32-Channel WDM Transmitter based on a Single Off-the-Shelf Transceiver and a Time Lens

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Abstract: We demonstrate simultaneous WDM-signal generation using an optical time-lens and off-the-shelf components. 32 WDM-channels with 50-GHz spacing are generated from a single SFP+ transceiver source and received using another SFP+ after 50-km unamplified transmission.

1. Introduction

The data throughput load and number of users in access networks are currently increasing massively due to the proliferation of online devices and perpetually growing popularity of bandwidth hungry video services. An important class of access networks are passive optical networks (PONs) [1], which are being deployed on a large scale for short reach fibre access to businesses and consumers with high bandwidth and low latency requirements. High-speed PON systems currently being deployed are largely based on time-division multiplexing (TDM) for multiple user access, with shared net throughput rates of 10 Gbit/s. On the other hand, PON standards with a wavelength-division multiplexing (WDM) multiple access scheme such as NG-PON2 has been specified for aggregate bit rates up to 40 Gbit/s. TDM-PON has the advantage of relying only on a single high-speed optical transceiver at the central office, thus providing equipment cost and space savings compared to WDM-PON, which requires N frequency stabilised transceivers to service N simultaneous users. However, TDM-PON necessitates the use of high-speed transceivers at the optical network units (ONUs), N-way power splitting, to broadcast the signal, limited reach, due to dispersion of the relatively high symbol rates, and a power budget depending on the number of users. WDM-PON features improved transmission properties and scalability with increased robustness to dispersion due to the reduced symbol rates of dedicated wavelength channels, and low-loss wavelength routing using e.g. arrayed waveguide gratings. Recently, we proposed a scheme which combines the benefits of a TDM transmitter at the central office with the beneficial transmission properties of a WDM-PON [2]. The scheme is based on optical Fourier transformation (OFT) [3-4], using a time lens [5], whereby the data of different tributaries constituting a high-speed TDM signal are mapped to different frequencies on a WDM grid. The scheme was demonstrated to convert a 256 Gbit/s optical TDM signal to 256×1 Gbit/s WDM channels, using a time lens based on four-wave mixing (FWM) with linearly chirped pump pulses [6], in a broadband AlGaAs on-insulator waveguide [7]. In this paper we demonstrate the first OFT-based WDM-PON transmitter driven by a field-programmable gate-array (FPGA) using a single off-the-shelf small form-factor pluggable (SFP+) dense WDM (DWDM) transceiver and a compact and rugged commercial mode-locked laser (MLL) source to generate 32x125 Mbit/s WDM channels from a time-to-frequency-converted 4 Gbit/s TDM signal. In conjunction with commercial dispersion-designed fibre Bragg gratings (FBGs) the transmitter achieves an unprecedented degree of stability for a broadband OFT system, and is shown to achieve receiver sensitivities at 1×10^{-3} bit-error rate (BER) below −38 dBm using an SFP+ transceiver, for all channels after 50 km fibre transmission.
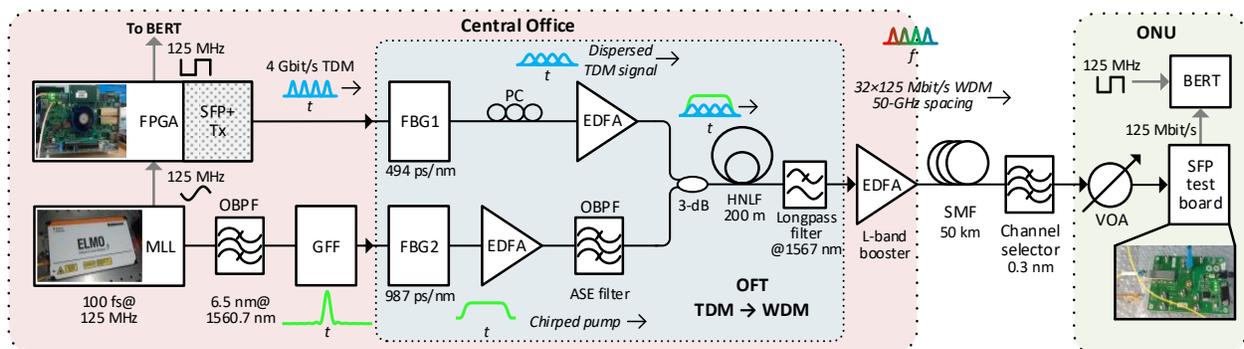

Fig. 1. Experimental setup schematic showing the single-transceiver 32-channel WDM transmitter at the central office, the 50-km transmission span and the receiver at the ONU. Photos indicate the location of some critical off-the-shelf components.

2. Experimental Setup

The experimental setup is shown schematically in Fig. 1. The user programmable part of an Intel Cyclone 10 FPGA device is used to generate 32 independent and decorrelated $2^{15}-1$ maximal length pseudo-random binary sequence data streams at 125 Mbit/s. Through a dedicated FPGA transceiver, the streams are serialised and converted to a 4 Gbit/s TDM signal with on-off keying modulation using a Finisar 10 Gbit/s DWDM SFP+ transceiver. The transceiver is operated at 10 Gbit/s with a 20% guard interval inserted for every 8-ns duration (corresponding to 125 MHz) to enable 4 Gbit/s RZ output to facilitate the OFT operation. Then the signal is linearly chirped in an FBG (FBG1) with 494 ps/nm dispersion in order to map the symbols with 200 ps duration to a 50-GHz grid after the OFT. The FBGs used for this experiment were designed to minimise third-order dispersion, in order to avoid spectral distortions of the converted WDM signal. Finally, the signal is amplified to couple 10 dBm power into a quadratic phase modulation stage based on FWM in a 200-m highly nonlinear fibre (HNLF). The pump is generated from a femtosecond mode-locked fibre laser (MLL) source centred at 1570 nm with a 125 MHz repetition rate, which doubles as a clock generator to synchronise with the FPGA. A flat-top 6.5-nm wide spectrum is carved out of the MLL output around 1560.7 nm using an optical bandpass filter (OBPF), followed by a tuneable Mach-Zehnder-based gain-flattening filter (GFF) used to control the spectral tilt. Then the pump pulses are linearly chirped in FBG2 with 987 ps/nm dispersion and amplified to couple 19 dBm average power into the HNLF. The dispersion results in the chirped pump pulses resembling the shape of the flat-top spectrum with ~80% duty cycle. During the degenerate FWM process, twice the linear chirp of the pump is transferred to the conjugate signal copy (idler), corresponding to the quadratic phase modulation of a time lens, thus completing the time-to-frequency OFT of the TDM signal to a 32-channel WDM signal with 50 GHz channel spacing. At the input to the HNLF, the pump and signal are synchronised by delaying the signal output in 100-ps increments using the FPGA. At the HNLF output the pump and input signal are suppressed using a longpass filter to extract the idler beyond 1570 nm. The WDM signal is amplified to 18 dBm launch power and transmitted over 50 km standard single-mode fibre (SMF), after which a tuneable filter with 0.3 nm 3-dB bandwidth is used to demultiplex a selected channel, followed by a variable optical attenuator (VOA) before being received using a 10 Gbit/s SFP+ transceiver on an evaluation board connected to a bit-error rate tester (BERT). The eye diagram measured at the output of the SFP+ transceiver using a digital sampling oscilloscope is shown in Fig. 2(a), showing the signal structure with 32 TDM tributaries and a guard interval every 8 ns. The FWM spectrum at the HNLF output is shown in Fig. 2(b) with the input TDM signal, the chirped pump and the generated WDM signal indicated. Note that the pump spectrum is deliberately tilted so that the resulting tilt on the WDM idler spectrum counters the gain tilt of the subsequent booster EDFA.

3. Results and Discussion

To evaluate the stability of the transmitter, the generated WDM spectrum at the output of the booster EDFA was measured every minute for an hour. All the 60 measurement results are plotted on top of each other in Fig. 2(c). The results indicate a high degree of system stability with very small frequency- or power-deviations. The ~5-dB spectral roll-off at the outermost channels is due to the pump pulse roll-off, which is inherited from the roll-off of the OBPF used to carve out the pump spectrum. Hence, inserting an OBPF with a sharper transfer function at the MLL output is expected to result in significantly improved channel equalisation. Aside from the spectral roll-off, the generated WDM spectrum can be seen to closely resemble the SFP+ transmitter output waveform seen in Fig. 2(a), including a characteristic dip for each channel, indicating that the time-to-frequency conversion is performed with high fidelity. Finally, Fig. 2(d) shows a 150-GHz wide zoom-in of Fig. 2(c), indicating very precisely controlled frequency
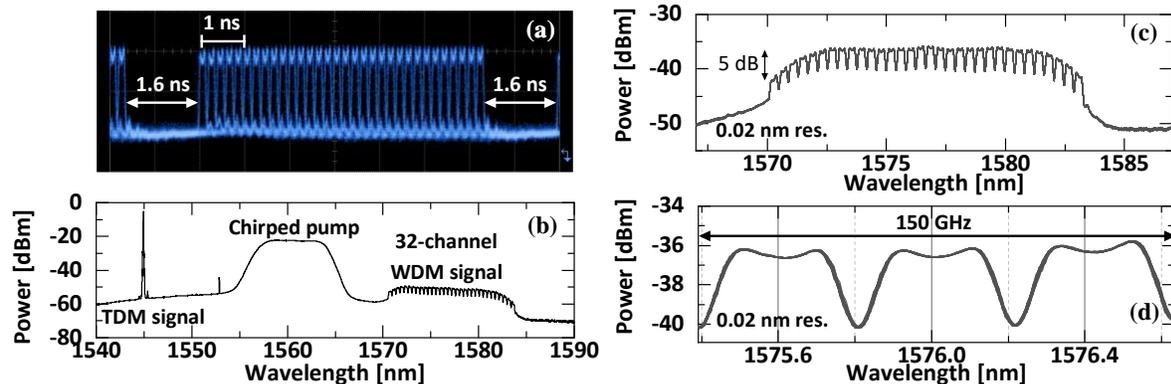

Fig. 2. (a) The measured optical SFP+ transceiver output, (b) FWM spectrum at the HNLF output with pre-emphasis on the pump spectrum, (c) 60 superimposed spectra of the WDM signal with 50 GHz channel spacing over 1 hour, showing great stability, (d) zoom-in on 3 channels in (c).
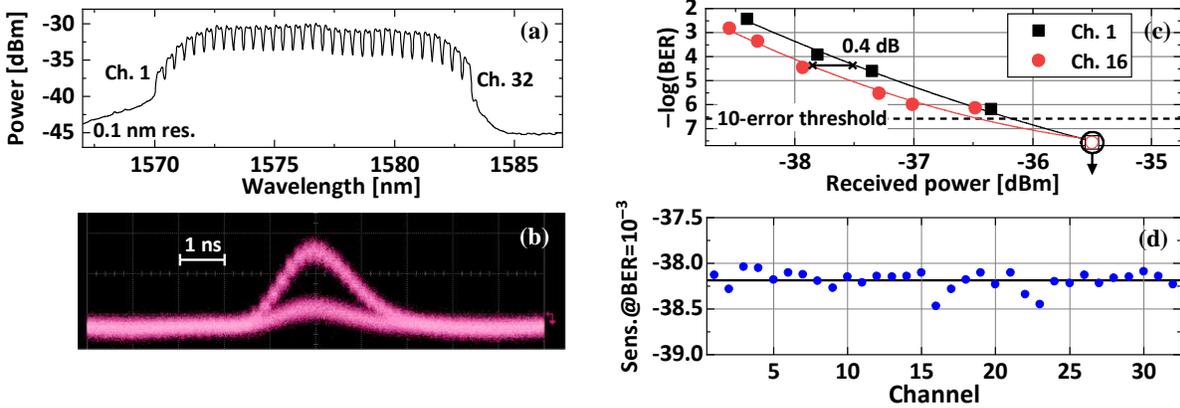
Fig. 3. (a) WDM spectrum after 50 km fibre transmission, (b) electrical eye diagram at SFP+ transceiver output for Ch. 16 at −35 dBm received power, (c) Measured BER vs. received power for channels 1 and 16 (symbols) and fits (lines), the threshold for 10 error events is indicated and the downward arrow indicates 10^{-7} errors or less, (d) Sensitivity at BER = 10^{-3} for all channels (symbols) and average sensitivity (line).

spacing. The WDM spectrum after 50 km fibre transmission is shown in Fig. 3(a). An electrical eye diagram of a demultiplexed WDM channel (Ch. 16) at the output of the SFP+ receiver at −35 dBm received power is shown in Fig. 3(b). Although the signal duty cycle is low at 125 Mbit/s due to the optical channel bandwidth, a clear eye opening can be observed. The BER performance is shown for a range of received power levels for channels 1 and 16 in Fig. 3(c). Here a ~0.4 dB penalty is indicated for channel 1 compared to channel 16, which is expected to be due to the reduced optical signal-to-noise ratio because of imperfect channel equalization at the transmitter. Note that the error counting cycle was repeated every 300 ms. Hence, to obtain at least 10 error events at 125 Mbit/s, the lowest measurable BER is 2.7×10^{-7}, which is indicated by the dashed line. Zero errors were measured above −35.5 dBm, suggesting that the BER is at or below the level indicated by the downward arrow. The received power sensitivity at the forward-error correction threshold BER = 10^{-3} is shown for all 32 channels in Fig. 3(d). The sensitivities are all within a range of 0.5 dB with an average sensitivity of −38.2 dBm, thus indicating similar and good performance for all channels. The decibel power budget can be calculated as $P_{budget} = P_{launch} - P_{sens} - (L_{fibre} + L_{demux} + 10\log(N))$, where P_{launch} is the WDM signal launch power, P_{sens} is the receiver sensitivity, L_{fibre} is the transmission fibre loss, L_{demux} is the loss due to channel filtering and N is the number of channels. Assuming a typical AWG, L_{demux} = 5 dB, which leads to an average power budget of 26.1 dB, a very good margin is indicated, allowing e.g. for further transmission.

4. Conclusion

We successfully demonstrated the simultaneous generation of 32 125-Mb/s WDM channels from a single off-the-shelf SFP+ transceiver using a time-lens-based signal processor with 50 km unamplified transmission. The novel transmitter exhibited no discernible frequency and power stability issues. All generated WDM channels are received by the same type of SFP+ transceiver, achieving BERs below the 10^{-3} FEC threshold after 50 km transmission with a 26.1 dB average power budget. This is the first and highest number of WDM channels carrying independent data generated from a single off-the-shelf transceiver using a time lens. These results show a clear potential of this solution in terms of practicality, efficiency and reliability.

6. References

[1] D. Nesset, "PON roadmap," IEEE J. Opt. Commun., 2017, 9(1), pp. A71-A79.
[2] P. Guan et al., "Highly Flexible WDM PON System with a Single TDM Time Lens Source Enabling Record 150 km Downstream Reach," OFC2018, Th2A.54.
[3] M. Nakazawa et al., IEEE Photon. Technol. Lett., 2004, 16(4), pp. 1059-1061.
[4] P. Guan et al., J. Lightw. Technol., 2017, 35(4), pp. 799-806.
[5] B. Kolner, "Space-time duality and the theory of temporal imaging," IEEE J. Q. Electron., 1994, 30(8), pp. 1951-1963.
[6] E. Palushani et al., IEEE J. Q. Electron., 2009, 45(11), pp. 1317-1324.
[7] P. Guan et al., "Simultaneous 256 WDM Channel Generation using a Single AlGaAsOI Waveguide based Time Lens Source," ECOC2019, M.1.A.6.