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650 Gbit/s OTDM Transmission over 80 km SSMF Incorporating Clock Recovery, Channel Identification and Demultiplexing in a Polarisation Insensitive Receiver

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Abstract: Error free low penalty 650 Gbit/s OTDM transmission is demonstrated using a polarisation independent receiver based on FWM for demultiplexing. Spectral shaping in the transmitter and filtering in the receiver are used for clock extraction.

OCIS codes: (060.2330) Fiber optics communications; (060.4510) Optical communications

1. Introduction

In recent years there has been an increasing interest in identifying schemes for optical data transmission which can supplement or substitute the schemes currently used in optical communication systems. This is done in the pursuit of higher data capacity and lower power consumption. Optical Time Division Multiplexing (OTDM) is one of the technologies which might potentially offer both of these benefits for many applications [1]. Some of the key challenges for OTDM transmission are however to incorporate a stable clock recovery scheme, and allow for distinction between the individual OTDM tributaries (channel identification). Another issue is the polarisation dependence frequently associated with the optical switches used for processing OTDM signals for e.g. demultiplexing. For long-term stable operation of an OTDM transmission system a polarisation insensitive receiver capable of performing these tasks is required.

This paper presents the first ever 650 Gbit/s OTDM transmission system using a polarisation insensitive receiver that offers OTDM demultiplexing and clock recovery with simultaneous channel identification. This constitutes a major step in maturing OTDM transmission technology by resolving several of the biggest obstacles faced when using this technology. Demultiplexing is performed by four wave mixing (FWM) in a polarisation diversity loop configuration. Clock recovery and channel identification are achieved by spectral shaping of the data channels in the transmitter and optical filtering in the receiver after 80 km transmission over standard single mode fibre (SSMF).

2. Principle and experimental procedure

The experimental setup used in this demonstration is shown in Fig. 1. The 650 Gbit/s transmitter is based on an erbium glass oscillator pulse source (ERGO) generating 2 ps pulses which are OOK data modulated at 2^7-1 PRBS. A two stage non-linear compressor reduces the pulse width to 530 fs while benefitting from spectral broadening and offset filtering to improve signal contrast [2]. The two HNLFs in the pulse compressor both have γ~10.5 (W km)$^{-1}$ and a slightly negative dispersion over the C-band with a slope of ~0.006 ps nm^{-2} km^{-1}. The 10 Gbit/s data signal is split in two – one arm forming a 640 Gbit/s signal (marked 'std' in Fig. 2a) using passive multiplexing with a small offset in the applied delays creating a vacant time slot for an additional OTDM channel in the multiplexed signal. The 640 Gbit/s signal is filtered with a fibre bragg grating (FBG) as notch filter at the edge of the data spectrum as shown in Fig. 2a. The remaining 10 Gbit/s signal (marked 'clk') is filtered at a slight offset compared to the 640 Gbit/s data (see Fig. 2a) and multiplexed into the empty time slot in the 640 Gbit/s signal. Power and polarisation

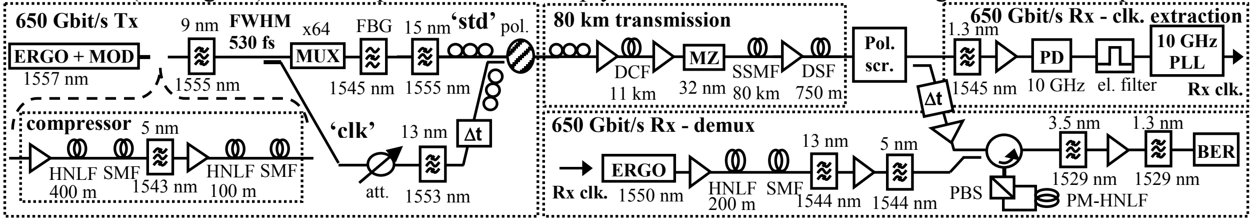

Fig. 1: Setup for 650 Gbit/s transmitter, transmission line and receiver for clock recovery and demultiplexing.

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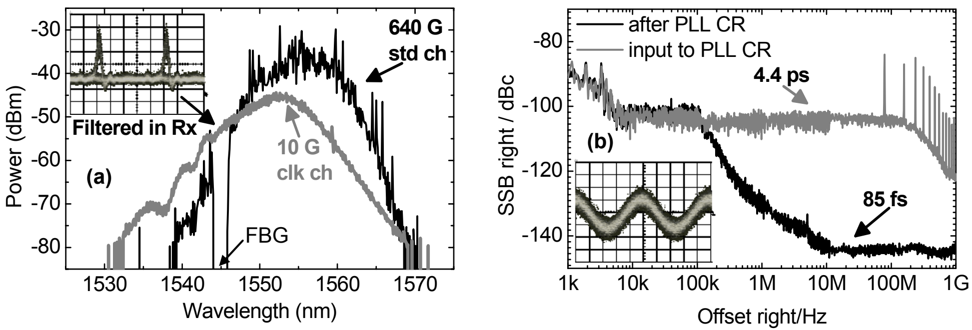

Fig. 2: (a) Optical spectra of the ‘clk’ and ‘std’ channels illustrating the CR scheme, (b) Electrical single sideband phase noise measurements of the recovered clock with and without PLL filter – inset oscilloscope trace shows extracted clock without PLL filtering.

are adjusted to generate an equalised 650 Gbit/s data signal in a single polarisation. In the receiver the difference between the spectra of the OTDM data channels can be extracted by adjusting an optical filter to the same wavelength as the FBG notch filter in the transmitter. In this way, part of the ‘clk’ 10 Gbit/s OTDM tributary is extracted as shown in the eye diagram inset in Fig. 2a. Further optical and electrical passive filtering of this signal results in a 10 GHz clock signal, which has a timing jitter of 4.4 ps as shown in Fig. 2b. A 10 GHz PLL with a 200 kHz bandwidth is locked to the noisy clock reducing the timing jitter to 85 fs. The recovered clock is locked in phase to a single OTDM tributary allowing for simple channel identification based on the phase between the recovered clock and the respective data channels. The 650 Gbit/s signal is transmitted over 80 km SSMF using 11 km dispersion compensating fibre (DCF) and 750 m dispersion shifted fibre (DSF) to compensate the dispersion and dispersion slope of the transmission fibre. In this way a dispersion profile is achieved where the signal suffers virtually no residual dispersion across the full data spectrum, see Fig. 3c. A Mach-Zehnder filter (32 nm FSR, shown in Fig. 3a) compensates for spectral shaping in the EDFAs which would otherwise cause detrimental pulse broadening. Fig. 3b shows the evolution in pulse width of both the ‘std’ and ‘clk’ data pulses as a function of added dispersion. The pulses are seen to evolve in very similar ways despite the differences in the optical spectra of the ‘std’ and ‘clk’ channels which are clear from Fig. 2a. All channels can be compressed to <550 fs making the transmission virtually transparent in terms of pulse width. The ‘clk’ pulses are slightly narrower than the ‘std’ pulses which is expected due to the slightly broader and unperturbed spectrum of the ‘clk’ pulses. The launch polarisation into the transmission fibre is aligned to a principal axis of the fibre span to reduce the impact of PMD.

The OTDM demultiplexer consists of a polarisation maintaining polarisation diversity four-wave mixing loop configuration. This makes the full receiver stable and insensitive to polarisation, which is verified by operating the system with a polarisation scrambler at the receiver input, yielding only 0.4 dB penalty. The demultiplexer comprises 100 m of polarisation maintaining HNLF (PM-HNLF, $\gamma \sim 10$ (W km)$^{-1}$, λ_0=1545 nm) and is described in detail and characterised in [3]. Control pulses for the demultiplexer are generated by a second ERGO pulse source and non-linear pulse compression in an HNLF identical to the ones used in the transmitter. The pulse source is synchronised by the recovered clock in the receiver. The spectra of the signals in the demultiplexer are shown in Fig. 4b where the FWM product and the extracted demultiplexed data are indicated. There is some overlap of the spectra of the data signal and the control pulses used for demultiplexing which also means that part of the FWM

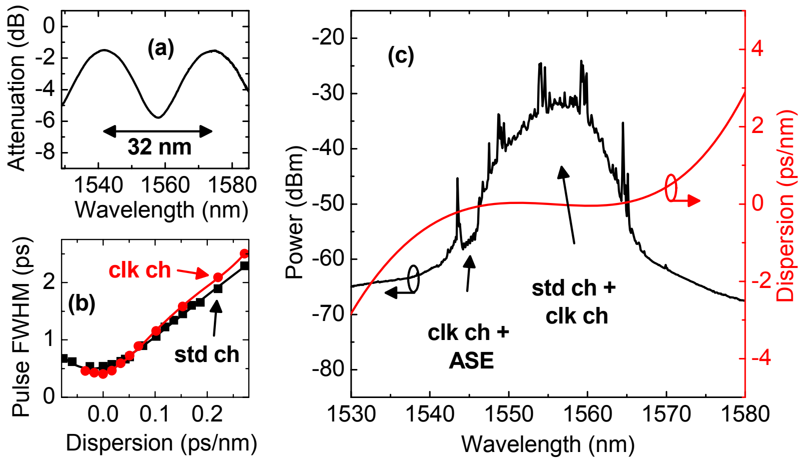

Fig. 3: (a) Gain flattening filter, (b) Pulse width evolution, (c) Optical spectrum of transmitted 650 Gbit/s signal and dispersion profile.

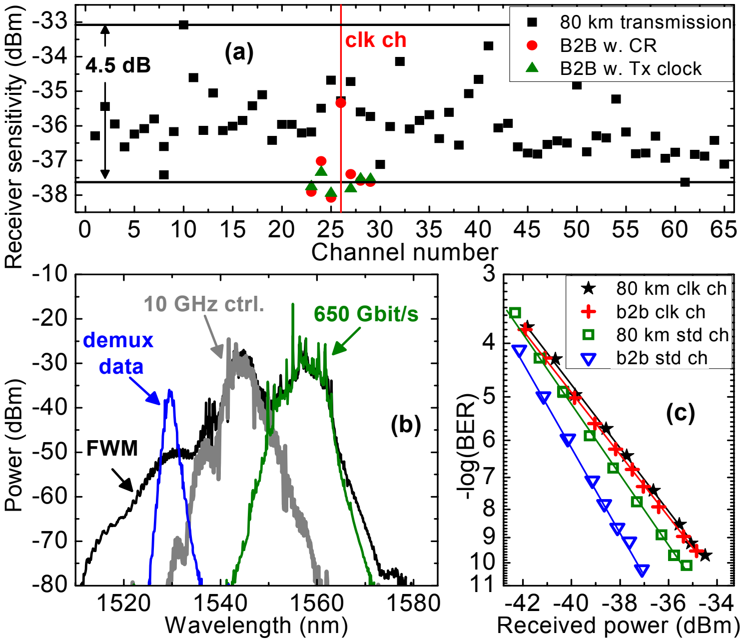

Fig. 4: (a) Receiver sensitivities for all 65 OTDM channels after 80 km transmission and polarization insensitive demultiplexing, (b) spectral allocation of signals in FWM demux, (c) Full BER curves for the 'clk' channel and one average 'std' channel.

product overlaps with the control pulses. A narrow optical filter (~1 nm FWM) is tuned to the side of the FWM product away from the control pulses in order to extract a clean output from the demultiplexer. The signal quality is characterised by bit error rate measurements on the demultiplexed data.

3. Results

Fig. 4a shows the receiver sensitivities at a BER of 10^{-9} for all 65 channels after 80 km transmission. All channels achieve error free operation with a BER better than 10^{-9} and the maximum variation in receiver sensitivity is 4.5 dB. This confirms successful generation, transmission and detection of the full 650 Gbit/s data signal. After transmission the 'clk' channel is only 0.6 dB above the average receiver sensitivity of all the transmitted channels which is -35.9 dBm. In back-to-back (b2b) configuration the 'clk' channel has virtually the same performance as after transmission while the other channels that were tested are improved ~2 dB. This would indicate slightly different noise properties of the 'clk' channel causing the 80 km transmission to not affect its receiver sensitivity in this characterisation. In the b2b configuration there is no additional penalty from using the recovered clock from filtering the optical signal compared to using the b2b clock from the transmitter – i.e. the clock from the RF synthesiser used to synchronise the transmitter. In Fig. 4c the BER performance of the 'clk' channel is shown together with an average performing channel from the remaining 64 'std' channels. Both are shown in b2b configuration and after 80 km transmission. Error free operation is achieved in all cases with no indication of an error floor down to a BER of 10^{-10}. For the 'clk' channel it is confirmed that the BER curves are virtually identical before and after transmission while the 'std' channel suffers a 2 dB penalty from transmission.

4. Conclusion and Acknowledgments

This paper has demonstrated for the first time error free transmission of a 650 Gbit/s OTDM data signal over 80 km of standard SMF using a polarisation insensitive receiver that offers clock recovery, channel identification and demultiplexing of the signal. We believe that this is a significant step in enabling practical application of OTDM transmission.

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