TDM-to-WDM Conversion from 130 Gbit/s to 3 × 43 Gbit/s Using XPM in a NOLM Switch

Philipp Vorreau, Francesca Parmigiani*, Kazunori Mukasa, Morten Ibsen*, Periklis Petropoulos*, David J. Richardson*, Andrew Ellis***, Wolfgang Freude, and Juerg Leuthold**
Institute of High-Frequency and Quantum Electronics, University of Karlsruhe, 76131 Karlsruhe, Germany
**Optoelectronics Research Centre, University of Southampton, Southampton SO 17 1BJ, United-Kingdom*
***The Furukawa Electric Company, Fitel Photonics Laboratory, Japan*
****Tyndall National Institute and Department of Physics University College Cork, Ireland*
Tel: +49 721 608 7173, Fax: +49 721 608 2786, e-mail: p.vorreau@ihq.uni-karlsruhe.de
Tel: +44 23 80593172, Fax: +44 23 80593149, e-mail: frp@orc.soton.ac.uk

ABSTRACT

We report the first demonstration of OTDM-to-WDM conversion from 130 Gbit/s simultaneously to 3 × 43 Gbit/s WDM channels in a nonlinear optical loop mirror (NOLM). The scheme is exploiting the ultra-fast Kerr based XPM in a NOLM and gives full flexibility for selecting the output WDM channel wavelengths. For the success of the experiment we rely crucially on a new specially designed highly nonlinear fiber (HNLF) exhibiting low dispersion and low dispersion slope such that low walk-off operation across the C-band is possible. Error free performance is achieved with penalties ranging from 0.5 dB to 3.5 dB for all three WDM channels.

Keywords: Nonlinear optical loop mirror, time division multiplexing, cross-phase modulation, WDM, OTDM.

1. INTRODUCTION

Future high-speed optical networks will require enhanced functionality in the optical layer in order to exploit the full potential of the optical fiber and to reduce the latencies associated with optical to electrical (O/E) conversion and other electronic processing functions [1]. Indeed, as a result of the steady annual growth of IP traffic, work is already focusing on the development of 100 Gbit/s Ethernet (100GbE) as the natural progression from the current 10GbE systems. After the standardization of the 100GbE line rate, it is most likely that ITU-T will extend the G.709 to the next higher rate. This new OTU4 bit rate will have to map 100GbE and probably also 3×OTU3 (3 × 43Gbit/s) channels therefore dictating a line rate close to 130 Gbit/s.

One of the key functions in such all-optical networks, operating at ultra-high bit rates, is the conversion from an optical time division multiplexed (OTDM) signal, running in a higher hierarchy part of the network (Metro/Backbone Network), to a wavelength division multiplexed (WDM) signal, running at lower bit rates, closer to the end user of the network (Metro/Access Network).

Yet, in order to be practical, simultaneous demultiplexing of all OTDM channels with a single device is needed. Simultaneous demultiplexing of four and three WDM channels has been reported using either four-wave mixing [2] or self-phase modulation related spectral broadening [3], respectively. However, neither of the aforementioned techniques allows for full flexibility in terms of wavelength allocation. Still, XPM based techniques in principle could give a user the freedom to map any OTDM channel onto any desired output wavelength.

And indeed, a XPM based technique where an OTDM channel has been mapped onto a sequence of rectangularly-shaped, linearly-chirped pulses within a nonlinear optical switch has been proposed. Such pulses can be generated using either a commercial dynamic gain equalizer [4],[5], or a chirped fiber Bragg grating (CFBG) [6]. However, the studies reported in [6] highlighted the close relationships between the key system parameters, such as chirp, switching efficiency and WDM channel separation at high repetition rates for optimal OTDM to WDM conversion performance. To relax these parameter dependencies, we used a specially designed and manufactured fibre minimizing the channel walk-off and reducing the cross-talk between the various WDM channels.

In this paper, we successfully demonstrate TDM-to-WDM conversion from 130 Gbit/s to 3 × 43 Gbit/s by using a single NOLM switch. The scheme is exploiting the ultra-fast Kerr based XPM in a NOLM and by using a specially designed HNLF we overcome bandwidth limitations due to channel walk-off and cross-talk between the various WDM channels. This enables full flexibility for selecting the output WDM channel wavelengths as required in future all-optical networks.

2. OPERATION PRINCIPLE

Fig. 1 shows the operating principle of the proposed technique [7]. The three WDM signals ($\lambda_{1,2,3}$) are temporally aligned to different time slots of the OTDM signal and are launched onto the input port of the NOLM. If

---

This work was partially funded by the STREP/EU project TRIUMPH IST-027638.

the OTDM pulse is absent ('zero') the two counter-propagating signals of each WDM signal acquire identical linear phase shifts as they traverse the loop and interfere constructively at the coupler with no signal transmitted at the output port of the NOLM ('zero'). If the OTDM pulse is present ('one') at another wavelength ($\lambda_{control}$), the loop is unbalanced by nonlinearly shifting its phase due to XPM. In this case, when the two counter-propagating signals interfere at the coupler as they traverse the loop, the input WDM signal will be transmitted at the output of the NOLM ('one'). This switch effectively transfers coded information from a signal at one wavelength ($\lambda_{control}$) to another at different wavelengths. Finally, by using an optical demultiplexer filter at the output port of the NOLM, each WDM switched signal is then properly filtered.

For multi-wavelength operation of the NOLM an accurate control of the dispersion and dispersion slope of the fiber is needed for a low walk-off and uniform switching efficiency across the whole bandwidth of the WDM channels.

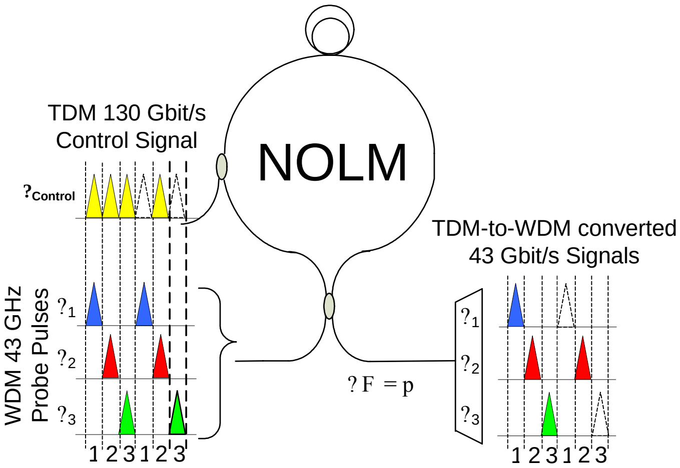


Fig. 1: Operation principle of the TDM-to-WDM conversion technique. Three WDM probe signals are temporally aligned to different time slots of the TDM data signal. The presence of TDM data pulses induces a phase imbalance in the loop, leading to constructive interference of the WDM probe pulses in the output port of the NOLM. The scheme effectively transfers coded information from a signal at one wavelength ($\lambda_{control}$) to another at different wavelengths (λ_1, λ_2, λ_3).

3. EXPERIMENTAL SETUP

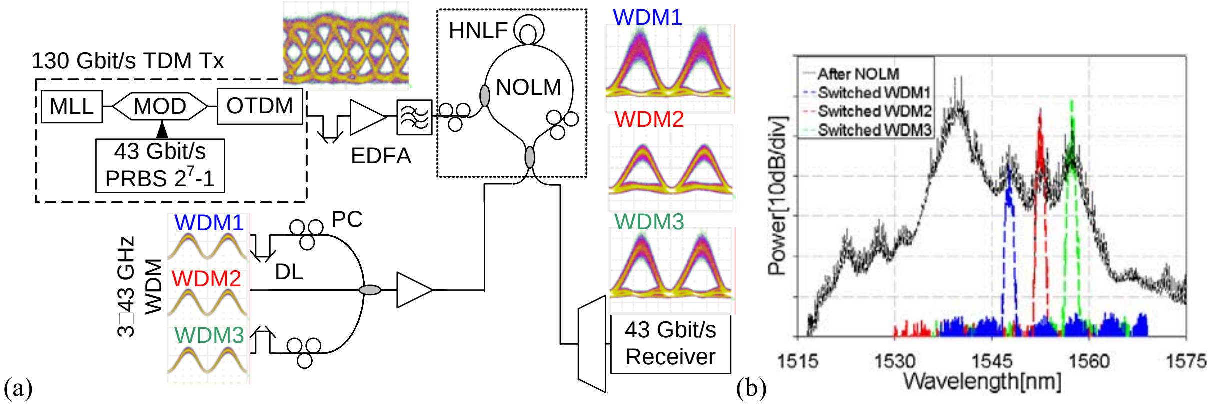


Fig. 2: (a) Experimental setup of the TDM-to-WDM conversion. The data pulses of the 130 Gbit/s transmitter (Tx) are simultaneously switching all three WDM probe signals in the NOLM. Inset: Eye diagrams at different positions in the system (oscilloscope bandwidth: 70GHz). MLL – mode locked laser, PC – polarization controller. (b) Spectral traces of the demultiplexed switched signal before (solid trace) and after (dashed traces) the WDM filter.

The experimental set-up of the OTDM to WDM converter is shown in Fig. 2(a). The WDM signals are generated using three CW lasers at wavelengths $\lambda_1 = 1547.8$ nm, $\lambda_2 = 1552.5$ nm and $\lambda_3 = 1557.4$ nm respectively, followed by a single EAM. Due to the wavelength dependence of the particular EAM used in this experiment and the resulting low output power levels, different pulse widths and extinction ratios are obtained for the various WDM channels (see corresponding eye-diagrams in Fig. 2(a)). The FWHMs (Full Width at Half Maximum) of the WDM channels vary from 5.5ps to 6.5ps. Each WDM signal has an independent polarization controller (PC) to maximize the switching efficiency in the NOLM. The WDM signals are subsequently coupled together and amplified up to ~20dBm and launched onto the NOLM. Two optical delay lines (DL) are included into two arms to temporally align the WDM pulses to the OTDM signal.

The ~2.5ps OTDM signal is generated by a tunable mode locked laser (MLL) at a repetition rate of 43 GHz, which operates at λ_0=1539.4 nm. It is modulated by a 2^7-1 pseudorandom bit sequence (PRBS) using a lithium niobate modulator, multiplexed up to 130 Gbit/s (see corresponding eye-diagrams in Fig. 2) and amplified up to ~23 dBm, before entering the NOLM via a 3dB coupler. An optical DL is included for temporal alignment with the WDM pulses, and a 5nm filter was used to suppress spontaneous emission.

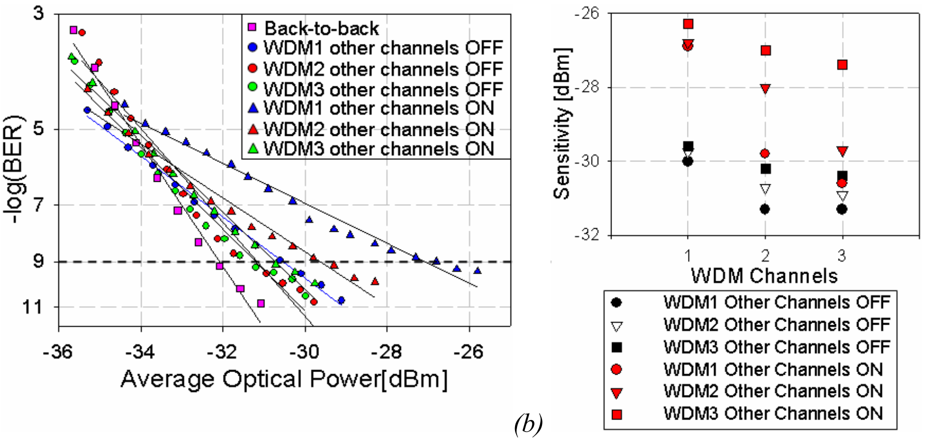
The specially designed HNLF (Furukawa Electric) used in the loop had a length of 310 m, a dispersion of $D = -0.31$ ps/nm/km, dispersion slope of $S = 0.0031$ ps/nm²/km, a nonlinear coefficient of $\gamma = 20$/W/km and loss of $\alpha_{dB} = 1.21$ dB/km. These fiber parameters gave a maximum walk-off time between the OTDM and the various WDM signals of 1.8ps only. The WDM signals switched by the NOLM were then separated by a WDM demultiplexer filter, which guarantees multichannel operation, and individually assessed using a single post-amplified receiver, which was constituted of a variable attenuator, an erbium doped fiber amplifier (EDFA), a ~1nm filter and a 40GHz receiver.

4. RESULTS

Fig. 2(b) shows the spectral traces at the output port of the NOLM, before (solid trace) and after (dashed traces) the WDM filter, while Fig.2(a) shows the eye diagrams of the three simultaneously switched WDM channels. A high extinction ratio of the switched eye was guaranteed by a controlled amount of optical bias (i.e. phase difference) between signals propagating through the loop in opposite directions, which was generated by the polarization controllers inside the NOLM [8], and tuned using the internal polarization controllers.

Bit-error rate (BER) measurements and receiver sensitivity for each WDM channel are shown in Fig. 3(a) and Fig. 3(b) in the presence/absence of the adjacent WDM channels, respectively, to assess the crosstalk between them. Error free operation (BER$\leq 10^{-9}$) is achieved for all the WDM channels with power penalties (p_i) of only $p_1 \approx 0.5$ dB, $p_2 \approx 1.7$ dB and $p_3 \approx 3.5$ dB for Channel 3, 2 and 1, respectively.

We believe that the different performance achieved for the various WDM channels, with Channel 1 being the worst, reflects the incomplete power equalization prior to entering the EDFA at the input to the NOLM. This causes the various WDM signals to have different average/peak power levels as ca be appreciated in Fig. 2(a), and consequently different optical signal to noise ratios. Furthermore, Channel 1 is spectrally closest to the TDM signal resulting in a further degradation of its optical signal-to-noise ratio. We measured the BER performance for each WDM channel with all three TDM channels by detuning the



(a) *(b)*

Fig. 3: (a) BER measurements of each WDM channel when the other WDM channels are absent (circles) and present (triangles), respectively, showing no error floor. The 40Gbit/s back-to-back measurement is also reported for (rectangles). (b) Receiver sensitivity for all the WDM channels for error free operation when the other WDM channels are switched off (full symbols) and on (empty symbols), respectively.

5. CONCLUSIONS

We have successfully demonstrated an all-optical technique that converts a 130 Gbit/s OTDM signal simultaneously to a 3 × 43 Gbit/s WDM signal. The proposed scheme is based on broadband XPM in a single NOLM. Using a specially designed low dispersion and low dispersion slope HNLF as a nonlinear element, a low walk-off time among the signals and thus a broadband gate was achieved. This enables full flexibility for selecting the output WDM channel wavelengths as required in future all-optical networks. BER measurements show error free operation for all the three WDM channels with power penalties of $p_1 = 3.5$ dB, $p_2 = 1.7$ dB and $p_3 = 0.5$ dB, respectively, and no error floor.

REFERENCES

[1] A. E. Willner, "All-Optical Signal Processing in Next-Generation Communication Systems," in *Proc. OFC 2008*, invited presentation, February 2008.

[2] Y. Awaji, T. Miyazaki, F. Kubota, "160/4x40Gb/s OTDM/WDM Conversion Using FWM Fibre," in *Proc. ECOC 2004,* Paper We1.5.6, September 2004.

[3] H. Sotobayashi and W. Chujo, "Photonic gateway: TDM-to-WDM-toTDM conversion and reconversion at 40 Gbit/s (4 channels × 10 Gbits/s)," *J. Opt. Soc. Am. B*, vol. 19, no 11, pp. 2810-2816, November 2002.

[4] K. Uchiyama, H. Takara, T. Morioka, S. Kawanishi and M. Saruwatari, "100Gbit/s multiple-channel output all-optical demultiplexing based on TDM-WDM optical demultiplexing based on TDM-WDM conversion in a nonlinear optical loop mirror", *Electron. Lett.*, vol. 32, no. 21, pp. 1989-1991, October 1996.

[5] K. Uchiyama, S. Kawanishi and M. Saruwatari, "Multiple-channel output all-optical OTDM demultiplexer using XPM-induced chirp compensation (MOXIC)", *Electron. Lett.*, vol. 34, no. 6, pp. 575-576, March 1998.

[6] P. J. Almeida, P. Petropoulos, F. Parmigiani, M. Ibsen, and D. J. Richardson, "OTDM Add-Drop Multiplexer Based on Time-Frequency Signal Processing," *J. Lightwave Technol.*, vol. 24, no. 7, pp. 2720-2732, July 2006.

[7] N. J. Doran and D. Wood, "Nonlinear-optical loop mirror," *Optics Lett.*, vol.13, no. 1, pp. 56-58, January 1988.

[8] A. Bogoni, M. Scaffardi, P. Ghelfi and L. Poti, "Nonlinear Optical Loop Mirrors: Investigation Solution and Experimental validation for Undesirable Counterpropagating Effects in All-Optical Signal Processing", *IEEE J. of Selected Topics in Quantum Electron.*, vol. 10, no. 5, pp. 1115-1123, September/October 2004.