Increase in data capacity utilising dimensions of wavelength, space, time, polarisation and multilevel modulation using a single laser

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ABSTRACT
Increasing the capacity of optical networks while have the objective of lowering the total consumed energy per bit is challenging. By exploiting several dimensions, i.e. wavelength, space, time, polarisation and multilevel modulation simultaneously, a single laser can offer formidable capacity performance with potentially reduced energy consumption per bit. Up to 43 Tbit/s has been demonstrated.
Keywords: OTDM, WDM, SDM, multi-core fibre, Nyquist, time-lens

1. INTRODUCTION

Data traffic is continuously increasing and predictions indicate that the capacity of individual optical communication systems will soon be too small to carry the network traffic if only frequency/wavelength, time, polarisation and multi-level modulation formats are used [1]. However, by employing a hitherto unused dimension, i.e. space, the capacity may be scaled sufficiently to keep pace [1]. Capacity experiments without Space Division Multiplexing (SDM) demonstrated around 100 Tbit/s [2][3]. With the introduction of multi-core fibres (MCF) the capacity demonstrations were increased significantly showing 305 Tbit/s [4], 1.01 Pbit/s [5] and 1.05 Pbit/s [6] using 19, 12 and 14 cores respectively. In parallel with the quest for more capacity, an additional challenge needs to be addressed, i.e. carbon emission (CO_2) from the information communications and technology (ICT) industry, which potentially may lead to global warming. ICT CO_2 emission contributes with 2 % of the total emission comparable with avionics and the emission is predicted to double in 2020 [7]. A discussion of energy efficient optical communications can be found in [8]. Thus, both an increase in capacity while lowering the emitted carbon emission per bit, are the challenges. It may be speculated if reducing the number of lasers will reduce the total cost and energy consumption compared to utilise a large number of individual lasers [9]. In this paper 43 Tbit/s using a single laser as seed using wavelength, time, polarisation, quadrature and SDM is presented [10].

2. CAPACITY INCREASING TECHNIQUES

Several physical dimensions can be utilised to increase the capacity of optical communication systems, i.e. frequency/wavelength, time, polarisation, quadrature and space. Wavelength and time have been used routinely for years, while polarisation and quadrature have been introduced within the last few years due to cheap fast available Digital Signal Processing (DSP). Finally, space is an untapped commercially deployed resource which may add the extra required capacity needed to keep up with the insatiable capacity need, hence the present focus around the world. The 5 dimensions are briefly summarised below.

Wavelength Division Multiplexing (WDM) has been used for many years and is standardised in the International Telecommunication Union (ITU) standardization body both for coarse and for dense WDM [11][12] and e.g. 370 lasers situated in the C and L-band with 25 GHz spacing has been reported [2] thus obtaining 101.7 Tbit/s over 3x55 km fibre. Use of many different carriers does not necessarily require multiple separate laser sources. In [13] a single laser source is used to generate 325 sub-carriers.

Using time division multiplexing (TDM) to allocate a number of independent data signals to unique timeslots has been a well-known technique in e.g. SONET/SDH for many years [14]. As the bit rate was increased, the influences of broad spectrum interacting with chromatic dispersion became an increasingly limiting factor combined with the relative low spectral efficiency [15] and thus a direct transition from 10 Gbit/s to 100 Gbit/s serial on-off keying (OOK) bit rates will probably not be realised in commercially deployed systems. Besides the expected increased sensitivity to fibre impairments, an additional limitation due to the operation speed of electronics also prevent a smooth transition to even higher serial bit rates. In parallel with the Electrical TDM (ETDM) systems, research groups in the world investigated Optical TDM (OTDM) utilising ultra-narrow temporal pulses emitted from a single laser with repetition rates applicable to electronic bandwidth electronics. By designing a transmitter with parallel branches including modulators and carefully tailored time-delays, the low data-speed optical signals can be multiplexed in time to an ultra-high aggregated bit rate at the output of the transmitter. In 1998 a symbol rate of 640 Gbit/s was demonstrated [16], a record standing more than 10 years

until 2009 where the symbol rate was doubled to 1.28 Tbit/s [17]. However, by employing quadrature multi-level modulation formats, the bit rate using a single laser was increased further by utilising QAM/QPSK and Polarisation Division Multiplexing (PDM) to 5.1 Tbit/s [18] and 9.5 Tbit/s [19]. As the temporal pulse widths are reduced, the corresponding spectrum is increased simultaneously rendering an efficient use of the available spectrum. In [20] it is suggested and demonstrated how Nyquist pulses in the time domain reduces the spectrum compared to the spectrum from Gaussian or hyperbolic pulses, thus reducing the influence of chromatic dispersion and allowing a more efficient utilisation of the spectrum. The Nyquist pulses are compatible with the OTDM scheme, i.e. N-OTDM [20]. When the bit rate is beyond the bandwidth of electronics, Optical Signal Processing (OPS) is required, e.g. in terms of time-lens schemes briefly addressed in paragraph 3.

With the introduction of Digital Signal Processing (DSP), polarisation rotations and Polarisation Mode Dispersion (PMD) can be tracked and compensated [21]. Thus two orthogonal polarisations can be utilised to carry individual data thus doubling the capacity, i.e. PDM or dual-polarisation [22]. Just as DSP enabled the use of polarisation, DSP also enabled utilising quadrature multi-level modulation formats which spurred a renewed focus as the spectral efficiency is increased compared to OOK modulation [15]. Despite no standardization is available [23] at the line side, 100 Gbit/s Ethernet is often based on QPSK plus additional PDM [24]. In order to increase the total capacity, the 2 bits per symbol offered by QPSK should in the future be increased. Indeed, impressive high-order level modulation formats have been demonstrated albeit at modest symbol rates; QAM 64 [3], QAM 128 [25], QAM 256 [26], QAM 512 [27], QAM 1024 [28][29].

A hitherto commercially unused dimension is being considered as an additional resource for increasing the data on single fibre [30]. By exploiting space in terms of either multiple cores encapsulated in one single fibre, i.e. MCF, or utilising individual modes as data channels [30] immense capacity increment has been reported as stated in the introduction. The potential capacity of MCF based on number of cores in a fibre and the associated crosstalk is addressed theoretically in [31][32]. Recently a MCF with 36 cores has been reported emphasising the potential for increasing the capacity significantly [33]. For recent comprehensive surveys of MMF please refer to [30][34][35]. Coupling in and out of MCFs require special attention to the fan-in fan-out (FI/FO) devices [34]. In [36] an on-chip 7-core FI/FO device on silicon-on-insulator platform is reported and utilised in [37] to transmit 1.2 Tbaud/s DPSK in each of the 6 cores and a clock signal in the 7th core. In parallel with multiple cores in the fibre, using photonic lanterns different modes can be specifically exited and carry independent data [30]. In [38] 15 spatial modes are supported and transmitted over 23.8 km of fibre.

3. EXPERIMENTAL SET-UP AND RESULTS

In Figure 1 the experimental set-up for generating and evaluating 43 Tbit/s using a single laser as seed is depicted [10]. An erbium glass oscillating mode-locked laser (ERGO-MLL) with a repetition frequency of 10 GHz is used. The interplay between high peak power and non-linearity in a dispersion flattened highly nonlinear fibre (DF-HNLF) generates a broad self-phase modulation (SPM) induced spectrum, which is used to carve out a clock signal and a signal part. The signal is QPSK modulated before being multiplexed to 320 Gbit/s using passive delay lines and finally polarisation multiplexed. In total, a 1.28 Tbit/s, i.e. 1.2 Tbit/s after subtracting 7 % FEC overhead, is generated at the output of the polarisation multiplexer. A Wavelength Selective Switch (WSS) is used to emulate a 6 wavelength WDM signal, each outlet of the WSS additionally induce a rectangular filtering at 320 GHz, thus generating a 320 Gbaud N-OTDM signal at each WDM wavelength. Using delay lines, splitters and amplifiers, 6 de-correlated SDM channels are generated and launched into the 6 outer cores of the MCF, while the clock signal is launched into the centre core, using a free-space (FI/FO) device.
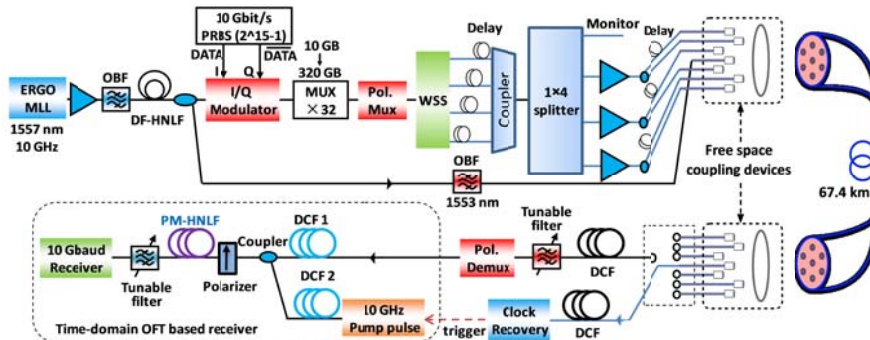

Figure 1. Experimental set-up used for generating and detecting 43 Tbit/s[10].

At the receiver, the clock signal after dispersion compensation is launched into a clock recovery circuit, which is used to generate the required trigger signal needed for the local laser source constituting the pump in a time-lens

scheme [39]. The data signal is dispersion compensated and polarisation demultiplexed before launched into the time-lens and converted from 320 Gbaud N-OTDM to an Optical Frequency Division Multiplexed (OFDM) signal with a sufficient large channel spacing to allow filtering of each individual channel using a 40 GHz tuneable optical bandpass filter. In Figure 2 the BER characterisation of all the total 2304 tributaries channels (SDM +WDM+OTDM in both polarisations) is shown. The BER is below BER = $3.8 \cdot 10^{-3}$ corresponding to the FEC threshold. As the I&Q components showed identical performance, it was concluded that successful transmission of all channels were obtained.
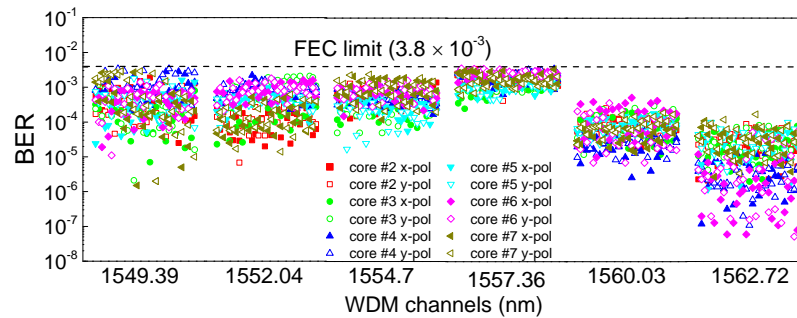

Figure 2. BER of all 2304 tributaries [10].

4. CONCLUSIONS

In this paper a single laser used as the seed to generate 43 Tbit/s deploying WDM, OTDM, PDM, SDM and QPSK is presented, motivated and discussed. The experimental characterisation shows error-free operation below the FEC threshold for all channels.

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