640Gbit/s Reconfigurable OTDM Add-Drop Multiplexer

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Abstract: A 640Gbit/s reconfigurable OTDM add/drop multiplexer is demonstrated, using a single periodically-poled Lithium-Niobate waveguide in a counter-propagating configuration. Error free operations confirm the effectiveness of a single device for simultaneous add/drop operations.

OCIS codes: (320.7110) Ultrafast nonlinear optics; **(**190.4360) Nonlinear optics, devices**.**

1. Introduction

Reconfigurable optical add/drop multiplexers (ROADMs) are key elements in the future optical networks in order to assure high throughput, low latency, transparency, and reconfigurability. Current ROADMs handle wavelength-division-multiplexing (WDM) traffic to obtain fine granularity and high capacity, but a further increasing of the network capacity will likely require optical time-division-multiplexing (OTDM) technique combined with the WDM technique. OTDM provides a granularity up to tributary channels and an easy reconfigurability since add/drop operations are carried out in time domain for each single wavelength. In the past, OTDM multiplexers have been demonstrated up to 160Gbit/s based on nonlinearities in semiconductor devices [1-3] and recently 640Gbit/s operation speed has been reached exploiting nonlinear optical fiber [4]. However, very high speed on-chip solutions remain of great interest due to their potential for integration.

In [5], we demonstrated the effectiveness of a periodically-poled Lithium-Niobate (PPLN) waveguide to perform channel extraction, and clearing from time-interleaved optical signals in the time domain at 640Gbit/s. The possibility of using PPLN waveguides at room temperature [6] makes this solution of great interest and it reduces the power requirements. However, we verified that each operation requires one PPLN waveguide opportunely optimized and no simultaneous operations are possible in a single waveguide [7].

Here we report on a 640Gbit/s reconfigurable OTDM add/drop multiplexer (OTDM ROADM) implementation based on a single PPLN waveguide. This ROADM acts in the time domain and it can carry out channel extraction, clearing and insertion for a single wavelength OTDM signal and also simultaneously for a WDM comb of OTDM channels [8]. Simultaneous add/drop operations are carried out with a counterpropagating configuration in a single PPLN waveguide. Moreover, reconfigurable operations have been verified through bit error rate (BER) measurements, including the case of simultaneous add/drop of more channels in the OTDM frame. These achievements represent a many-fold improvement in complexity and reconfigurability when using a single nonlinear element for ultra-fast time domain add/drop multiplexer in high capacity optical networks.

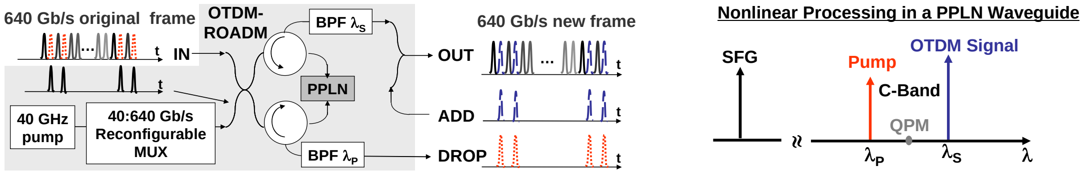

Fig. 1. (left) OTDM-ROADM architecture; (right) nonlinear effects in PPLN waveguide involved in the OTDM ROADM.

2. OTDM-ROADM description

Fig. 1(left) shows the OTDM-ROADM architecture. Optical add/drop operation is obtained by nonlinear interaction between the incoming 640Gbit/s OTDM signal and an optical pump with pulses synchronized with the channel to be dropped. Nonlinear effects in a single PPLN waveguide allow extracting the tributary channels and removing them from the original frame, i.e. the dropped channels and the survived channels can be obtained. The two operations are simultaneously carried out exploiting pump depletion effects in both propagation directions inside the PPLN waveguide. Fig. 1(right) shows the two pump configuration used in the PPLN waveguide for nonlinear processing. The two input signals that act as pumps can nonlinearly interact, and sum-frequency generation (SFG) occurs under the quasi-phase matching condition (QPM) generating pump depletion on the two original signals. In our experiment, the two input signals correspond to the 640Gbit/s OTDM frame and the multiplexed optical pump. Looking at the 640Gbit/s OTDM signal at the output of the PPLN, we can observe that the channels to be dropped are depleted by the SFG interaction with the pump, while the other channels can survive. Therefore new channels can be added through an optical coupler in the OTDM frame at the same position of the dropped channels. Meanwhile, looking at the multiplexed pump at the output of the PPLN, we can observe that it is depleted during the

SFG interaction when the corresponding 40Gbit/s channels to be dropped from the 640Gbit/s OTDM frame are at high level. In this way, the pump at the output of the PPLN represents the inverted and wavelength converted dropped channels. Unfortunately, as shown in [5] and [7], pump depletion effect can not be simultaneously maximized for both the signal and the pump. Therefore, when the pump depletion is optimized for the OTDM signal, we get the survived channels, but we can not extract high quality dropped channels. On the other hand, the dropped channels are obtained when the depletion is optimized for the multiplexed pump. In this implementation, we overcame this issue without requiring an additional PPLN waveguide, exploiting a counterpropagating configuration, with advantages in terms of complexity, cost and power consumption. OTDM frame and multiplexed pump are lunched into the PPLN in both the propagation directions and they independently interact in each direction. In such a way pump depletion can be separately optimized for the two involved signals in the two opposite propagation directions. Moreover, in order to show the reconfigurability of the add/drop multiplexer, the optical pump is generated by multiplexing a 40GHz pulsed clock through a reconfigurable OTDM multiplexer that allows to enable all pulses synchronized with the channels to be dropped.

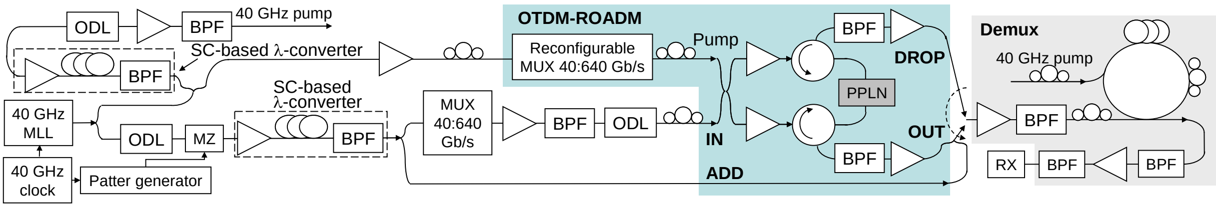

Fig. 2.Experimental setup

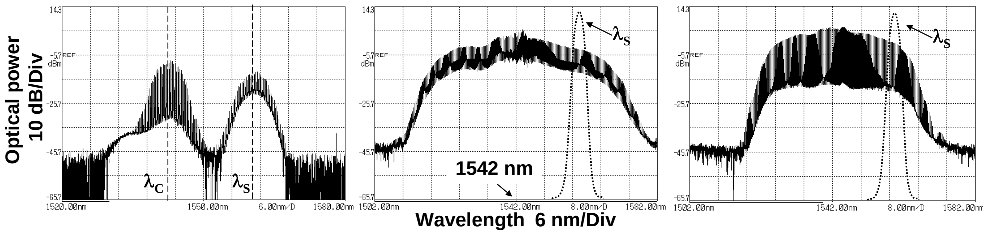

Fig. 3. (left): optical spectrum at the inputs of the PPLN waveguide, (center): modulated SC optical spectrum for generating the OTDM signal , (right): SC spectrum for generating the demux pump at λ_s.

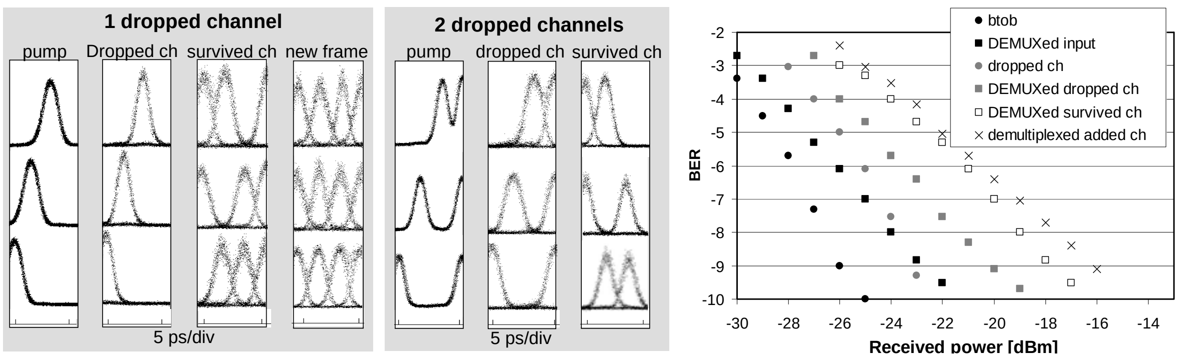

Fig. 4. (left): eye diagrams of the OTDM-ROADM optical pump, dropped, and survived channels, and new frame at the output of the OTDM-ROADM, (right): BER measurements.

3. Experimental setup and results

Fig. 2 shows the experimental setup. A 40GHz mode-locked laser (MLL) producing ~1ps pulses at λ_C = 1542nm is used to generate a modulated 40Gbit/s supercontinuum (SC) spectrum through propagation in a 200m piece of highly nonlinear fiber (HNLF) with a chromatic dispersion value of -0.9ps/nm/km at 1550nm and a dispersion slope of 0.01ps/km/nm^2. Then we filter the supercontinuum spectrum to obtain the 40Gbit/s data signal at λ_S = 1560nm. A 40-to-640Gbit/s optical fiber-based multiplexer produces the 640Gbit/s OTDM signal. The same 40GHz MLL is also used to generate a 40GHz pulse train, multiplexed by a reconfigurable 40-to-640GHz optical fiber-based multiplexer in order to obtain the OTDM-ROADM pump. Both the fiber-based multiplexers have a polarizer at the output so that up to 16 tributary channels in the 640Gbit/s data frame or the pump pulses have aligned polarizations.

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Then the 640Gbit/s OTDM frame and pump are coupled together and lunched into the PPLN waveguide in both propagation directions through two optical circulators. Besides, the PPLN waveguide requires polarization aligned signals at its input to maximize the conversion efficiency. We use polarization controllers (PCs) for both the 640Gbit/s OTDM signal and multiplexed pump before they are coupled, amplified and sent into the PPLN waveguide. In order to obtain the drop operation, the peak powers used are 27 and 16dBm, respectively, for the OTDM signal and the pump. The reverse power levels are used at the opposite PPLN waveguide input for the case of obtaining the survived channels, i.e., 27dBm peak power for the pump and 16 dBm for the OTDM signal. The input pulsewidths are ~1ps for both pump and OTDM signal. The length, loss, domain inversion period, effective cross-section area and the QPM bandwidth for SFG/DFG of the used PPLN waveguide are ~5cm, ~8dB, ~15um, ~50um^2 and 0.6nm, respectively. At each output of the PPLN waveguide, two cascaded tunable band-pass filters (BPFs) and a low noise erbium-doped fiber amplifier (EDFA) are used to extract the dropped channel and the survived frame. The channel to be added is obtained by splitting the 40Gbit/s data signal before generating the original 640Gbit/s OTDM frame. Finally, a 640-to-40Gbit/s nonlinear optical loop mirror (NOLM)-based optical demultiplexer is used to test the performance of the involved signals. A 100m HNLF with a zero-dispersion wavelength (ZDW) of 1558nm and a dispersion slope of 0.02ps/km/nm^2 is used in the NOLM. The 40GHz clock with a ~1ps pulsewidth for demultiplexing is obtained by splitting the output of the MLL. Depending on the signal wavelength to be demultiplexed, a SC-based λ-converter is needed in order to tune the demultiplexer pump wavelength. Supercontinuum generation is obtained through propagation in a 500-m piece of HNLF with a ZDW of 1565 nm and a dispersion slope of ~0.017 ps /nm^2/km.

Fig. 3 shows the optical spectrum of the involved signals at the inputs of the PPLN waveguides (left), the modulated SC spectrum for generating the λ-converted 40Gbit/s data (center) and the SC spectrum for generating the λ-converted de-multiplexer pump. Fig 4 (left) shows the eye diagrams of the involved signals at the input and output of the PPLN waveguide and at the output of the OTDM ROADM. In particular, the generated OTDM-ROADM optical pump, the dropped and survived channels at the two ports of the PPLN waveguide and the new OTDM frame obtained after add operation at the OTDM-ROADM output are reported. The cases of one or two channels to be dropped are considered. Note that for sake of simplicity, the add operation has been carried out just in case of one dropped channel. The eye diagrams confirm that the pump depletion effect, simultaneously optimized in both propagation directions, introduces little distortions on all involved signals. Just a slight pulsewidth broadening of less than 100 fs, due to the residual chromatic dispersion, which can be noticed. Fig. 4 (right) shows the 640Gbit/s BER performance. BER measurements are made on the original 40Gbit/s signal, the 40Gbit/s demultiplexed tributary channels of the input 640Gbit/s signal, the 40Gbit/s dropped channel and the 40Gbit/s demultiplexed survived and added channels in the case of one channel to be dropped. Moreover, the performance of the demultiplexed dropped and survived channels in the case of two channels to be dropped, is also measured. Note that, for the sake of clarity, we report here the BER performance concerning just one of the tributary channels and for just one position of the dropped channels. It is verified that the power penalty variations for all the channels and for all treated cases are within 2.5 dB, partially due to the non-perfect channel equalization during the optical multiplexing operations. Fig. 4 confirms the effectiveness of the proposal reconfigurable OTDM-ROADM. The OTDM-ROADM required energy/bit is about 1 pJ/bit considering all the coupling loss of the PPLN waveguide. A further reduction of power consumption is possible by use of improved devices.

Acknowledgements

We acknowledge the support of DARPA (#FA8650-08-1-7820), US-Italy Fulbright Commission and European Commission through EUROFOS and ACEPLAN and GOSPEL. We thank Prof. Martin Fejer's group in Stanford University for providing the PPLN waveguide.

4. References

[1] H.-F. Chou, et al, “Compact 160-Gb/s Add–Drop Multiplexer With a 40-Gb/s Base Rate Using Electroabsorption Modulators”, IEEE Photon. Technol. Lett., vol. 16, n. 6, 2004.

[2] C. Schubert, et al, “Error-free all-optical add-drop multiplexing at 160 Gbit/s”, Electronics Letters, vol. 39, n.14, 1074-1076, 2003.

[3] JP Turkiewicz, et al, “Field trial of 160Gbit/s OTDM add/drop node in a link of 275 km deployed fiber”, OFC 2004, paper PDP1.

[4] H. C. Hansen Mulvad, et al, “640 Gbit/s Optical Time-Division Add-Drop Multiplexing in a Non-Linear Optical Loop Mirror,” IEEE LEOS Winter Topical Meeting 2009, paper MC4.4.

[5] A. Bogoni, et al, “640 Gb/s All-Optical Add/Drop Multiplexing Based on Pump Depletion in a PPLN waveguide”, Photonics in Switching 2010, paper PTuB6, 2010.

[6] M.V. Drummond, et al, “Error-free wavelength conversion at 160 Gbit/s in PPLN waveguide at room temperature,” Electron. Lett. 45, 22, 1135-1137, 2009.

[7]A. Bogoni, et al, “160 Gb/s Time-Domain Channel Extraction/ Insertion and All-Optical Logic Operations Exploiting a Single PPLN Waveguide,” IEEE J. of Lightwave Technol. 27 (23), pp. 4221-4227 (2009).

[8] A. Bogoni, et al, “Ultra-fast all optical signal processing based on PPLN waveguides”, Photonics in Switching 2010, paper PWA1, 2010