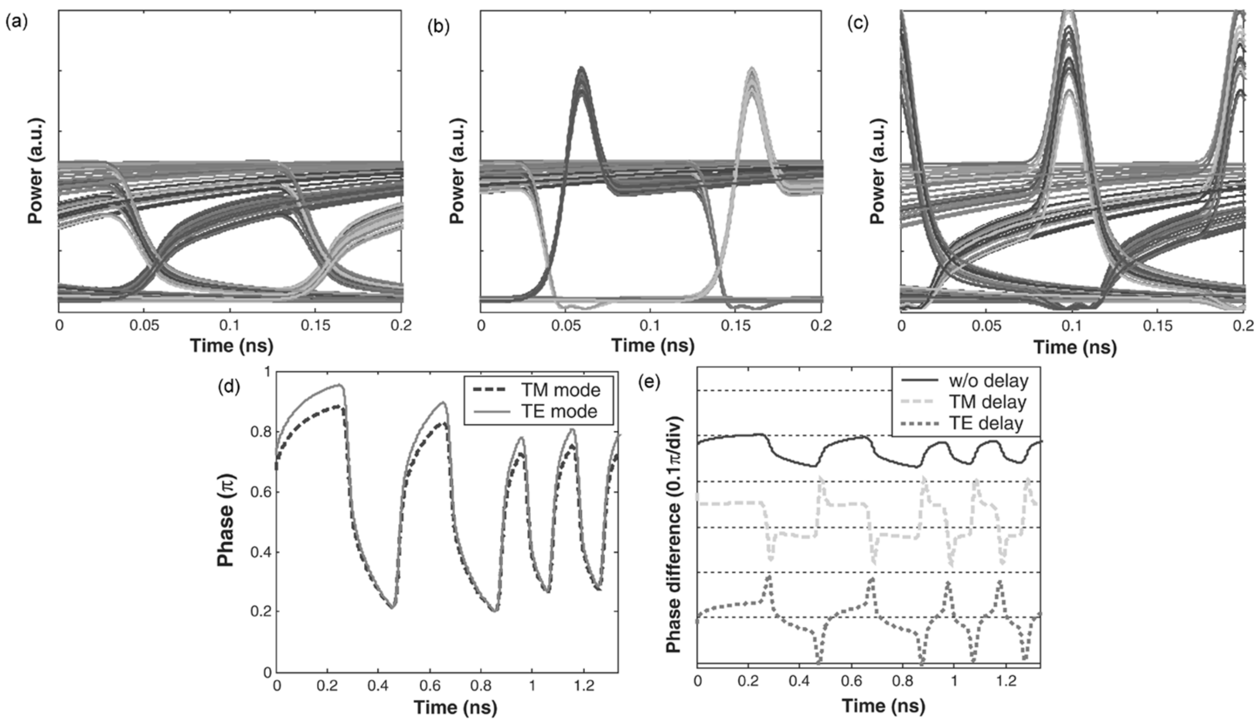

Fig. 2. Simulated eye diagram of converted signal based on (a) XPoM, (b) DXPoM with TM delay, and (c) DXPoM with TE delay; (d) the phase of TM and TE modes; (e) the phase difference between TM and TE modes.

where $i = 1, 2$ represent the signal and CW beam, respectively. α is linewidth enhancement factor, $g_{m,i}$, g_i, and ω_i are the material gain, the net gain, and the optical angular frequency for the i beam, E_i^k is the optical field for the i beam polarized at k mode, Γ^k is the confinement factor of an SOA at k mode, v_g is the group velocity in an SOA, N is the carrier density, A_{eff} is the effective area of the waveguide, $\hbar$ is the reduced Planck constant, I is the injected current, q is the electron charge, V is the active volume, and τ_s is the spontaneous carrier lifetime. In (1), the polarization-dependent properties of an SOA are simply contributed by different confinement factors.

Fig. 2(a)–(c) compares the simulated eye diagrams of 10-Gb/s wavelength conversion employing XPoM, DXPoM with TM delay, and DXPoM with TE delay, respectively. In Fig. 2(b), the extra delay added on the TM mode was 7 ps, and in Fig. 2(c), the extra delay added on the TE mode was 5.5 ps. Fig. 2(b) and (c) illustrates that DXPoM with TM delay performs much better than the other schemes. The ER is better, the timing jitter is lower, and the rise time is markedly improved. However, if the extra delay is added on the TE mode, the conversion performs worse than that of XPoM. Because in the simulation model, the power gain in the TE mode is 1 dB higher than that in the TM mode, the TE mode induces larger phase changes than the TM mode, as shown in Fig. 2(d). Fig. 2(e) compares the phase difference between the TE and TM modes corresponding to Fig. 2(a)–(c). Due to the asymmetric shape of the phase variation, the phase difference introduced by TM delay shows a square-wave type of sharp transition and flatness. Conversely, the phase difference by TE delay shows continuously slow rising and falling bit patterns. Because of the interferometric principles of XPoM, the phase difference between the TE and TM modes controls the output power of the CW beam after the polarizer. Therefore, a square wave style phase difference translates into a square wave style intensity pattern. And the slow and irregular rising and falling differential phase bit patterns cause a larger timing jitter and eye closure. This explains why the TM delay performs much better than the TE delay.

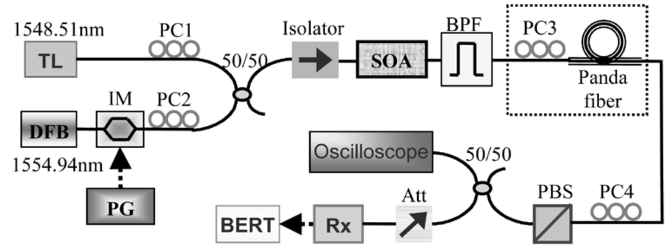

Fig. 3. Experimental setup of DXPoM. (IM: Intensity modulator. PG: Pattern generator. BPF: Optical bandpass filter. PBS: Polarization beam splitter. Att: Optical attenuator. BERT: Bit-error-rate tester).

III. Experimental Results

Fig. 3 shows the experimental setup of DXPoM. A distributed feedback (DFB) signal pump laser at 1554.9 nm was intensity modulated at 10 Gb/s with a pseudorandom binary sequence (PRBS) length of $2^7 - 1$. A tunable CW probe laser at 1548.5 nm was combined with the signal and injected into the SOA. The average power of the DFB and the tunable laser was 1.5 and 5.5 dBm, respectively. The bias current of the SOA (JDSU CQF872) was set at 300 mA and the polarization-dependent gain (PDG) of this SOA is 1 dB. After the SOA, the signal pump beam was filtered out by an optical bandpass filter. The combination of the polarization controller (PC) and the PANDA polarization-maintained (PM) fiber acted as a tunable

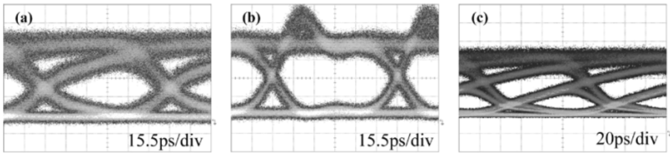

Fig. 4. Measured eye-diagrams of 10-Gb/s converted signal based on (a) XPoM, (b) DXPoM, and (c) XGM.

birefringence delay line. The time delay has been optimized by using different lengths of the PANDA fiber. The optimized differential delay introduced by the PM fiber was 14 ps. Proper control of PC3 allowed the relative delay between the TE and TM modes to be adjusted and this produced a desired DXPoM function. The TE and TM modes were then coherently combined at the polarization beam splitter. Because of the small PDG of the SOA, the variation of the carrier density followed on the variation of the polarization states of the signal beam and the corresponding phase fluctuation of the CW beam are small. In our experiments, the small dc drift of the converted eye diagrams was induced when the PC2 was adjusted. In practical application, one may want to use the SOA with small PDG (<1 dB) to mitigate this dc drift. If this polarization variation is relatively slow (similar to millisecond range), then one can use the electronic eye pattern monition to provide feedback signal for PC4 to remove this dc offset.

Fig. 4(a) and (b) displays the 10-Gb/s eye diagrams of the measured XPoM and DXPoM, respectively. Comparing Fig. 4(a) and (b) revealed that the rise time was improved by more than 300%, from 74 to 23 ps, the ER showed a 9% enhancement, from 11 to 12 dB, and the root mean square timing jitter decreased by 50%, from 5.4 to 2.7 ps. In the configuration of Fig. 4(a) and (b), PC4 was adjusted to form a destructive interference between the TE and TM modes when only the CW beam was present, thus, noninverted conversion was obtained. As a comparison, Fig. 4(c) shows the eye diagram of XGM with -7 dBm of the CW beam and 2.3 dBm of the signal beam which are quite different from the operating condition of XPoM due to the optimized performance and high output ER in XGM obtained with the high ER of the total input optical power [2]. This demonstrated that the SOA could not support 10-Gb/s XGM due to the constraint of the carrier's slow recovery time which is contributed mainly by the short length of the SOA [2].

Fig. 5 shows the bit-error-rate measurement results of source (back-to-back), XPoM and DXPoM. According to Fig. 5, the DXPoM scheme improved the sensitivity by more than 7 dB compared with XPoM. Furthermore, the wavelength conversion itself had a conversion penalty of roughly 1.5 dB compared with the back-to-back result. The power penalty was contributed mainly by the amplified spontaneous emission (ASE) noise of the SOA that not only lowered the signal-to-noise ratio but also limited the ER of the converted signal.

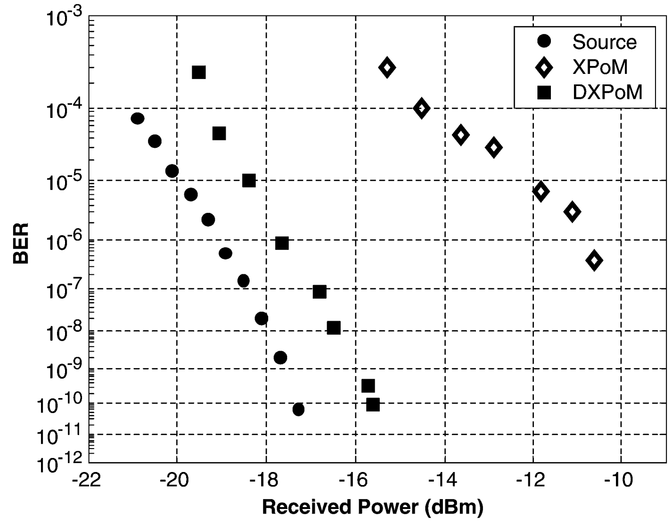

Fig. 5. BER curves for wavelength conversion at 10 Gb/s.

IV. Conclusion

This work has proposed a novel wavelength conversion scheme called DXPoM by simply adding an extra birefringence delay line in the standard XPoM. The delay line adjusts the time differential between two orthogonal modes to overcome the limitation of the carrier's lifetime. Both the simulation and experimental results indicate that the proposed method significantly improves the wavelength conversion performance. The new technique exhibits an error-free wavelength conversion operation with more than 7-dB power penalty improvement over XPoM. The DXPoM scheme shows a pulse reshaping function, an improvement of more than 300% in rise time, reduced timing jitter, and a higher ER.

References

[1] D. Nesset, T. Kelly, and D. Marcenac, "All optical wavelength conversion using SOA nonlinearity," *IEEE Commun. Mag.*, vol. 36, no. 12, pp. 56–61, Dec. 1998.

[2] T. Durhuus, B. Mikkelsen, C. Joergensen, S. L. Danielsen, and K. E. Stubkjaer, "All-optical wavelength conversion by semiconductor optical amplifiers," *J. Lightw. Technol.*, vol. 14, no. 6, pp. 942–954, Jun. 1996.

[3] S. Diez, C. Schmidt, R. Ludwig, H. G. Weber, K. Obermann, S. Kindt, I. Koltchanov, and K. Petermann, "Four-wave mixing in semiconductor optical amplifiers for frequency conversion and fast optical switching," *IEEE J. Sel. Topics Quantum Electron.*, vol. 3, no. 5, pp. 1131–1145, Oct. 1997.

[4] Y. Liu, M. T. Hill, E. Tangdiongga, H. de Waardt, N. Galabretta, G. D. Khoe, and H. J. S. Dorren, "Wavelength conversion using nonlinear polarization rotation in a single semiconductor optical amplifier," *IEEE Photon. Technol. Lett.*, vol. 15, no. 1, pp. 90–92, Jan. 2003.

[5] P. Öhlén and E. Berglind, "BER caused by jitter and amplitude noise in limiting optoelectronic repeaters with excess bandwidth," *Proc. Inst. Elect. Eng., Optoelectron.*, vol. 145, no. 3, pp. 147–150, Jun. 1998.

[6] B. Mikkelsen, K. S. Jepsen, M. Vaa, H. N. Poulsen, K. E. Stubkjaer, R. Hess, M. Duelk, W. Vogt, E. Gamper, E. Gini, P. A. Besse, H. Melchior, S. Bouchoule, and F. Devaux, "All-optical wavelength converter scheme for high speed RZ signal formats," *Electron. Lett.*, vol. 33, pp. 2137–2139, Oct. 1997.

[7] S. Nakamura and K. Tajima, "Bit-rate-transparent nonreturn-to-zero all-optical wavelength conversion at up to 42 Gb/s by operating symmetric-Mach-Zehnder switch with new scheme," in *OFC 2004*, Los Angeles, CA, 2004, Paper FD3.

[8] H. Lee, H. Yoon, Y. Kim, and J. Jeong, "Theoretical study of frequency chirping and extinction ratio of wavelength-converted optical signals by XGM and XPM using SOAs," *IEEE J. Quantum Electron.*, vol. 35, no. 8, pp. 1213–1219, Aug. 1999.