OTDM-WDM Conversion Based on Time-Domain Optical Fourier Transformation with Spectral Compression

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Abstract: We propose a scheme enabling direct serial-to-parallel conversion of OTDM data tributaries onto a WDM grid, based on optical Fourier transformation with spectral compression. Demonstrations on 320 Gbit/s and 640 Gbit/s OTDM data are shown.
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1. Introduction

Optical Time-Division Multiplexing (OTDM) is the time-interleaving of optical data signals based on very low duty-cycle pulse trains at identical wavelengths. The OTDM technique is a simple method for high-speed data generation beyond the bandwidth limitation of electronics. Indeed, the OTDM technique enables the generation of serial data signals with a symbol rate up to 1.28 Terabaud by optically multiplexing data signals (tributaries) of pulse durations well below 1 picosecond [1]. As opposed to wavelength division multiplexed (WDM) systems where each electrically generated tributary is allocated to its own wavelength channel (parallel), OTDM enables the allocation of a large number of tributaries to the same wavelength channel. Therefore, OTDM could offer some potential advantages in terms of simpler channel management. On the receiver side, however, each tributary needs to be demultiplexed in a separate high-speed switch to enable electrical detection. Therefore, the complexity of an OTDM receiver essentially scales with the number of OTDM tributaries. To overcome this problem, a number of schemes for demultiplexing all or several tributaries in a single switch by serial-to-parallel conversion have been proposed, e.g. [2-4]. Among such schemes, a true OTDM-WDM conversion is particularly challenging since it requires the converted tributary spectra to conform to the narrow channel spacing of a WDM grid.

Here, we propose to use Time-Domain Optical Fourier Transformation (OFT) [5] for OTDM-WDM conversion of several tributaries in a single operation. The OFT is accomplished by dispersion followed by phase modulation using linearly chirped pump pulses in a four-wave mixing (FWM) process [6]. In this implementation, the OFT conversion is associated with an efficient spectral compression [7], enabling the converted tributaries to be mapped directly onto a WDM grid. The principle is demonstrated for a 320 Gbit/s OTDM data signal, from which 9×10 Gbit/s tributaries are converted to a ~1.1 nm channel spacing. A full system characterization with bit error rate (BER) measurements is performed. Finally, BER results are shown for a 640 Gbit/s OTDM data signal.

2. Principle

In general, OFT is accomplished by a dispersive medium and phase-modulation. Using OFT, it is possible to interchange an optical waveform between the frequency-domain and the time-domain, as described e.g. in [5]. Here, the input waveform consists of a number of time-interleaved, transform-limited OTDM tributaries, which are converted into the frequency domain by OFT, as shown in Fig. 1 (a). As a consequence of the OFT time-to-frequency conversion, the difference in timing allocation of the input tributary pulses will translate into a different wavelength allocation at the output. The present OFT implementation simultaneously leads to a spectral compression of the output tributaries, which is achieved by placing the dispersive medium before the phase-modulation. The spectral compression is the result of a cancellation of the dispersive linear chirp of the broadened pulses by the subsequent phase-modulation. The phase-modulation is achieved by a FWM process using linearly chirped pulses as pump signal. The dispersed OTDM pulses act as probe signal, and the FWM process will generate a phase-conjugated idler signal which combines the phases of the pump and probe [6]. As a result, the idler signal

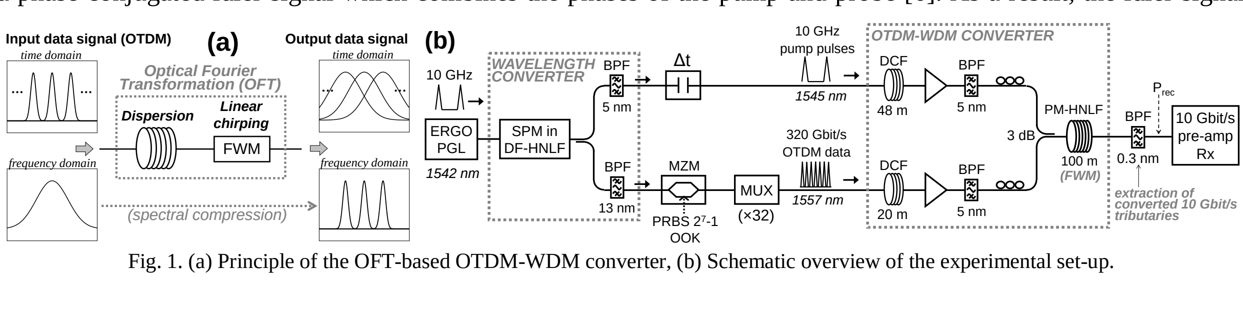

Fig. 1. (a) Principle of the OFT-based OTDM-WDM converter, (b) Schematic overview of the experimental set-up.

will contain the chirp-free converted tributaries. The number of converted tributaries, their conversion efficiency, as well as their spectral width and spacing will depend on experimental parameters such as the temporal width, shape and chirp rate of the pump pulses. These parameters need to be optimized in order to correctly map the converted tributaries onto a WDM grid with a specific channel spacing. In the following experiment, the minimum spacing is limited by the bandwidth of the optical bandpass filter (BPF) which is available to extract the converted tributaries.

3. Experimental set-up

A schematic of the experimental set-up is shown in Fig. 1 (b). An erbium glass oscillating pulse-generating laser (ERGO-PGL) emits 10 GHz pulses at a wavelength of 1542 nm with a temporal duration of ~1.5 ps full-width at half-maximum (FWHM). The ERGO-PGL output pulses are amplified and spectrally broadened by self-phase modulation (SPM) in 400 m of dispersion-flattened highly non-linear fibre (DF-HNLF). The SPM-broadened spectrum is filtered at 1545 nm using a 5 nm BPF to obtain the 10 GHz pump pulses for the FWM-based OTDM-WDM converter. Similarly, the 10 GHz pulses for the data signal are obtained by filtering at 1557 nm with a 13 nm BPF. The 10 GHz pulses at 1557 nm are encoded by on/off keying (OOK) with a 10 Gbit/s 2^7-1 PRBS pattern in a Mach-Zehnder modulator (MZM), followed by multiplexing up to 320 Gbit/s using a passive fibre-based delay-line multiplexer (MUX). The FWHM pulse width is 1.3 ps for the 320 Gbit/s OTDM data signal and 1.3 ps for the 10 GHz pump pulses. Next, the generated OTDM data signal and pump pulses enter the OTDM-WDM converter. As the first step of the OFT process, the 320 Gbit/s OTDM data signal is dispersed in a 20 m dispersion-compensating fibre (DCF). The resulting temporally broadened data pulse FWHM could not be measured due to pulse overlap. The pump pulses are linearly chirped by dispersive propagation through a 48 m DCF, resulting in a broadened FWHM of 17.5 ps. The pump and data signals are then amplified, filtered, and combined using a 3 dB coupler before undergoing FWM. The non-linear medium for the FWM is a polarization-maintaining highly non-linear fiber (PM-HNLF) of length 94 m, zero-dispersion wavelength 1545 nm, dispersion slope 0.025 ps/(nm^2·km), and non-linear coefficient γ~10 $W^{-1}km^{-1}$. The average input powers to the PM-HNLF are +20.3 dBm for the pump and +2.6 dBm for the 320 Gbit/s data. At the PM-HNLF output, a narrow 0.3 nm tuneable BPF extracts the converted 10 Gbit/s tributaries at different wavelengths from the FWM-generated idler signal. The filtered tributaries are sent into a 10 Gbit/s pre-amplified receiver for BER evaluation. Note that a 10 GHz electrical synthesizer is used to synchronise the ERGO-PGL, the PRBS pattern generator and the receiver.

4. Results and discussion

The operation of the OTDM-WDM is successful with error-free performance of the converted tributaries. First of all, Fig. 2 (a) shows the output spectrum of the PM-HNLF. The FWM process results in an idler signal consisting of more than 10 tributaries mapped to different wavelengths in the range 1525-1540 nm. The idler spectrum is shown

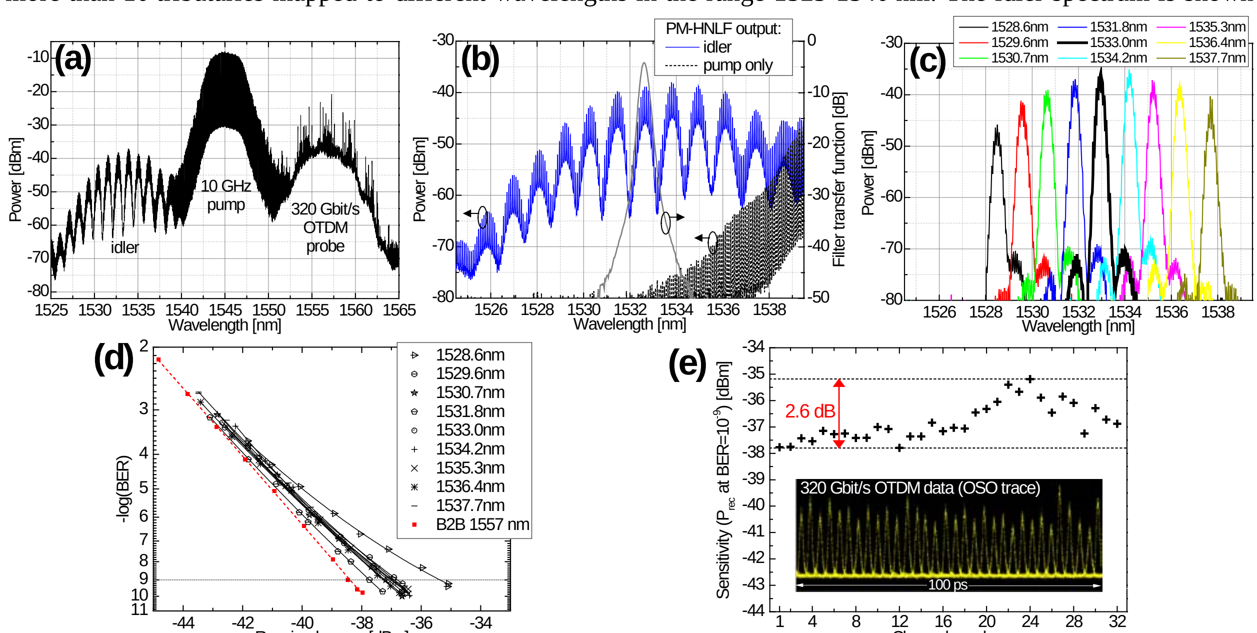

Fig. 2. 320 Gbit/s OTDM-WDM conversion: (a) Output spectrum of the PM-HNLF. (b) Zoom-in on the idler signal spectrum and transfer function of 0.3 nm BPF, (c) Spectra of 9 converted 10 Gbit/s tributaries after filtering (resolution is 0.01 nm), (d) corresponding BER curves. (e) Sensitivities of 32×10 Gbit/s tributaries, all extracted at 1533 nm by tuning Δt. Inset: 320 Gbit/s optical sampling oscilloscope (OSO) trace.

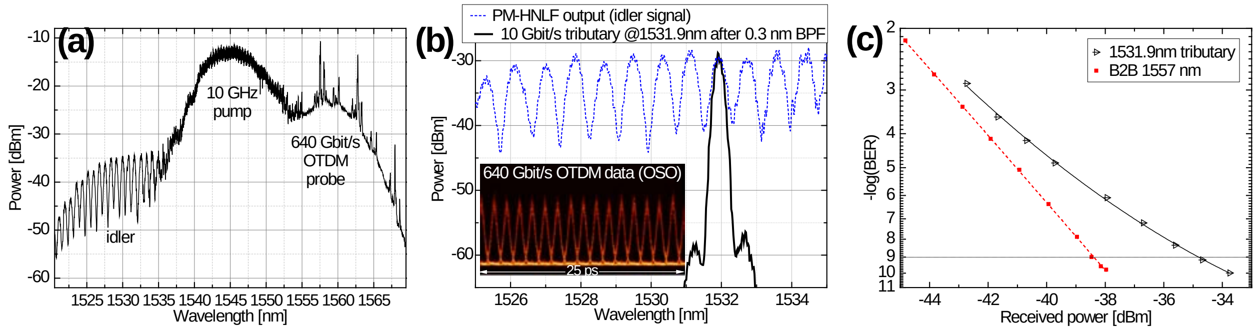

Fig. 3. 640 Gbit/s OTDM-WDM conversion: (a) output spectrum of PM-HNLF, (b) zoom-in on idler and extracted 1531.9 nm tributary (res. 0.1 nm). Inset: OSO trace of 640 Gbit/s transmitter output. (c) BER curve of the converted 10 Gbit/s tributary extracted at 1531.9 nm.

in detail in Fig. 2 (b). The tributary spacing is ~1.1 nm and the spectral 3-dB width is ~0.47 nm. The 9 tributaries from 1528.6 nm to 1537.7 nm are extracted by tuning the 0.3 nm BPF, while keeping the tunable time-delay Δt fixed (the BPF transfer function is shown in Fig. 2 (b)). The resulting spectra are shown in Fig. 2 (c), and the corresponding BER curves in Fig. 2 (d). The performance is error-free with a penalty less than 1.6 dB compared to the 10 Gbit/s B2B reference at 1557 nm (extracted at the MZM output with the 0.3 nm BPF). Only the 1528.6 nm tributary exhibits a larger penalty of 3.0 dB, which is attributed to a 5-10 dB lower conversion efficiency compared to the other tributaries, c.f. Fig. 2 (b). To verify the integrity of the entire 320 Gbit/s OTDM signal, each tributary is extracted by keeping the 0.3 nm BPF fixed to 1533.0 nm and by tuning Δt to extract each tributary. All 32 tributaries have error-free performance with a sensitivity variation of 2.6 dB as shown in Fig. 2 (e).

Finally, it is demonstrated that the OTDM-WDM scheme can also be scaled to 640 Gbit/s operation. The set-up is similar to Fig. 1 (b). The pulse widths are 490 fs (pump) and 600 fs (640 Gbit/s data). The DCF lengths are set to 36 m (pump) and 15 m (data). The pump pulse width at the PM-HNLF input is ~28 ps. The resulting output spectrum of the PM-HNLF is shown in Fig. 3 (a). The idler spectrum in Fig. 3 (b) shows that the tributaries are successfully mapped to different wavelengths, in this case with ~0.83 nm spacing. The 10 Gbit/s tributary at 1531.9 nm is extracted using the 0.3 nm BPF, and the corresponding BER curve is shown in Fig. 3 (c). The performance is error-free with a penalty of 3.6 dB compared to the 10 Gbit/s reference. Error-free performance was verified for the 8 converted tributaries from 1527.8 nm to 1533.6 nm, having penalties between 2.3 dB and 5 dB.

5. Conclusion

We have introduced a novel scheme for OTDM to WDM conversion, based on an OFT scheme with dispersion followed by FWM-based phase-modulation. The OFT implementation is associated with a spectral compression enabling the OTDM tributaries to be converted directly onto a WDM grid. The method was successfully demonstrated on a 320 Gbit/s OTDM signal, where 9 tributaries were simultaneously converted to ~1.1 nm spaced 10 Gbit/s WDM channels having error-free performance with low penalty. Preliminary results at 640 Gbit/s with error-free performance demonstrate scalability to even higher OTDM data rates.

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