64-Channel WDM Transmitter based on Optical Fourier Transformation using a Portable Time Lens Assembly

Mads Lillieholm, Michael Galili, Leif K. Oxenløwe, Pengyu Guan*

DTU Fotonik, Dept. of Photonics Engineering, Technical University of Denmark, H.C. Ørsteds Plads Bldg. 343 DK-2800, Denmark
**pengu@fotonik.dtu.dk*

Abstract: We demonstrate 64-WDM-channel generation with 25-GHz spacing from a single SFP+ transceiver using a portable time lens optical processor. After transmission in a 50-km unamplified link, -39.1 dBm average received power sensitivity at BER=10^{-3} is measured.

1. Introduction

Optical signal processing (OSP) is often cited as a grand solution to meet the rapidly growing demands for internet data throughput, for its unmatched potential to process ultrahigh bandwidth signals, with low latency and high energy efficiency compared to electronic solutions [1]. Many promising OSP applications in telecommunication are based on four-wave mixing [2], e.g. for high-speed wavelength conversion [3] or optical phase conjugation [4], which are in a class of OSP relying largely on a single continuous-wave pump and a nonlinear fiber or photonic waveguide. This class has relatively simple, albeit powerful functionality, and in principle a straightforward path to practical implementation. More advanced classes of FWM-based OSP applications include phase-sensitive amplification which relies on multiple coherent pumps for regeneration of phase-encoded signals [5] and optical time lenses based on linearly chirped FWM pump pulses [6]. Optical time lenses have been shown to enable highly advanced OSP such as spectral magnification [7] and optical Fourier transformation (OFT) for time-to-frequency conversion [8] or vice versa. This type of system has added complexity and is more sensitive to temperature changes and vibrations, which cause temporal walkoff and polarization instability respectively. Therefore, demonstrations are often significantly tethered to lab resources and equipment, making a practical demonstration outside of a lab-environment highly challenging. Previously, we demonstrated the simultaneous generation of 32 WDM channels with 50 GHz spacing from a single off-the- shelf SFP+ transceiver using a time-lens [9].

In this demonstration, to further improve the energy and spectral efficiency, we completely untether an OFT-based WDM transmitter producing 64×125-Mbit/s WDM channels with 25 GHz spacing from a single TDM source. The optical signal processing assembly is mounted on a 120×55 cm^2 wooden base. Connecting wires consist of a wall plug cable for power and an optical input for the TDM signal, with outputs comprising the generated WDM signal and an electrical synchronization signal (and USB connections for laser and EDFA control). The build, weight and dimensions of this unit make it suitable to transport outside of the lab. All in all, this constitutes a significant leap forward with double the data rate and number of channels using the same transmitter, compared to our previous demonstration [9]. Doubling the channel number fills the existing guard band, hence some crosstalk is expected, although a suitably narrow optical filter should enable low-penalty demultiplexing. As before, the OFT is based on chirped-pump FWM in highly nonlinear fiber (HNLF), although a number of components, including the HNLF, have been replaced with compact devices. After 50-km transmission, the measured performance using an SFP+ receiver and a ~0.3-nm Gaussian channel filter is -39.1 dBm average received power sensitivity at BER = 10^{-3}, with up to 1.5 dB improvement for edge channels due to reduced crosstalk.

2. Experimental Setup

The experimental setup is shown in Fig. 1. Note that the size of the components in the serial-to-parallel converter is

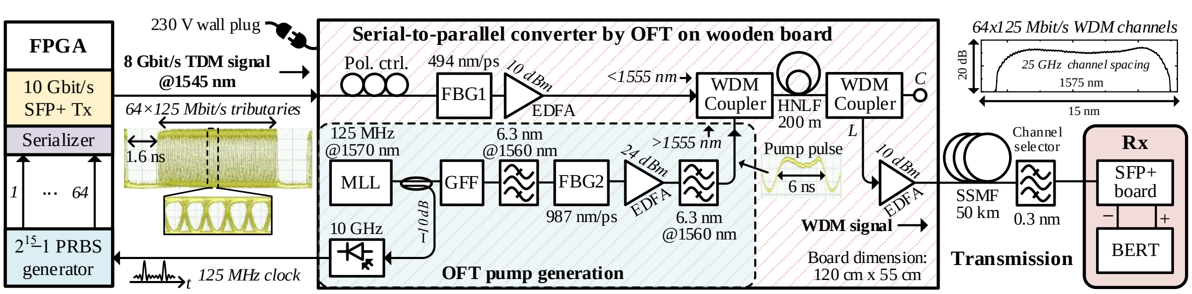

Fig. 1. Setup schematic showing a TDM signal with 64×125 Mbit/s tributaries converted into a WDM signal with 64×125 Mbit/s WDM channels.

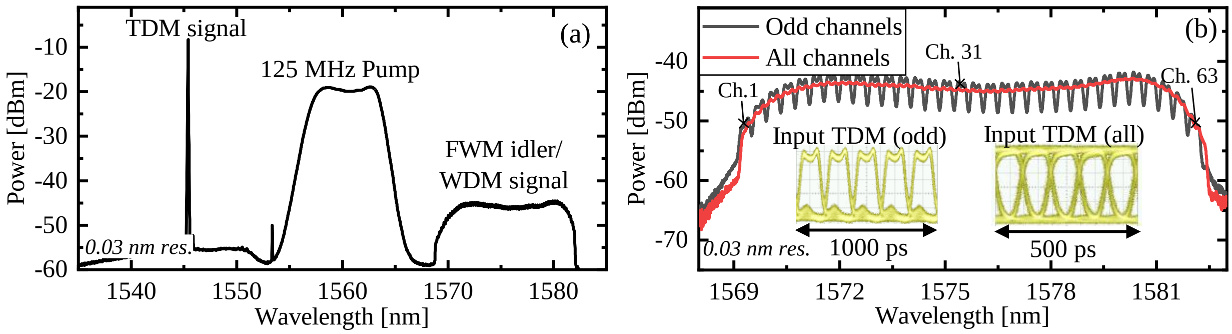

Fig. 2. (a) FWM spectrum showing input TDM signal, pump and resulting WDM signal. (b) WDM spectra after pump suppression for all channels and odd channels respectively. Insets show the TDM waveforms before conversion.

not to scale, and the positioning is changed to increase readability. The input to the serial-to-parallel converter is an optical 8-Gbit/s TDM signal consisting of 64×125-Mbit/s tributaries at 1545 nm on-off keying modulated with uncorrelated 2^{15}-1 pseudo-random binary sequences (PRBSs). The signal is generated from a 10-Gbit/s small form-factor pluggable (SFP+) transceiver, controlled by logic on a field-programmable gate-array (FPGA). A 20% guard interval of 1.6 ns is inserted for every 8-ns period to facilitate the OFT process. The PRBS sequence generators are synchronized with the mode-locked laser (MLL) which acts as the OFT pump source. The MLL is fundamentally mode-locked in a robust and lightweight design. The converter system itself is mounted on a 120 cm by 55 cm wooden particle board, consisting of rugged and compact components to facilitate stability and portability. An onboard power supply delivering 120 W powers three OEM erbium-doped fiber amplifiers (EDFAs) with USB control via microcontrollers, whereas two independent supplies power the MLL and the 10 GHz photo-diode which generates the synchronization clock for the FPGA. Four 40 mm by 40 mm fans assist with convection cooling of the EDFAs and power supply. At the input to the converter the TDM pulses are broadened in a fiber-Bragg grating (FBG1) with 494 ps/nm accumulated 2nd order chromatic dispersion, which after the OFT results in a time-to-frequency mapping of 100 ps to 25 GHz. Then the dispersed signal is amplified to 10 dBm power before low-loss coupling with the OFT pump in a WDM-coupler at the HNLF input. The OFT pump is generated from the MLL source which is spectrally carved into a flat-top spectrum with 6.3 nm 3-dB bandwidth, using a combination of a gain flattening filter (GFF) and an optical bandpass filter (OBPF) with a relatively sharp stopband attenuation profile. By dispersing the flat-top spectrum in FBG2 with 987 ps/nm accumulated dispersion, the pump obtains ~6 ns full-width at half maximum duration pulses with the same shape as the spectrum, and a linear chirp. The pulses are then amplified to 24 dBm, followed by another 6.3-nm OBPF to remove out-of-band ASE and to further shape edges of the spectrum with an additional 4 dB loss. The combined signal and pump are then launched into a compact 200-m highly nonlinear fiber (HNLF) on a 15-cm diameter aluminum reel, with zero-dispersion wavelength near 1560 nm and a dispersion slope of 0.011 ps/(nm^2·km). The pump and signal induce a degenerate FWM process, whereby the resulting idler becomes a conjugate copy of the signal, in addition to the time lens effect where two times the parabolic phase of the pump transfers to the idler. The process follows the equation $E_i \propto E_p^2 E_s^*$, where E_i, E_p and E_s denote the idler, pump and signal fields respectively. In this case the resulting idler becomes a 64-channel WDM signal with 25 GHz channel spacing, where each TDM tributary is mapped to a unique frequency. The FWM spectrum can be observed in Fig. 2(a). The WDM spectrum after pump suppression can be seen in Fig. 2(b) for all 64 channels, as well as for only odd tributary only numbers enabled. The envelope can be seen to be approximately constant in the case of 64 channels, due to OFT imaging of non-return-to-zero modulation. Enabling only every other tributary at the transceiver results in a return-to-zero-like TDM signal, which reveals the channel positions after the OFT with precise and uniform 50 GHz spacing between channels. At the HNLF output the pump and signal is suppressed with <0.5 dB insertion loss by directing them to the C-band output of a WDM coupler, whereas the WDM signal is directed to the L-band output. The WDM signal is boosted to 10 dBm total average power in an L-band EDFA, before transmission in 50 km SSMF with 10 dB propagation loss. The power is

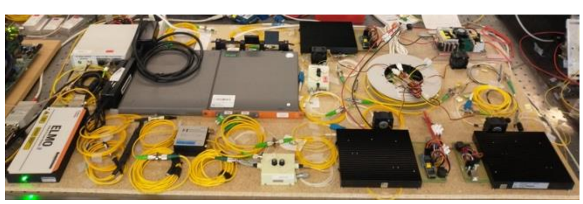

Fig. 3. Photograph of the parallel-to-serial converter board.

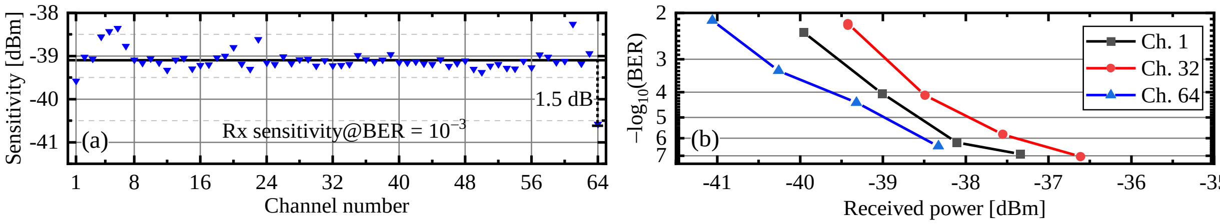

Fig. 4. (a) Received power sensitivity at BER = 10^{-3} for all channels. Black line indicates the mean, and the difference from the best channel (64) to the mean sensitivity is indicated to be 1.5 dB. (b) BER vs. received power curves for representative WDM channel wavelengths.

optimized to avoid nonlinear propagation effects. At the receiver a tunable Gaussian ~0.3 nm 3-dB bandwidth OBPF is used to select one channel before photo-detection by a 10 Gbit/s SFP+ receiver on a test board. Finally, the differential outputs are connected to a bit-error rate tester (BERT) for performance evaluation. A photograph of the real implementation of the OSP board is shown in Fig. 3, to provide a more accurate impression of the setup.

3. Results and Discussion

The received power sensitivity for the common forward-error correction threshold at BER = 10^{-3} is shown for all 64 channels in Fig. 4(a). The overall performance is good and uniform, with an average sensitivity of -39.1 dBm, and all channels within ~1 dB of each other, except for the edge channels. Channels 1 and 64 show up to 1.5 dB improved performance attributed to reduced crosstalk, although with a 6.5-dB reduced power budget compared to the central channels. The crosstalk is expected to be significantly reduced with a higher order Gaussian filter with <25 GHz (0.2 nm) bandwidth. The power budget difference stems from imperfect spectral shaping of the FWM pump, resulting in the outermost TDM tributaries overlapping with the reduced pump power of the pump pulse tail. The pump pulse shape closely resembles the pump spectrum after FBG2, in which a dispersive frequency-to-time OFT is essentially performed. The observed fidelity of the imaging from the spectral shape to the time domain indicates that using OBPFs with rectangular features instead will result in rectangular pulses, thus equalizing the channel powers. Fig. 4(b) shows the BER vs. received power for representative channels at the edges and the middle. The BER is not shown below ~10^{-7}, as that implies a statistically insignificant number of error-events within the 300-ms measurement window. A slow vibration-induced polarization drift of the system was noted with the cooling fans operating at 12 V. The drift was not observed with the fans operating at 5 V, although the pump EDFA case temperature then rose to slightly above the recommended operating levels (>50 °C). It is expected that mounting the fans on shock-absorbent material can alleviate the issue.

4. Conclusion

In conclusion, we have demonstrated the generation of 64 WDM channels with 25 GHz spacing from a single TDM source, showing good, uniform performance with a received power sensitivity of -39.1 dBm at BER = 10^{-3}. This is double the data throughput and number of channels, compared to our last demonstration. The optical processor assembly was mounted on a wooden board with suitable dimensions for e.g. transportation in a foam padded flight case, with no more wire connections for power and signaling than many existing turnkey equipment solutions. This work improves the efficiency and reliability of the proposed solution, and is a significant step towards getting advanced OSP applications out of the lab.

The authors would like to acknowledge Peter D. Ekner and Finn Kræmer for FPGA and electronics work and advice. Project grants VILLUM LENS-PON (19158), IFD INCOM (8057-00059B), DNRF CoE SPOC (DNRF123).

5. References

[1] A. E. Willner et al., “Optically efficient nonlinear signal processing”, IEEE J. Sel. Top. Quantum Electron., vol. 17, pp. 320-332, 2011.
[2] J. Hansryd et al., “Fiber-based optical parametric amplifiers and their applications”, IEEE JST. Quantum Electron., vol. 8, pp. 506–520, 2002.
[3] H. Hu et al., “Ultra-high-speed wavelength conversion in a silicon photonic chip”, Opt. Express, vol. 19, no. 21, pp. 19886-19894, 2011.
[4] A. D. Ellis et al., “40 Gbit/s transmission over 202 km of standard fibre using midspan spectral inversion”, Electron. Lett., vol. 31, pp. 299-301, 1995.
[5] Z. Tong et al., “Towards ultrasensitive optical links enabled by low-noise phase-sensitive amplifiers”, Nat. Photon., vol. 5, pp. 430-436, 2011.
[6] P. Guan et al., “Time Lens-Based Optical Fourier Transformation for All-Optical Signal Processing of Spectrally-Efficient Data”, J. Lightw. Technol., vol. 35, no. 4, 2017.
[7] P. Guan et al., “All-optical OFDM system using a wavelength selective switch based transmitter and a spectral magnification based receiver”, in The European Conference on Optical Communication (ECOC), 2014, pp. 1-3.
[8] H. C. H. Mulvad et al., “Ultra-high-speed optical serial-to-parallel data conversion by time-domain optical Fourier transformation in a silicon nanowire”, Opt. Express, vol. 19, no. 26, pp. 825-835, 2011.
[9] M. Lillieholm et al., “32-Channel WDM Transmitter based on a Single Off-the-Shelf Transceiver and a Time Lens”, in OFC, T4G.3, 2020.