Demonstration of 5.1 Tbit/s data capacity on a single-wavelength channel

Mulvad, Hans Christian Hansen; Galili, Michael; Oxenløwe, Leif Katsuo; Hu, Hao; Clausen, Anders; Jensen, Jesper Bevensee; Peucheret, Christophe; Jeppesen, Palle

Published in:
Optics Express

Link to article, DOI:
10.1364/OE.18.001438

Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Mulvad, H. C. H., Galili, M., Oxenløwe, L. K., Hu, H., Clausen, A., Jensen, J. B., ... Jeppesen, P. (2010). Demonstration of 5.1 Tbit/s data capacity on a single-wavelength channel. Optics Express, 18(2), 1438-1443. DOI: 10.1364/OE.18.001438

Demonstration of 5.1 Tbit/s data capacity on a single-wavelength channel

Hans Christian Hansen Mulvad,* Michael Galili, Leif K. Oxenløwe, Hao Hu, Anders T. Clausen, Jesper B. Jensen, Christophe Peucheret, and Palle Jeppesen

DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, Ørsteds Plads 343,
DK-2800 Kgs. Lyngby, Denmark
**hchm@fotonik.dtu.dk*

Abstract: We have generated a single-wavelength data signal with a data capacity of 5.1 Tbit/s. The enabling techniques to generate the data signal are optical time-division multiplexing up to a symbol rate of 1.28 Tbaud, differential quadrature phase shift keying as data format, and polarisation-multiplexing. For the first time, error-free performance with a bit error rate less than 10^{-9} is demonstrated for the 5.1 Tbit/s data signal. This is achieved in a back-to-back configuration using a direct detection receiver based on polarisation- and time-demultiplexing, delay-demodulation and balanced photo-detection.

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

References and links

1. H. C. Hansen Mulvad, L. K. Oxenløwe, M. Galili, A. T. Clausen, L. Grüner-Nielsen, and P. Jeppesen, "1.28 Tbit/s single-polarisation serial OOK optical data generation and demultiplexing," Electron. Lett. **45**(5), 280–281 (2009).
2. M. Nakazawa, T. Yamamoto, and K. R. Tamura, "1.28Tb/s-70 km OTDM transmission using third- and fourth-order simultaneous dispersion compensation with a phase modulator," Electron. Lett. **36**(24), 2027–2029 (2000).
3. H. G. Weber, S. Ferber, M. Kroh, C. Schmidt-Langhorst, R. Ludwig, V. Marembert, C. Boerner, F. Futami, S. Watanabe, and C. Schubert, "Single channel 1.28 Tbit/s and 2.56 Tbit/s DQPSK transmission," Electron. Lett. **42**(3), 178–179 (2006).
4. C. Schmidt-Langhorst, R. Ludwig, D. Groß, L. Molle, M. Seimetz, R. Freund, and C. Schubert, "Generation and coherent time-division demultiplexing of up to 5.1 Tb/s single-channel 8-PSK and 16-QAM signals," in *Optical Fiber Communication Conference*, OSA Technical Digest (CD) (Optical Society of America, 2009), paper PDPC6.
5. E. Tangdiongga, H. C. Hansen Mulvad, H. de Waardt, G. D. Khoe, A. M. J. Koonen, and H. J. S. Dorren, "SOA-based clock recovery and demultiplexing in a lab trial of 640-Gb/s OTDM transmission over 50-km fibre link", *European Conference on Optical Communication, ECOC' 07*, Paper PD 1.2 (2007).
6. L. K. Oxenløwe, F. Gomez-Agis, C. Ware, S. Kurimura, H. C. Hansen Mulvad, M. Galili, H. Nakajima, J. Ichikawa, D. Erasme, A. T. Clausen, and P. Jeppesen, "640-Gbit/s data transmission and clock recovery using an ultrafast periodically poled lithium niobate device," J. Lightwave Technol. **27**(3), 205–213 (2009).
7. P. Mamyshev, "All-optical data regeneration based on self-phase modulation effect", in *Proceedings of 24th European Conference on Optical Communication, 1998*, vol. **1**, pp. 475–476 (1998).
8. A. T. Clausen, H. N. Poulsen, L. K. Oxenløwe, A. I. Siahlo, J. Seoane, and P. Jeppesen, "Pulse source requirements for OTDM systems", in *Proceedings of The 16th Annual Meeting of the IEEE Lasers and Electro-Optics Society, 2003. LEOS 2003*, vol. **1**, pp. 382–383, paper TuY2 (2003).

1. Introduction

The needs for more bandwidth and reduction of the accompanying power consumption have emerged as two clear trends in optical communication in recent years, and the use of fewer lasers and higher single-channel bit rates is being explored as a possible solution. In order to explore the limits of the bit rate that can be achieved on a single-wavelength channel, the technique of optical time division multiplexing (OTDM) is used. This technique is based on bit-interleaving a large number of optical data channels at identical wavelengths, with a low symbol rate (base rate) and a very short duty cycle. Recently, OTDM has been used to generate a single-channel data symbol rate exceeding 1 Terabaud [1]. In terms of generating higher data rates using OTDM, continuous progress has been made over the past decade. In

#119544 - $15.00 USD Received 4 Nov 2009; revised 3 Jan 2010; accepted 6 Jan 2010; published 15 Jan 2010

2000, a single-wavelength data rate of 1.28 Tbit/s was demonstrated with error-free performance, that is, with a bit-error rate (BER) less than 10^{-9} [2]. Here, the data signal was generated by multiplexing a 10 Gbaud channel encoded with the binary on-off keying (OOK) format up to 640 Gbaud, followed by polarisation-multiplexing (pol-mux). To further increase the data rate, a modulation format enabling several bits per symbol can be used in combination with OTDM and pol-mux. The differential quadrature phase shift keying (DQPSK) format yields 2 bits/symbol, and has been used together with 640 Gbaud OTDM and pol-mux to demonstrate an error-free data rate of 2.56 Tbit/s [3]. More recently, the data formats of 8PSK (3 bits/symbol) and 16-QAM (4 bits/symbol) have been combined with OTDM up to 640 Gbaud and pol-mux, followed by coherent detection and offline digital signal processing to assess the BER performance of the generated data signal [4]. A net error-free data rate up to 3.56 Tbit/s was obtained with 8PSK, under the assumption that forward error-correction (UFEC) is applied. A data rate of 5.1 Tbit/s was attempted by using 16-QAM, but a BER below the UFEC limit of 2×10^{-3} was not obtained in this case.

In this paper, we report the generation and first successful detection of a 5.1 Tbit/s single-wavelength data rate by demonstrating error-free real-time performance with a BER lower than 10^{-9}. The data signal is based on a 1.28 Tbaud OTDM symbol rate, the highest symbol rate reported so far [1], followed by pol-mux. The DQPSK format is used for data-modulation. The BER performance of the 5.1 Tbit/s data signal is measured in a direct detection receiver based on polarisation- and time-demultiplexing, followed by delay-demodulation and balanced photo-detection, resulting in a BER better than 10^{-9}.

2. Experimental set-up

A schematic of the experimental set-up is shown in Fig. 1, where the 5.1 Tbit/s transmitter is shown in (a) and (b), and the 5.1 Tbit/s receiver is shown in (c). The experimental set-up is built in a back-to-back configuration where the electrical clock signal to the receiver is obtained directly from the transmitter. Furthermore, the control pulses for demultiplexing in the receiver are obtained from the transmitter pulse source. For a transmission experiment, a separate control pulse source would be required in the receiver, as well as a clock recovery mechanism to extract the base rate clock from the OTDM data signal, see e.g [5,6].

The 5.1 Tbit/s transmitter is based on a 10 GHz Erbium-glass oscillating pulse generating laser (ERGO-PGL), emitting pulses at 1542 nm with a full-width at half-maximum (FWHM) pulse width of ~1.5 ps. The ERGO-PGL pulses are sent into a Mamyshev regenerator [7], based on self-phase modulation (SPM) in a dispersion-flattened highly non-linear fibre (DF-HNLF1) followed by off-carrier filtering with tuneable band-pass filters (BPFs). The purpose of the Mamyshev regenerator is to generate signals at separate wavelengths for the data signal and the control pulses needed for demultiplexing in the receiver. Before entering DF-HNLF1, the 10 GHz ERGO-PGL pulses at 1542 nm are amplified to an average power of 24.9 dBm and then filtered on-carrier with a 5 nm BPF in order to suppress the amplified spontaneous emission (ASE) noise from the EDFA at the converted data and control wavelengths. The 10 GHz control pulses (ctrl) are obtained by filtering the SPM-broadened spectrum with a 9 nm BPF tuned to 1535 nm. The 10 GHz pulses for the data signal are obtained by filtering at 1550 nm with a 5 nm BPF. The parameters of DF-HNLF1 are: length 400 m, dispersion $D = -0.45$ ps/(nm·km) and slope $S = 0.006$ ps/(nm^2·km) at 1550 nm, and non-linear coefficient $\gamma = 10.5$ $W^{-1}km^{-1}$. Note that the Mamyshev regeneration for the 10 GHz data signal effectively suppresses small trailing pulses present in the ERGO-PGL output. Such trailing pulses would be detrimental to the quality of the 5.1 Tbit/s data signal since they can cause interferometric cross-talk to other data pulses with which they overlap in time. As the next step, the pulses obtained at 1550 nm are compressed from a FWHM of ~1 ps down to ~200 fs by SPM-based spectral broadening in DF-HNLF2, followed by spectral shaping with a broad 14 nm BPF centered at 1550 nm. The average input power of the uncompressed 10 GHz pulses into DF-HNLF2 is 25 dBm. The parameters of DF-HNLF2 are: length 100 m, $D = -1.11$ ps/(nm·km) and $S = 0.005$ ps/(nm^2·km) at 1550 nm, and $\gamma = 10.5$ $W^{-1}km^{-1}$. As shown in Fig. 1 (b), the 10

Received 4 Nov 2009; revised 3 Jan 2010; accepted 6 Jan 2010; published 15 Jan 2010

GHz compressed pulses are then encoded with 10 Gbaud DQPSK data by using a push-pull LiNbO$_3$ Mach-Zehnder modulator (MZM, realising π phase-shifts) and a LiNbO$_3$ phase-modulator (realising $\pi/2$ phase shifts), both driven from de-correlated 10 Gbit/s 2^7-1 PRBS data patterns. The data pulses are then OTDM-multiplexed from 10 Gbaud up to 1.28 Tbaud (in a single-polarisation) using passive fibre-based delay-line multiplexer stages (MUX). Finally, the 1.28 Tbaud DQPSK pulses are polarisation-multiplexed (POL-MUX) by using a polarisation-maintaining 50:50 coupler and a polarisation beam splitter (PBS), resulting in a 5.1 Tbit/s single-wavelength data signal centered at ~1555 nm.

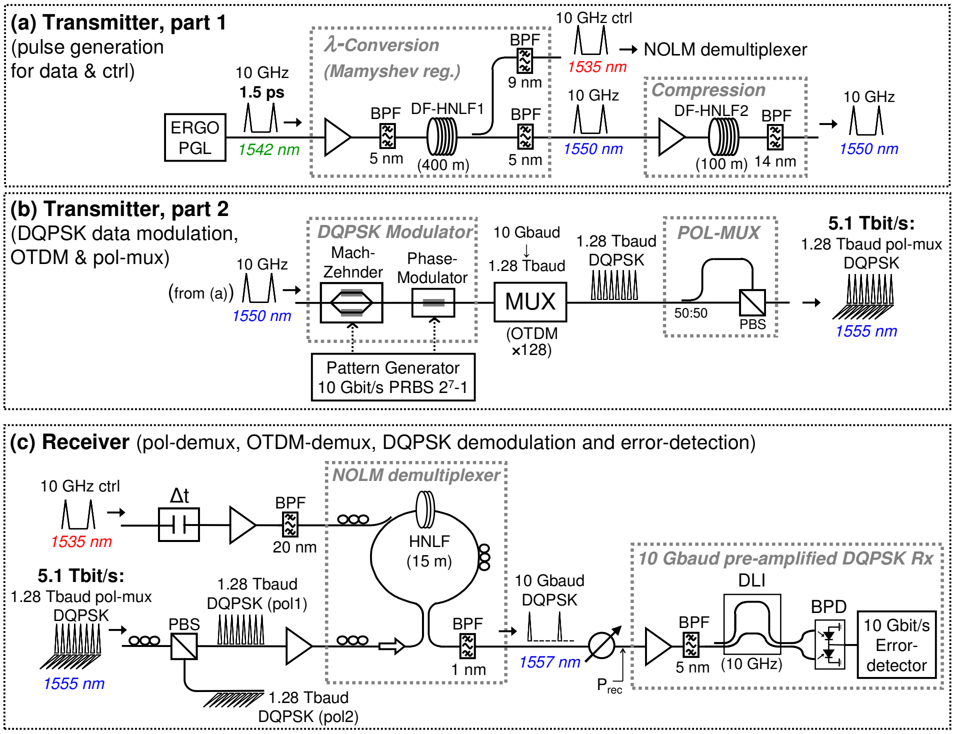

Fig. 1. Experimental set-up. (a), (b) 5.1 Tbit/s transmitter, (c) 5.1 Tbit/s receiver.

The 5.1 Tbit/s data signal is then detected in the receiver set-up shown in Fig. 1 (c). Firstly, the PBS performs polarisation-demultiplexing of the incoming 5.1 Tbit/s data by separating each constituent 1.28 Tbaud polarisation-component (pol1 and pol2). In this experiment, the input polarisation to the PBS is manually adjusted. In a real system, an automatic polarisation tracking and control mechanism would be required. A non-linear optical loop mirror (NOLM) is then used for OTDM-demultiplexing the 1.28 Tbaud data (e.g. pol1) down to a 10 Gbaud symbol rate. The NOLM operation is based on cross-phase modulation in a 15 m HNLF using the 10 GHz control pulses at 1535 nm. The individual channels can be selected using a tuneable optical time-delay Δt. The parameters of the 15 m HNLF are: a zero-dispersion wavelength at ~1545 nm, a dispersion slope of $S = 0.015$ ps/(nm^2·km) at 1550 nm, and $\gamma = 10.5$ W^{-1}km^{-1}. The average output powers of the amplifiers before the NOLM are 20 dBm for the control pulse EDFA and 27.6 dBm for the 1.28 Tbaud data EDFA. The FWHM pulse widths at the HNLF input are 440 fs (control) and 410 fs (data). The spectra of the control and data signals at the input to the HNLF are shown in Fig. 2. The pulse broadening and control-data walk-off in the HNLF are negligible. The demultiplexed 10 Gbaud pulses are extracted using a 1 nm BPF at 1557 nm, as shown in Fig. 2, and finally detected using a 10 Gbaud DQPSK receiver. Here, the 10 Gbaud DQPSK data are pre-amplified, filtered and then demodulated using a 1-symbol delay interferometer (DLI), with a tuneable phase-shift to select the 10 Gbit/s in-phase (I) and quadrature (Q) components.

The DLI outputs are detected using a balanced photo-detector (BPD), followed by a 10 Gbit/s error-detector for BER evaluation. The ERGO-PGL, the pattern generator and the error-detector are synchronised by an electrical synthesiser running at 9.9535 GHz.

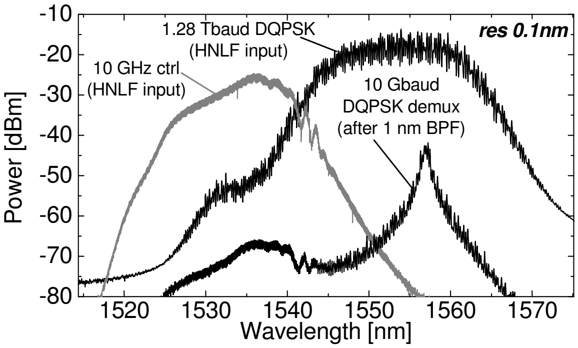

Fig. 2. Optical spectra, measured in the NOLM demultiplexer.

3. Results and discussion

The system is tested using both DPSK and DQPSK data-modulation, and using symbol rates of 640 Gbaud and 1.28 Tbaud. Error-free operation with a BER less than 10^{-9} is obtained in all cases.

The DPSK data-modulation is obtained simply by turning off the driving signal to the phase-modulator in the DQPSK modulator, c.f. Figure 1 (b). Autocorrelation traces of the 1.28 Tbaud DPSK data signal and the 10 GHz control pulse used for demultiplexing are shown in Fig. 3 (measured at the input to the NOLM-HNLF). The timing and amplitude of the 128 channels is obtained by manual adjustment of the multiplexer stages, and the data autocorrelation shows that a well-aligned OTDM data signal is obtained.

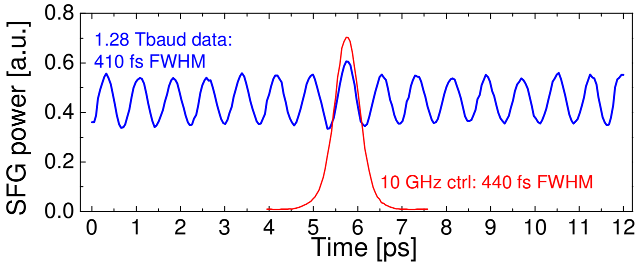

Fig. 3. Autocorrelations of the 1.28 Tbaud DPSK signal and 10 GHz control pulse (the specified FWHMs are for a corresponding Gaussian pulse profile).

The BER curves of eight consecutive (neighbouring) 10 Gbaud DPSK channels after detection (OTDM-demultiplexing, delay-demodulation and balanced photo-detection) are shown in Fig. 4. Polarisation-multiplexing is not used here. All eight channels have error-free performance with a variation in sensitivity of only ~0.7 dB. The power penalty with respect to the 10 Gbaud DPSK reference sensitivity of –40.8 dBm, measured immediately after the data-modulator, is ~2.6 dB. These measurements show that a very even performance is obtainable for the different OTDM channels. In principle, all channels should be demultiplexed with error-free performance in order to verify the integrity of the entire OTDM data signal, as it was done in the first demonstration of 1.28 Tbaud OTDM, where on-off keying was used as data format [1]. However, such a complete characterisation was not carried out in this work.

#119544 - $15.00 USD Received 4 Nov 2009; revised 3 Jan 2010; accepted 6 Jan 2010; published 15 Jan 2010

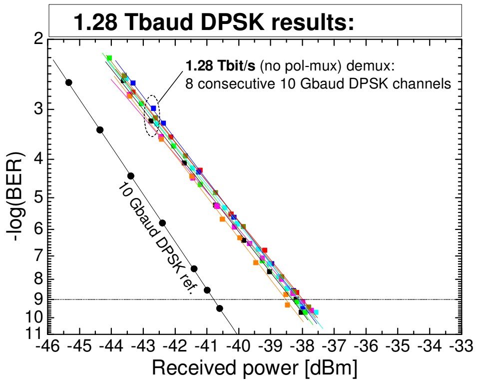

Fig. 4. BER curves for 8 consecutive 10 Gbaud DPSK channels demultiplexed from 1.28 Tbaud.

The DQPSK data modulation is obtained by turning on the driving signal to the phase-modulator, following the MZM generating the DPSK, cf. Figure 1 (b). The pulse widths are the same as above. Figure 5 (a) shows BER curves for a 10 Gbaud DQPSK channel demultiplexed from 640 Gbaud. Without pol-mux, yielding a data rate of 1.28 Tbit/s, the demultiplexed 10 Gbit/s I- and Q-components have sensitivities of −34.8 dBm and −35.2 dBm. There is a penalty of less than 3 dB compared to the 10 Gbaud reference I/Q sensitivity of −37.6 dBm. When adding pol-mux to reach 2.56 Tbit/s, the sensitivity of the same demultiplexed 10 Gbit/s I-component (as without pol-mux) is only increased by 0.5 dB to −34.3 dBm, which is a penalty of 3.3 dB compared to the reference. These particular measurements show that 2.56 Tbit/s can be generated from 640 Gbaud with low penalty using pol-mux and DQPSK.

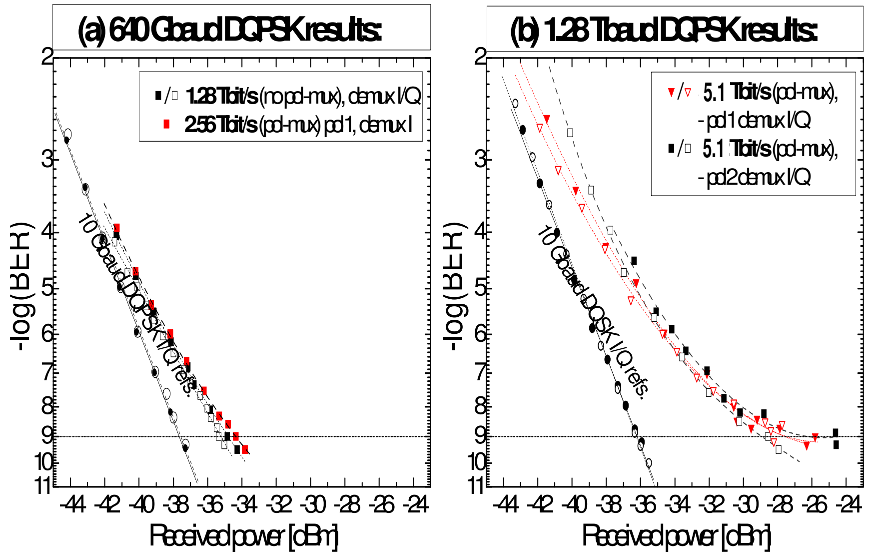

Fig. 5. BER curves for 10 Gbaud DQPSK channels demultiplexed from 640 Gbaud (a) and 1.28 Tbaud (b). I/Q components are plotted with filled/empty symbols.

The symbol rate is then doubled to 1.28 Tbaud, and with pol-mux a total bit rate of 5.1 Tbit/s is obtained. The resulting BER curves are found in Fig. 5 (b), showing the I/Q components of a 10 Gbaud DQPSK channel demultiplexed from each 1.28 Tbaud polarisation-component (pol1 and pol2) of the 5.1 Tbit/s data signal. The corresponding eye-diagram is shown in Fig. 6. BER values better than 10^{-9} are detected for all measured curves,

#119544 - $15.00 USD Received 4 Nov 2009; revised 3 Jan 2010; accepted 6 Jan 2010; published 15 Jan 2010

hence demonstrating that error-free performance can be obtained at 5.1 Tbit/s. However, there is an error-floor below 10^{-9} and a penalty of about 7-10 dB relative to the 10 Gbaud DQPSK reference sensitivity. The error-floor is primarily attributed to a slightly too large data pulse FWHM (410 fs) compared to the 1.28 Tbaud bit slot of 785 fs, implying some pulse tail overlap between neighbouring channels. As a consequence, there is a certain amount of interferometric cross-talk that deteriorates the DQPSK performance at 1.28 Tbaud. An ideal pulse FWHM should not exceed about 0.4 × time-slot, which is 314 fs at 1.28 Tbaud [8]. In this experiment, the broadened data pulse FWHM of 410 fs at the NOLM, compared to the compressor output FWHM of ~200 fs, is primarily attributed to spectral shaping by the data EDFAs in the set-up. Note that two additional EDFAs (not shown in Fig. 1) are used within the MUX to compensate for a total loss of ~35 dB in the seven delay-line stages used to reach 1.28 Tbaud (the loss is ~5 dB per stage). None of the EDFAs in the set-up are equipped with gain-flattening filters. Hence, we expect that the error-floor at 5.1 Tbit/s can be avoided if only gain-flattened data EDFAs are used, since this will strongly reduce the pulse broadening due to spectral shaping. As another remark, the 2^7-1 PRBS pattern used to drive the data-modulator was held fixed, and longer bit sequences were not tested. However, no pattern dependence of the performance is expected in this experimental set-up.

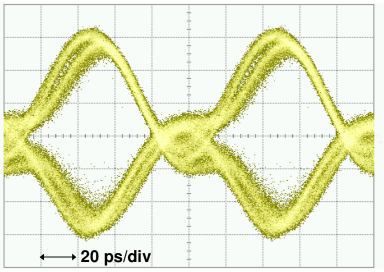

Fig. 6. 5.1 Tbit/s DQPSK eye after demultiplexing, demodulation, and balanced photo-detection.

Finally, note that there is a small mismatch of ~564 fs between the ERGO-PGL repetition period and the 1-symbol delay of the DLI, the effect of which is somehow corrected by narrow filtering in the receiver. For the 640 Gbaud DQPSK measurements in Fig. 5 (a), 0.3 nm and 0.9 nm BPFs are used instead of the 1 nm and 5 nm BPFs shown in Fig. 1 (c). This resulted in an improved sensitivity as can be observed by comparing the reference BER curves in Fig. 5 (a) and (b). However, this narrow filtering also limited the amount of power (P_{rec}) that could be obtained in the receiver, and there was not sufficient power to reach a BER below 10^{-9} when increasing the symbol rate to 1.28 Tbaud. In this case, the 1 nm and 5 nm BPFs were used to receive sufficient power to obtain the error-free performance as seen in Fig. 5 (b).

4. Conclusion

We have demonstrated a 5.1 Tbit/s data capacity on a single-wavelength channel by obtaining, for the first time, a BER performance below 10^{-9}. The 5.1 Tbit/s data signal was generated by using 1.28 Tbaud OTDM, DQPSK data-modulation, and polarisation-multiplexing. The data signal was detected in a back-to-back configuration, using a direct-detection type receiver based on polarisation-demultiplexing and time-demultiplexing, followed by delay-demodulation and balanced photo-detection. This experiment clearly demonstrates the considerable bit rates that can be obtained using single-channel data generation.

Acknowledgments

The Danish Research Council for Technology and Production Sciences (FTP) is acknowledged for funding (grant 274-08-0055). OFS Fitel Denmark ApS is acknowledged for kindly providing the highly non-linear fibres used in this experiment.

Received 4 Nov 2009; revised 3 Jan 2010; accepted 6 Jan 2010; published 15 Jan 2010