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# DWDM-to-OTDM Conversion by Time-Domain Optical Fourier Transformation

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**Abstract:** We propose DWDM-OTDM conversion by time-domain optical Fourier transformation. Error-free conversion of a 16×10 Gbit/s 50 GHz-spacing DWDM data signal to a 160 Gbit/s OTDM signal with a 2.1 dB average penalty is demonstrated.

**OCIS codes:** (060.4510) Optical communications; (190.4380) Nonlinear optics, four-wave mixing.

## 1. Introduction

Future high-capacity communication systems might require technologies for optical conversion between parallel and serial data formats [1]. Converting many low data rate parallel channels to fewer serial high data rate channels could simplify network management. A potential application is interfacing between lower speed access networks and core networks operating at high line rates. A DWDM-OTDM converter performs the parallel-to-serial conversion of dense wavelength division multiplexed (DWDM) low bit rate data channels into a single-wavelength optical time-division multiplexed (OTDM) data channel at the aggregate bit rate. In this process, each DWDM channel must be confined within a separate OTDM time-slot, an operation which might become increasingly difficult for larger numbers of DWDM channels. Previous WDM-OTDM demonstrations are based on a variety of techniques with different degrees of complexity, see [1-2] and references therein. However, no publications have yet reported time-domain optical Fourier transformation (OFT) [3] for this functionality. The OFT technique inherently transfers the spectral profile of an optical waveform into the time-domain intensity profile (or vice-versa), and it is therefore a well-suited candidate for conversion between serial and parallel data formats [4].

Here, we propose to use time-domain OFT for DWDM-OTDM conversion, allowing large numbers of DWDM channels to be converted in a single switching operation. Time-alignment of the incoming WDM channels is necessary, but some tolerance towards misalignment can be expected from the time-lens effect associated with the OFT method [3,5]. The scheme is experimentally demonstrated on a 16×10 Gbit/s DWDM signal with 50 GHz channel spacing. The resulting 160 Gbit/s OTDM signal is demultiplexed with error-free performance, with an average penalty of only 2.1 dB compared to the DWDM channels.

## 2. Principle

Time-domain OFT of an optical waveform is achieved by a combination of parabolic phase-modulation (chirp rate  $K$ ) and second order chromatic dispersion  $D$ . The principle is shown in the upper left inset in Fig. 1, where the input waveform is a DWDM data signal consisting of spectrally distinct channels (here synchronized in the time-domain). The OFT transfers the input spectral profile to the output temporal intensity profile, provided the condition  $D = 1/K$  is fulfilled [3]. In this experiment, the phase-modulation is achieved by a four-wave mixing (FWM) process [5]. Linearly chirped, flat-top pulses of chirp rate  $K/2$  serve as pump signal (field  $E_p(t)$ ), and the DWDM pulses act as probe signal (field  $E_s(t)$ ). The flat-top pump pulses must fully overlap the DWDM pulses. The FWM process will then generate an idler field  $E_i(t) \propto E_p^2(t) E_s^*(t)$ , thus transferring the pump chirp onto the idler signal (with a factor 2). After the FWM, the idler is propagated through a dispersive fibre  $D$  that cancels the FWM-generated chirp. The final result is a simultaneous temporal compression and time-interleaving of the DWDM channels into OTDM tributaries. A DWDM channel spacing  $\Delta\nu$  is mapped into an OTDM tributary spacing  $\Delta\tau$  according to  $\Delta\tau = \Delta\nu / K$ . The temporal shape of the output OTDM waveform is robust to timing misalignment of the incoming DWDM pulses, as long as the latter are overlapped by the pump. Within this tolerance, a timing shift at the OFT input will be translated into a spectral shift at the output [3]. However, this so-called time-lens effect is not experimentally verified in this work, where only the case of synchronous incoming DWDM channels is investigated.

## 3. Experimental set-up

The experimental set-up is shown in Fig. 1, including optical sampling oscilloscope (OSO) traces of the various waveforms (upper right insets). An erbium glass oscillator 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 undergo self-phase modulation (SPM) in 400 m of dispersion-flattened highly non-linear fibre

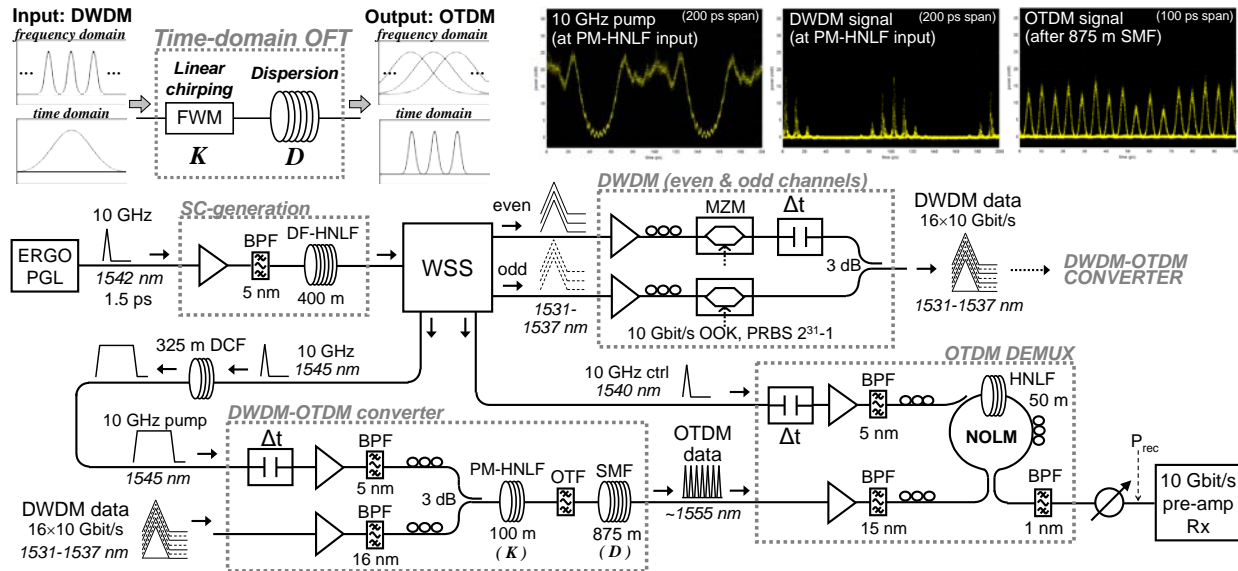


Fig. 1. Experimental set-up. Insets: Time-domain OFT principle (top left); waveforms measured with an OSO (top right).

(DF-HNLF) to generate a supercontinuum spanning the C-band, which is used as input to a programmable filter with 4 output ports (wavelength selective switch - WSS). The odd and even channels are obtained using two programmed filters consisting of eight 100 GHz-spaced Gaussian-profiled channels of spectral FWHM  $\sim 13$ -14 GHz, both centered at 1534 nm with a relative shift of 50 GHz. The odd and even channels are directed to different WSS output ports, then separately encoded by on/off keying (OOK) with 10 Gbit/s  $2^{31}-1$  PRBS patterns in Mach-Zehnder modulators (MZM), and finally combined using a 3-dB coupler, resulting in a single-polarisation 16 $\times$ 10 Gbit/s DWDM signal with 50 GHz channel spacing. The DWDM-OTDM converter is optimised for a periodic 160 Gbit/s OTDM output with a tributary spacing of  $\Delta\tau = 6.25$  ps, which requires  $K = 8$  GHz/ps. The pump pulses are obtained from the WSS using a 10<sup>th</sup> order super-Gaussian filter of FWHM 300 GHz at 1545 nm, and then linearly chirped by dispersive propagation through a 325 m DCF, resulting in a broadened flat-top pulse of FWHM  $\sim 75$  ps and chirp rate  $K/2 = 4$  GHz/ps. The non-linear medium for the FWM between pump and data is a polarization-maintaining, elliptical core highly non-linear fiber (PM-HNLF) of length 100 m, zero-dispersion wavelength 1545 nm, dispersion slope 0.025 ps/(nm<sup>2</sup>·km), and non-linear coefficient  $\gamma \sim 10$  W<sup>-1</sup>km<sup>-1</sup>. The average input power to the PM-HNLF is  $\sim 25$  dBm for the pump, and  $\sim 5$  dBm for the DWDM signal. All DWDM pulses are synchronised and temporally aligned with the pump pulses at the PM-HNLF input using the variable time-delays ( $\Delta t$ ). After the FWM, the idler generated at 1555 nm is extracted using an optical tunable filter OTF (Santec OTF-350), and then passed through 875 m of standard SMF (with dispersion  $D = 1/K$ ) to obtain the 160 Gbit/s OTDM signal. A non-linear optical loop mirror (NOLM) is used for time-demultiplexing the OTDM tributaries, using 10 GHz Gaussian control pulses of 3.4 ps FWHM at 1540 nm obtained from the WSS. The demultiplexed 10 Gbit/s tributaries are extracted by a 1 nm BPF, followed by bit-error rate (BER) measurement in a 10 Gbit/s pre-amplified receiver. For synchronisation of the receiver and PRBS generator, a 10 GHz clock is extracted from the ERGO-PGL which is in free-running mode.

#### 4. Experimental results

Fig. 2 shows the output spectrum of the PM-HNLF for three different numbers of DWDM channels at the input. As seen in Fig. 2 (a) and (b), the idler is spectrally broadened due to the linear chirping by the pump pulse. Furthermore, different DWDM channels are mapped to different center wavelengths, since they all have the same temporal alignment with the pump pulse. Consequently, the bandwidth of the resulting OTDM signal is relatively broad, as seen in Fig. 2 (c). Mapping to the same central idler wavelength requires a time-delay between the DWDM channels

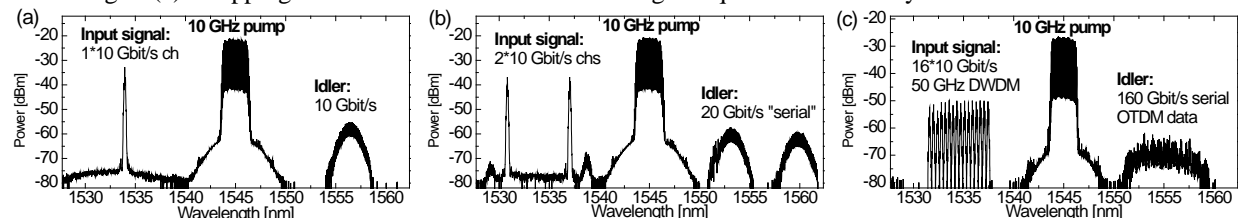


Fig. 2. Output spectra of the PM-HNLF for different DWDM inputs: (a) one channel, (b) two channels, and (c) 16 channels (res. 0.01 nm).

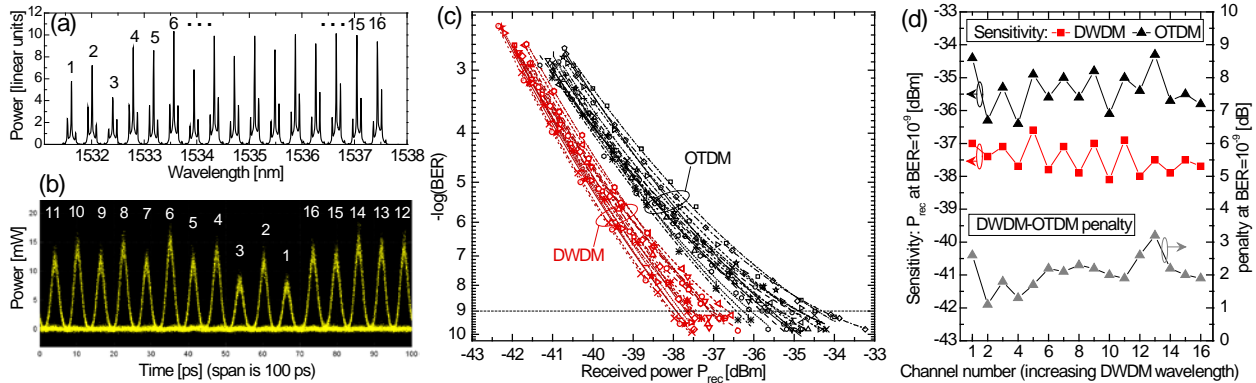


Fig. 3. Experimental results of 16×10 Gbit/s DWDM-OTDM conversion. (a) Spectrum of DWDM signal measured at the PM-HNLF output, (b) Waveform of the output 160 Gbit/s OTDM signal (OSO trace), (c) BER curves of filtered DWDM channels and demultiplexed OTDM tributaries after conversion, (d) corresponding sensitivities and resulting penalty of the DWDM-OTDM conversion.

equal to the target OTDM bit slot, which could be achieved in this set-up by propagating the synchronous DWDM signal through an extra dispersive fibre before the PM-HNLF. However, it would imply that not all DWDM channels can be covered by the pump pulse and thereby converted to OTDM. The case of non-synchronous DWDM pulses will be examined in future work.

The 16×10 Gbit/s DWDM-OTDM conversion is successfully achieved, and the results are shown in Fig. 3. In Fig. 3 (a), a zoom-in on the DWDM spectrum from Fig. 2 (c) is shown. Fig. 3 (b) shows the temporal waveform of the OTDM signal obtained after the 875 m SMF. The 16 tributaries are periodically distributed over 100 ps, since a tributary spacing very close to the target 6.25 ps is achieved. There is also a good correspondence with the DWDM spectrum in Fig. 3 (a), in terms of clearly resolved tributaries and relative powers. The variation in channel power is attributed to non-linear interactions in the PM-HNLF, and is not observable at the input. The DWDM temporal waveform displays strong intensity peaks, since all channels are coherent (see inset in Fig. 1). The resulting non-linear effects in the PM-HNLF were minimised by lowering the average input power, but could not be completely avoided. For the BER measurement, each DWDM channel is extracted at the PM-HNLF output (pump signal off) by filtering with the OTF adjusted to a ~0.3 nm bandwidth, and then sent into the receiver. Fig. 3 (c) shows the BER curves of the 16 DWDM channels, as well as the 16 OTDM tributaries after conversion and demultiplexing. All OTDM tributaries have error-free performance. The OTDM tributary sensitivities and the corresponding DWDM channel sensitivities at BER=10<sup>-9</sup> are plotted in Fig. 3 (d). The relative penalties range from 1.1 dB to 3.2 dB, with an average of 2.1 dB. We expect an improved performance if the non-linear effects in the FWM medium attributed to the DWDM signal intensity peaks can be avoided, such as for a DWDM signal with non-coherent channels.

## 5. Conclusion

We have proposed DWDM-OTDM conversion by time-domain OFT, allowing simultaneous conversion of all channels using a single FWM-based switch. The scheme was successfully demonstrated by converting a synchronized 16×10 Gbit/s DWDM signal with 50 GHz channel spacing to a 160 Gbit/s OTDM signal with 6.25 ps tributary spacing. The BER performance was error-free with an average conversion penalty of only 2.1 dB.

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