Optical Signal Processing up to 1.28 Tbit/s

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Abstract

Techniques for 640 Gbit/s optical signal processing are described, including demultiplexing, clock recovery, transmission, wavelength conversion, add-drop multiplexing, and timing-jitter tolerance. Demultiplexing at 1.28 Tbit/s is presented, with preliminary results for 1.28 Tbit/s transmission.

Introduction

The single channel bit rate has continuously increased in deployed optical transmission systems and networks, reaching 10–40 Gbit/s in commercially available systems. Recently, technologies for optical transmitters and receivers operating near a serial rate of 100 Gbit/s have appeared [1]. For ultra-high-speed serial data at rates above 100 Gbit/s, signal processing becomes increasingly challenging and only optical signal processing seems possible at the present time. However, such serial rates might soon become relevant. With the introduction of internet video transmission, the traffic has exploded and internet exchange office congestion is becoming a real limitation. At OFC 2008, plenary speaker Bob Metcalfe professed that 1 Terabit/s Ethernet (TE) will be needed soon, and that it is essential to conduct fundamental research on new technologies that can carry this burden [2]. For almost twenty years now, optical time division multiplexing (OTDM) has been explored as a possible route to generate high serial bit rates in the optical domain, as demonstrated most notably in [3,4]. Whether 1 TE will be best created serially or in parallel is an open question, but to answer it, it is necessary to conduct research on high-speed serial communications.

Here, we will present some recent demonstrations of several important functionalities for 640 Gbit/s OTDM, namely techniques for demultiplexing, transmission, clock recovery, wavelength conversion, time-division add-drop multiplexing (TADM), and timing-jitter tolerance. Several materials and components are shown to be able to operate at high speeds, including highly non-linear fibres (HNLF), and more compact devices such as periodically poled Lithium Niobate (PPLN), chalcogenide waveguides and semiconductor optical amplifiers (SOAs). Finally, a record serial rate of 1.28 Tbaud is presented, followed by preliminary results for 1.28 Tbaud transmission.

640 Gbit/s generation and demultiplexing

Fig. 1 shows a laboratory OTDM system where various functionalities can be tested. Pulse compression is usually required for 640 Gbit/s generation and most demonstrations, e.g. [3-6], utilise soliton compression which requires subsequent pedestal suppression. We use the compression technique of linear up-chirping by SPM in a dispersion-flattened HNLF, followed by filtering and propagation in SSMF to compensate the chirp. This method allows for the generation of pulses below 200 fs with negligible pedestals, see Fig. 1 (inset).

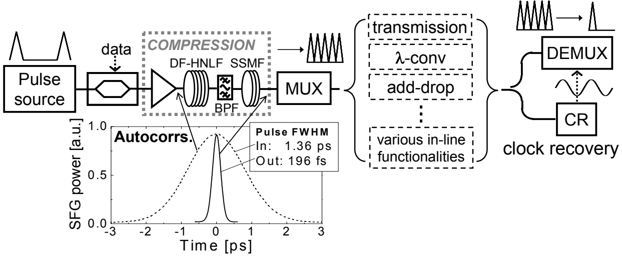

Fig. 1. Schematic of a 640 Gbit/s laboratory communication system. Inset: autocorrelations showing the pulse compression.

Most 640 Gbit/s demultiplexing demonstrations, such as the first one in 1998 [5], involve HNLF which has become a mature commercial product from several companies. The HNLF-based non-linear optical loop mirror (NOLM) [3-6] and Kerr switch [7] are often used for demultiplexing. Note that polarisation-independence can be invoked in a NOLM simply by adjusting the switching power, as shown at 320 Gbit/s [8]. Other types of fibre have also been used, such as photonic crystal fibre [9] or bismuth-oxide fibre [10], though only for 160 Gbit/s demonstrations. Recently, compact components have been used for 640 Gbit/s demux. Filtering-assisted (f-a) XPM in an SOA was demonstrated at 640 Gbit/s in [11]. Chalcogenide waveguides have been shown to operate at 160 Gbit/s [12] and also at 640 Gbit/s [13].

640 Gbit/s transmission and clock recovery

Ultra-high-speed clock recovery (CR) has proven to be exceptionally challenging, and only very recently was 640 Gbit/s reached allowing for full transmission demonstrations [14]. In [14], f-a XPM in an SOA was used for phase comparison in a PLL-type CR, as in [15] at 320 Gbit/s. This was followed by a second 640 Gbit/s demonstration [16]. In [16-17], a PPLN device was used, relying on the $\chi^{(2)}$–mediated process of sum-frequency generation, which is truly ultra-fast and not depending on any carrier recovery. Adding a base rate phase mark on one channel allows for simultaneous clock recovery and channel identification, as shown at 320 Gbit/s [18].

640 Gbit/s wavelength conversion

Four wave mixing (FWM) in HNLF was used to convert at 640 Gbit/s between the C- and L-band in [19]. In [20], Raman-enhanced XPM was used to convert a 640 Gbit/s data signal to a lower wavelength within the C-band, see Fig. 2 (a). Recently, FWM was shown to enable 640 Gbit/s wavelength conversion in the C-band [21], see Fig. 2 (b). So far, these demonstrations are the only reported 640 Gbit/s wavelength conversions, and all are HNLF-based. A SOA with f-a XPM has been used for 320 Gbit/s conversion [22], but carrier recovery issues might prevent 640 Gbit/s operation at the present.

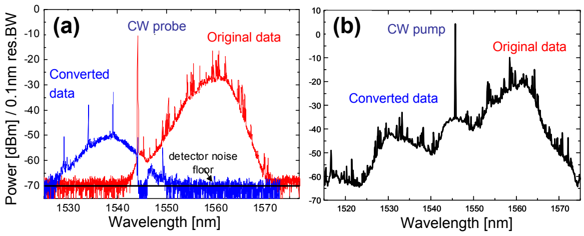

Fig. 2. 640 Gbit/s wavelength conversion in C-band: (a) by Raman-enhanced XPM in HNLF, (b) by FWM in PM-HNLF

640 Gbit/s time-division add-drop multiplexing

TADM with simultaneous add- and drop-operation has been demonstrated in a NOLM at 640 Gbit/s [23]. In [24], 640 Gbit/s TADM is performed in a non-linear polarisation-rotating fibre loop (see Fig. 3). Previous TADM demonstrations showed error-free operation up to 160 Gbit/s, e.g. using a HNLF-based Kerr switch [25], a NOLM [26], or a 1 m bismuth oxide fibre [10].

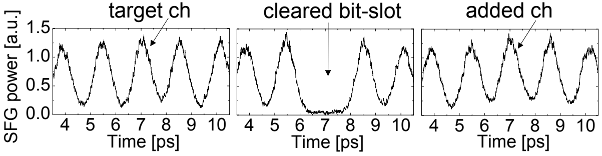

Fig. 3. 640 Gbit/s TADM cross-correlations, from [24].

Pulse shaping for timing-tolerance/stability

Flat-top pulses can increase the timing tolerance of high-speed switches and enable retiming. Various approaches have been followed, such as the optical Fourier transform technique [27], super-structured fibre Bragg gratings [28] or optical differentiation based on detuned long-period gratings for 640 Gbit/s [29].

1.28 Tbit/s demultiplexing

A 1.28 Tbit/s OOK single-polarisation OTDM data signal has been generated using 350 fs FWHM pulses with ~0.78 ps spacing, followed by error-free demultiplexing in a NOLM [30], see Fig. 4.

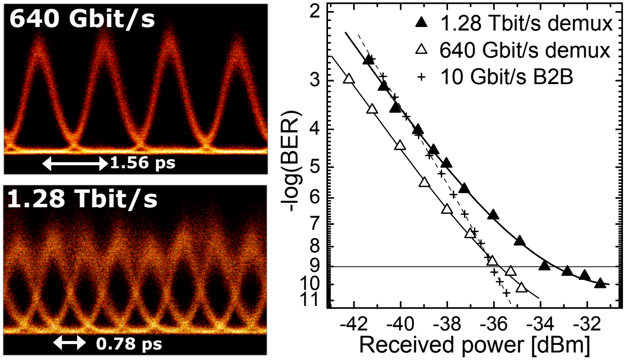

Fig. 4. 1.28 Tbit/s demultiplexing: Eye-diagrams, BER curves.

Preliminary experiments show promising results for transmission of such narrow pulses. Fig. 5 shows the residual dispersion of a 80 km SSMF span compensated by 11 km DCF (kindly provided by OFS Fitel Denmark). A 1 km DSF used for additional slope compensation yields a residual disp. within ±50 fs/nm over nearly 20 nm. The data pulses for 1.28 Tbit/s (at ~1556 nm) can then be transmitted with negligible broadening, see Fig. 5. Note: the PMD is mitigated by launching the data signal into a principal state of polarisation.

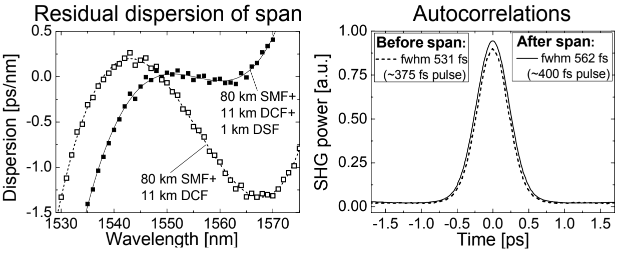

Fig. 5. 1.28 Tbit/s transmission, preliminary results.

Conclusion

This paper has provided highlights of high-speed signal processing demonstrations up to 640 Gbit/s, and has shown the first results of 1.28 Tbit/s signal processing.

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