All-Optical Wavelength Conversion of a 100-Gb/s Polarization-Multiplexed Signal

P. Martelli[1,2], P. Boffi[1], M. Ferrario[1,2], L. Marazzi[1,2*], P. Parolari[1,2], R. Siano[2], V. Pusino[3], P. Minzioni[3], I. Cristiani[3], C. Langrock[4], M. M. Fejer[4], M. Martinelli[1], V. Degiorgio[3]

[1]PoliCom, Dept. of Electronics and Information, Politecnico di Milano, Via G. Colombo 81, 20133 Milano, Italy
[2]Fondazione Politecnico di Milano, Via Garofalo 39, 20133 Milano, Italy
[3]CNISM and Electronics Dept. University of Pavia, Via Ferrata 1, 27100 Pavia, Italy
[4]Edward Ginzton Laboratory, Stanford University, 450 Via Palou, 94305 Stanford, CA, USA
**marazzi@elet.polimi.it*

Abstract: We present the results of an in-depth experimental investigation about all-optical wavelength conversion of a 100-Gb/s polarization-multiplexed (POLMUX) signal. Each polarization channel is modulated at 25 Gbaud by differential quadrature phase-shift keying (DQPSK). The conversion is realized exploiting the high nonlinear $\chi^{(2)}$ coefficient of a periodically poled lithium niobate waveguide, in a polarization-independent configuration. We find that slight non-idealities in the polarization independent setup of the wavelength converter can significantly impair the performance of POLMUX systems. We show that high-quality wavelength conversion can be nevertheless achieved for both the polarization channels, provided that an accurate optimization of the setup is performed. This is the first demonstration, to the best of our knowledge, of the possibility to obtain penalty-free all-optical wavelength conversion in a 100-Gb/s POLMUX transmission system using direct-detection.

OCIS codes: (060.2330) Fiber optics communications; (230.7405) Wavelength conversion devices; (130.3730) Lithium niobate

References and links

1. P. Boffi, M. Ferrario, L. Marazzi, P. Martelli, P. Parolari, A. Righetti, R. Siano, and M. Martinelli, P. Parolari, A. Righetti, R. Siano, and M. Martinelli, "Stable 100-Gb/s POLMUX-DQPSK transmission with automatic polarization stabilization," IEEE Photon. Technol. Lett. **21**(11), 745–747 (2009).
2. C. R. S. Fludger, T. Duthel, D. van den Borne, C. Schulien, E.-D. Schmidt, T. Wuth, J. Geyer, E. De Man, G.-D. Khoe, and H. de Waardt, "Coherent equalization and POLMUX-RZ-DQPSK for robust 100-GE transmission," J. Lightwave Technol. **26**(1), 64–72 (2008).
3. P. Boffi, M. Ferrario, L. Marazzi, P. Martelli, P. Parolari, A. Righetti, R. Siano, and M. Martinelli, "Measurement of PMD tolerance in 40-Gb/s polarization-multiplexed RZ-DQPSK," Opt. Express **16**(17), 13398–13404 (2008), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-16-17-13398.
4. A. Zapata-Beghelli, and P. Bayvel, "Dynamic versus static wavelength routed optical networks," J. Lightwave Technol. **26**(20), 3403–3415 (2008).
5. M. P. Fok, C. Shu, and D. J. Blumenthal, "40-Gb/s polarization multiplexed RZ-ASK-DPSK signal wavelength conversion using a 32-cm bismuth-oxide highly nonlinear fiber," in *Conference on Lasers and Electro-Optics Europe* CLEO/Europe-IQEC, paper CI4–2-Thu (2007).
6. J. Yu, M.-F. Huang, and G.-K. Chang, "Polarization insensitive wavelength conversion for 4x112Gbit/s polarization multiplexing RZ-QPSK signals," Opt. Express **16**(26), 21161–21169 (2008), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-16-26-21161.
7. J. Yu, M. Huang, and G. Chang, "Wavelength conversion based on copolarized pumps generated by optical carrier suppression," IEEE Photon. Technol. Lett. **21**(6), 392–394 (2009).
8. G. Contestabile, L. Banchi, M. Presi, and E. Ciaramella, "Transparency of FWM in SOAs to phase/amplitude and polarization," in *Optical Fiber Communication Conference*, OSA Technical Digest (CD) (Optical Society of America, 2009), paper OThM6 (2009).
9. G. Contestabile, L. Banchi, M. Presi, and E. Ciaramella, "Investigation of transparency of FWM in SOA to advanced modulation formats involving intensity, phase and polarization Multiplexing," J. Lightwave Technol. (to be published).
10. I. Cristiani, and V. Degiorgio, "Optical frequency conversion through cascaded nonlinear processes," Riv. Nuovo Cim. **27**(12), 1–49 (2004).
11. K. R. Parameswaran, R. K. Route, J. R. Kurz, R. V. Roussev, M. M. Fejer, and M. Fujimura, "Highly efficient second-harmonic generation in buried waveguides formed by annealed and reverse proton exchange in periodically poled lithium niobate," Opt. Lett. **27**(3), 179–181 (2002).

#112806 - $15.00 USD Received 15 Jun 2009; accepted 19 Aug 2009; published 18 Sep 2009

12. M. H. Chou, K. R. Parameswaran, M. M. Fejer, and I. Brener, "Optical signal processing and switching with second-order nonlinearities in waveguides," IEICE Trans. Electron E **83-C**, 869–874 (2000).
13. D. Caccioli, A. Paoletti, A. Schiffini, A. Galtarossa, P. Griggio, G. Lorenzetto, P. Minzioni, S. Cascelli, M. Guglielmucci, L. Lattanzi, F. Matera, G. M. T. Beleffi, V. Quiring, W. Sohler, H. Suche, S. Vehovc, and M. Vidmar, "Field demonstration of in-line all-optical wavelength conversion in a WDM dispersion managed 40-Gb/s link," IEEE J. Sel. Top. Quantum Electron. **10**(2), 356–362 (2004).
14. V. Pusino, P. Minzioni, I. Cristiani, V. Degiorgio, L. Marazzi, P. Boffi, M. Ferrario, P. Martelli, P. Parolari, A. Righetti, R. Siano, M. Martinelli, C. Langrock, and M. M. Fejer, "Wavelength Conversion of Real-Time 100 Gb/s POLMUX RZ-DQPSK," in *Optical Fiber Communication Conference*, OSA Technical Digest (CD) (Optical Society of America, 2009), paper OThS3.
15. M. Martinelli, P. Martelli, and S. M. Pietralunga, "Polarization Stabilization in Optical Communications Systems," J. Lightwave Technol. **24**(11), 4172–4183 (2006).
16. P. Minzioni, "Nonlinearity Compensation in a Fiber Optic Link by Optical Phase Conjugation," Taylor, Francis, Fiber Integ. Opt. **28**, 179–209 (2009).
17. P. Minzioni, I. Cristiani, V. Degiorgio, L. Marazzi, M. Martinelli, C. Langrock, and M. M. Fejer, "Experimental demonstration of nonlinearity and dispersion compensation in an embedded link by optical phase conjugation," IEEE Photon. Technol. Lett. **18**(9), 995–997 (2006).

1. Introduction

The combination of the quadrature phase-shift keying (QPSK) modulation technique with polarization multiplexing (POLMUX) is a very attractive solution for the realization of wide-area transmission networks at 100 Gb/s and beyond exploiting either direct [1] or coherent detection [2]. By using this combination, the symbol rate is at first halved, with respect to an equivalent bit-rate on-off keying (OOK) signal, by multilevel data encoding and then further reduced by the POLMUX technique, thus achieving an increased robustness to chromatic dispersion. Higher polarization-mode dispersion (PMD) margin is obtained by quadrupling the symbol period, though POLMUX formats are actually more sensitive to PMD [3].

In next-generation networks, the availability of an all-optical wavelength converter (AOWC), enabling dynamic signal routing, wavelength reuse, path protection and restoration, will be a key feature [4]. In order to comply with real transmission systems, and in particular with POLMUX-QPSK signals, the availability of polarization-independent and phase-preserving AOWCs is a fundamental requirement. This objective can be pursued by exploiting phase-preserving processes in polarization-independent configurations such as four-wave-mixing (FWM) in fibers or in semiconductor optical amplifier (SOA) and the cascade of second-harmonic and difference-frequency generation in a $\chi^{(2)}$-material. Even if many different polarization-independent AOWC topologies have been proposed, few experiments on this topic can be found in the literature [5–9]. The lack of BER measurements in the earliest work [5] suggests that the experimental setup presents some critical aspects. Recently a renewed interest towards the wavelength conversion of POLMUX formats is demonstrated by the increase in the number of papers being published on the topic. In particular wavelength conversion based on orthogonal-pumps and four-wave mixing in highly nonlinear fiber has been demonstrated for POLMUX return-to-zero (RZ) -QPSK [6] and POLMUX RZ-8PSK [7]. Both papers obtained successful wavelength conversion exploiting DSP-assisted coherent detection. SOA-based POLMUX wavelength conversion has been also investigated both in configurations exploiting orthogonal or parallel pumps [8,9]. The authors have been able to significant improve their initial results [8], yet they underline that realizing a "transparent" AOWC suitable for POLMUX formats is still a challenging target [9].

In this paper, we describe a thorough analysis and optimization of an AOWC for 100-Gb/s POLMUX-DQPSK signal exploiting the cascading technique in a periodically poled lithium niobate (PPLN) waveguide. The 100-Gb/s POLMUX-DQPSK signal is directly detected by means of two Mach-Zehnder delay interferometer after polarization demultiplexing. In particular we discuss the experimental setup, highlighting the related problems and the required optimization. BER curves obtained with the optimized AOWC setup are also shown.

2. Experimental setup and analysis

The experimental setup is mainly composed by three elements: the AOWC, the transmitter and the receiver apparatus, which are here described in details.

The investigated AOWC is based on a PPLN waveguide performing wavelength conversion by the cascade of two second-order nonlinear effects, which is equivalent to a four-wave-mixing process in a $\chi^{(3)}$ material. The main advantages of this approach are: high conversion efficiency (thanks to the high nonlinear $\chi^{(2)}$ coefficient, d_{33}, of the material), large operating bandwidth and no significant degradation of the signal quality [10]. The core of the AOWC is a 67-mm-long PPLN waveguide fabricated by means of the reverse-proton-exchange (RPE) technique [11]. The end-faces of the waveguide are cut at an angle of 6° to avoid back-reflections, and are fiber-coupled to PM-pigtails by means of UV-curing epoxy glue with a good resistance to high temperatures. Indeed, the device needs to be maintained at a temperature above 100°C in order to mitigate the effects of photorefractive damage. The RPE-PPLN waveguide propagates only the TM mode with a measured polarization extinction ratio higher than 40 dB.

Polarization independence is obtained by using an AOWC scheme, shown in Fig. 1a, based on a ring configuration [12,13]. The incoming signal (at the wavelength of 1550.12 nm) is combined with the pump (1552.52 nm) using an add-drop multiplexer (ADM). Then a 4-port optical component (PBSC, by AC Photonics) combining a circulator and a polarizing beam splitter (PBS), splits both the pump and the signal in two orthogonal polarization components, coupled to the slow axis of two polarization-maintaining (PM) fibers, which counter-propagate through the ring. Thanks to the manually-adjustable fiber polarization controller PC-1, the pump splitting ratio can be adjusted in order to achieve the same conversion efficiency for both polarization components of the signal. TM input at both sides of the PPLN waveguide is ensured by PBSC. After the wavelength-converted signal has been generated inside the PPLN waveguide, its orthogonal polarization components are recombined at the PBSC port-4, then a tunable filter separates both the pump and the original signal from the converted signal (1554.94 nm). Using this scheme, a polarization-independent AOWC can be obtained, provided that PM-fiber is used in the ring configuration, and that the PBSC has perfect polarization discrimination. The insertion losses, measured from amplifier outputs to PBSC port-4, are lower than 9 dB and 8 dB for the signal and the pump respectively.

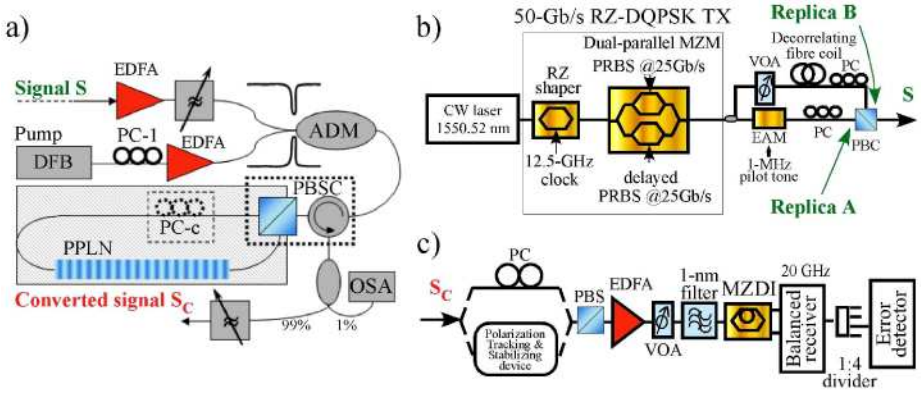

Fig. 1. a. AOWC setup. The ADM is centered at the pump frequency of 1552.52 nm. The dashed area includes the PM-fiber ring. The dashed polarization controller PC-c is not present in the initially implemented setup and compensates for setup non-idealities (see Section 3). b. 100-Gb/s POLMUX RZ-DQPSK transmitter. c. RZ-DQPSK direct receiver. Before polarization-demultiplexing the SOP of the POLMUX converted signal, S_C, is properly adjusted either exploiting manually-adjustable polarization controllers (PC) or an automatic endless polarization tracking and stabilizing device.

The 100-Gb/s RZ-DQPSK POLMUX signal used for the experiments is obtained modulating a DFB laser with a RZ-carver driven by a 12.5-GHz clock, and then by a dual-parallel Mach-Zehnder modulator driven by two mutually delayed 25-Gb/s pseudo-random bit sequences (PRBS), as can be seen in Fig. 1b. The resulting 50-Gb/s RZ-DQPSK signal is split into two replicas (referred as A and B in the following), which are uncorrelated by a fiber coil. One of the two channels (A) is then labeled by a 1-MHz pilot tone, which is superimposed to the signal as intensity modulation (peak-to-peak amplitude $\cong$10% of the average), in order to identify the channel whose state of polarization (SOP) is to be monitored and controlled at the direct-detection receiver. The channels are recombined after their SOPs are made orthogonal, thus obtaining an overall capacity of 100 Gb/s.

At the receiver, shown in Fig. 1c, the SOPs of the POLMUX channels are properly adjusted before demultiplexing the two polarization channels by means of a PBS. The in-phase and quadrature components of each single polarization demultiplexed RZ-DQPSK channel are detected by a pair of integrated-optic Mach-Zehnder delay interferometers, with 40-ps delay and a ±π/4 bias. A 20-GHz balanced differential detector is used. By means of a 1:4 demultiplexer, we extract four 6.25-Gb/s data sequences, which are fed to the error detector in the BER tester.

A first set of BER measurements (preliminary reported in [14]) unexpectedly showed a marked dependence of the conversion performance on the SOP of the signal. Moreover we found a polarization fluctuation of the SOP of the wavelength-converted signal, both in case of single polarization and POLMUX conversion. The time scale was about 0.1-s. This fact prevented manual polarization-demultiplexing.

BER curves, assessing the system performance under these conditions, were acquired by exploiting an endless automatic polarization stabilizer [15], and the results are shown in Fig. 2. With respect to the back-to-back curve of channel A (BTB - full circles), it can be observed that the conversion of a single polarization-channel (open triangles) presents only a slight penalty (≅ 0.5 dB), which could be due to the automatic polarization stabilizer [15].

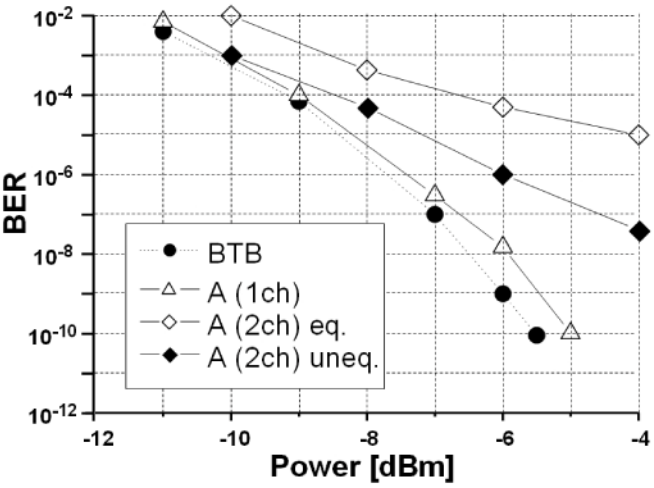

Fig. 2. BER versus received power with AOWC non-optimized setup for channel A: back-to-back curve (full circles), single-channel conversion (open triangles), POLMUX conversion equalized (open diamonds) and unequalized (full diamonds). Polarization demultiplexing is assisted by an endless automatic polarization stabilizer to cope with the converted signal polarization fluctuations.

Conversely, when both channels were converted, the performance was much worse and it depended on signal SOPs at the input of the AOWC setup. If the SOPs were adjusted so as to obtain the same performance for both polarization channels, the measured BER curve (open-diamond curve in Fig. 2) showed a floor at 10^{-5}. On the other hand, if the SOP of the input signal was modified in order to optimize the performance of channel A, we obtained the full-diamond curve for this channel (A), but we could not perform any BER measurement on the other channel (B), due to a significant signal distortion.

These results immediately suggested that the above described AOWC setup induces some interplay between the two POLMUX channels and consequently, when a POLMUX format is considered, it is not possible to obtain a good BER performance for both channels simultaneously.

3. Setup optimization and experimental results

After a careful analysis carried out by means of a polarimeter, we actually verified that the AOWC caused a reduction of the two SOP orthogonality, which is the origin of a significant crosstalk between the POLMUX channels. The angular separation between the SOPs, measured onto the Poincaré sphere, reduces from 180° at the AOWC input to about 175° at its output. Measuring the polarization extinction ratio after a PM-pigtailed PBS, we found that the orthogonality-loss is due to a very small rotational misalignment ($\Delta\theta$) between the PPLN waveguide and the PM-fiber pigtails. In particular one pigtail is well aligned ($\Delta\theta < 0.5°$), conversely the other is slightly misaligned of $\Delta\theta \cong 3°$. Such a value, that is usually negligible for single polarization formats, is sufficient to cause a significant AOWC performance degradation due to the polarization crosstalk.

In order to compensate for the 3°-angular misalignment and to verify its impact on the conversion performance, we inserted a manually-adjustable polarization controller (PC-c in Fig. 1) between the PPLN pigtail and the PBSC port. By properly adjusting PC-c, so as to compensate for the pigtail misalignment, we were able to eliminate fluctuations in the converted signal SOP. In order to determine the penalty strictly associated with the AOWC impact on the POLMUX signal, the automatic polarization stabilizer was removed from the setup. Polarization demultiplexing was then performed with a PBS, by properly orienting the SOPs of the POLMUX channels with a manually-adjusted fiber polarization controller. BER measurements as a function of the received power are presented in Fig. 3. We first checked the performance of both 50-Gb/s RZ-DQPSK polarization-channels separately. The full-circle BER curve refers to the BTB of the labeled single polarization-channel (A), while the two triangle BER curves refer to the separate conversion of each polarization channel, showing that when a single-polarization channel was converted, the AOWC penalty was less than 0.5 dB with respect to the BTB.

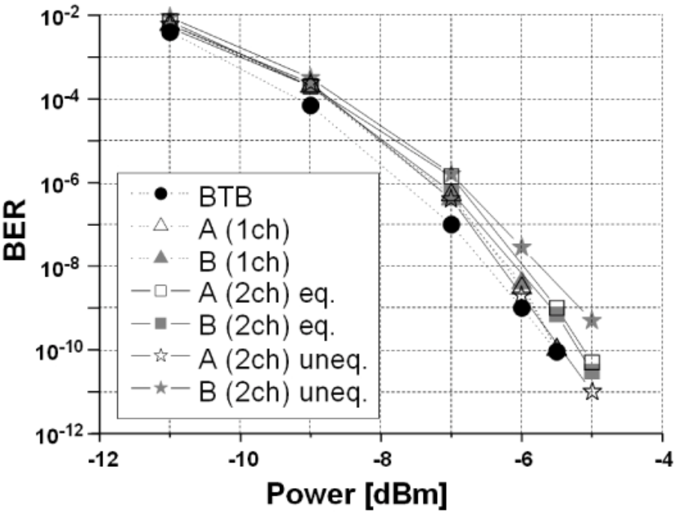

Fig. 3. BER versus received power with the AOWC optimized setup: back-to-back curve (full circles) for channel A, single-channel conversion for channel A and B (open and full triangles respectively), POLMUX conversion equalized for channel A and B (open and full square respectively) and unequalized for channel A and B (open and full star respectively) by varying input signal SOP.

We subsequently measured the BER for the overall 100-Gbit/s POLMUX signal. We verified that, if PC-c is properly adjusted, a variation of the input signal SOPs produces only a small variation of the AOWC performance, as it can be seen comparing square and star curves in Fig. 3. In the case of square curves almost identical performance was obtained for both POLMUX channels, and the penalty with respect to the single-channel BTB is less than 0.5 dB.

By varying the signal SOP at the AOWC input through the polarization controller we could still find a performance difference lower than 0.2 dB between channels A and B (open and full stars in Fig. 3). This indicates that the setup still presented a small polarization dependence that, anyway, can be considered negligible. This result demonstrates that PPLN setup allows obtaining excellent performance in 100 Gbit/s POLMUX formats. Even in the worst case, the penalty with respect to the single-polarization BTB is less than 1 dB. Crosstalk between the two polarization channels is avoided if a fine alignment of the waveguide pigtails is provided. Such a requirement can be easily achieved by means of the current packaging technology.

#112806 - $15.00 USD Received 15 Jun 2009; accepted 19 Aug 2009; published 18 Sep 2009

4. Conclusion

In this paper we demonstrate successful all-optical wavelength conversion of a 100 Gb/s POLMUX signal. The AOWC setup is based on a PPLN waveguide in a polarization-independent ring configuration.

We verified that POLMUX format imposes very strict requirements in polarization-independent schemes. Indeed, even a small non-ideal polarization behavior of the AOWC components degrades the orthogonality of the polarization channels, thus causing a significant optical crosstalk at the receiver. Indeed in our setup a slight rotational misalignment (≅ 3°) between the TM-mode of the PPLN waveguide and the slow-axis of one PM-fiber pigtail caused a residual polarization dependence producing a relevant degradation of the performance in case of POLMUX signals, due to the loss of orthogonality between the polarization channels and the consequent polarization crosstalk. By compensating the rotational misalignment, it is possible to achieve all-optical wavelength conversion of a 100-Gb/s POLMUX RZ-DQPSK signal with a "worst-case penalty" of less than 1 dB with respect to back-to-back operation.

As a final comment, recalling that the wavelength conversion process here described causes also signal phase-conjugation, we note that an important application of our results may consist in the simultaneous compensation of signal distortions due to dispersion and nonlinearity in high bit rate optical communication systems [16,17].

Acknowledgements

This work was partially supported by the project, and by a grant from Fondazione CARIPLO, FIRB-MIUR RBIN043TKY.

Received 15 Jun 2009; accepted 19 Aug 2009; published 18 Sep 2009