Doubly periodic dispersion maps for 10 and 40 Gbit/s ultra-long-haul transmission

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Optical transmission employing doubly periodic dispersion maps at 10 and 40 Gbit/s data rates is reported. The implications of these transmission results in providing added degrees of flexibility in network design, in particular, in applications such as optical add-drops and hybrid data rate systems, are discussed.

Introduction: In the recent past, technologies such as dense wavelength division multiplexing (DWDM), optical amplification, novel data formats, and forward error correction (FEC), among others, have contributed significantly in realising high-capacity and long-reach optical communication systems. Future applications may require provisions such as 10–40 Gbit/s hybrid data rate and/or multiple optical add/drop modules (OADMs) located at arbitrary sites along the network.

In the context of hybrid data rate systems, different dispersion management requirements arise for the two data rates: long-haul and ultra-long-haul 10 Gbit/s networks will, in general, require a constant amount of dispersion pre-compensation at end terminals and 'add' points [1]. Conversely, 40 Gbit/s channels will require a varying amount of pre-compensation for better nonlinear performance [2]. At the 'drop' points, 10 Gbit/s channels will require either a fixed amount of dispersion post-compensation or 'banded' post-compensation. However, 40 Gbit/s traffic needs precise cancellation of any residual dispersion thus requiring the use of tunable dispersion compensation (TDC) devices.

A promising dispersion-management scheme employed in recent years makes use of doubly periodic (DP) dispersion maps where the residual dispersion is periodically reset close to that at the beginning of the transmission line (i.e. the pre-compensation value) after a designated number of fibre spans [3], in general coincident with the OADM sites placed along the network. Consequently, in a DP map, the residual dispersion at OADM sites becomes independent of the transmitted distance.

In this Letter we report experimental results on error-free transmission of 128 × 10.7 Gbit/s and 64 × 42.7 Gbit/s using DP dispersion maps. The experiments are aimed at understanding the implications and limitations of such dispersion maps for both data rates.

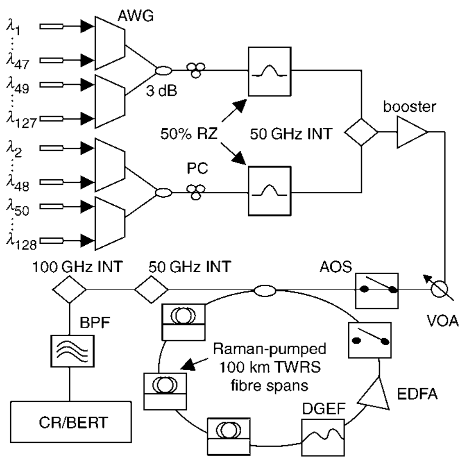

Fig. 1 *Experimental setup (10 Gbit/s)*

AWG: array waveguide router; INT: interleaver; VOA: variable optical attenuator; AOS: acousto-optic switch; DGEF: dynamic gain equalisation filter; EDFA: erbium-doped fibre amplifier; BPF: bandpass filter; CR/BERT: receiver, clock recovery, and bit error rate detector set

Experimental setup: Transmission experiments at 10 and 40 Gbit/s were conducted separately using the basic setup shown (for 10 Gbit/s) in Fig. 1. The 128 (64) signal lasers, spanning a wavelength range from 1554.95 to 1607.47 nm, are spaced at 100 (200) GHz and grouped into two banks for 10 Gbit/s (40 Gbit/s) experiments. For the 10 Gbit/s set of experiments each bank is independently modulated with a $2^{31}-1$ PRBS sequence of 50% duty-cycle RZ data, obtained by driving a single Mach-Zehnder modulator with 50% RZ electrical data. The use of long data pattern lengths is important, especially for the case of 10 Gbit/s transmission, where interchannel-nonlinear interactions, such as cross-phase modulation (XPM), may represent the main source of transmission penalty. For 40 Gbit/s experiments, odd and even channels were separately modulated by two $LiNbO_3$ modulators in series, with the first modulator generating 67% duty-cycle carrier-suppressed pulses. Electrical time-domain multiplexing (ETDM) is used to generate the 42.7 Gbit/s data signal, from four delayed copies of 10.7 Gbit/s $2^{31}-1$ PRBS data streams, that drives the second modulator. For experiments at 10 (40) Gbit/s, channels are combined by an optical interleaver resulting in channels spaced at 50 GHz (100 GHz) and are launched co-polarised. Although the Reed-Solomon forward error correction (FEC) data rate with 7% overhead is used for both 10 and 40 Gbit/s Gbit/s experiments, FEC is actually not implemented in the experiments. A high-power erbium-doped fibre amplifier (EDFA) operating in the extended L-band is used as a booster to obtain −5 dBm per-channel launch power (−2 dBm for 40 Gbit/s).

Several spans (five and four in the 10 and 40 Gbit/s experiments, respectively) of 100 km of True-Wave Reduced Slope (TWRS) fibre, each followed by a slope-matched dispersion compensating module (DCM), are arranged in a recirculating loop. Each span is forward- and backward-Raman pumped for an on–off gain of 20 dB, with 4 dB forward gain. The DCM is also backward-pumped with an on–off gain of 14.5 dB. Details of the Raman amplification scheme were described earlier [4]. A single dynamic gain equalising filter (DGEF) is placed within the loop after the last span to equalise channel powers and is followed by an EDFA to compensate for the bulk losses from the DGEF, the acousto-optic switches and the 3 dB coupler.

The DP dispersion map used in this study consists of −350 ps/nm (−87 ps/nm for 40 Gbit/s) pre-compensation and slope-matched DCMs after each span, except after the last span in the loop. The last span is followed by a DCM compensating 130 km rather than 100 km TWRS. This arrangement allows the residual dispersion after the last span to approach the pre-compensation value. Accumulated dispersion for 10 and 40 Gbit/s transmission is shown in Fig. 2 for both a DP and a uniform map. From Fig. 2 it is evident that for wavelengths around 1550 and 1600 nm the accumulated dispersion for the DP map deviates considerably from the pre-compensation value, and while the accumulated dispersion after each circulation is strictly not equal to the pre-compensation value for the other wavelengths, it is close, and provides a good indication about the transmission performance of systems employing DP maps. After transmission, the 128 × 10.7 Gbit/s (64 × 42.7 Gbit/s) channels were separated using a 50-to-100 GHz and a 100-to-200 GHz de-interleaver in series (100-to-200 GHz de-interleaver) followed by an EDFA preamplifier. A single 10 Gbit/s channel was selected for reception by a 0.25 nm tunable optical filter, while individual 40 Gbit/s channels were separated by an arrayed waveguide (AWG) device.

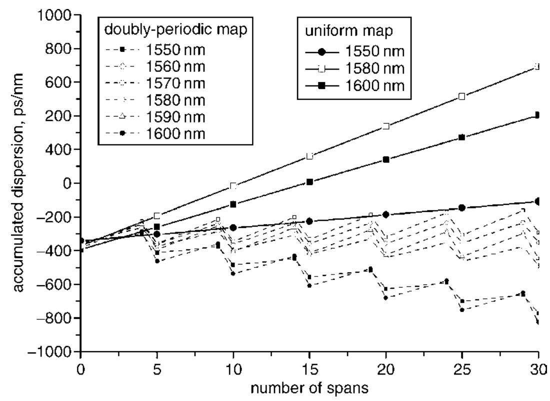

Fig. 2 *Accumulated dispersion with doubly periodic and uniform dispersion maps against transmitted distance*

For post-compensation, 25 km of standard singlemode fibre (SSMF) was used for all 10 Gbit/s channels at the target distance. For 40 Gbit/s a TDC brought the individual channel residual dispersion close to zero (within ±10 ps/nm). A 43 Gbit/s electrical receiver/demultiplexer was then used to measure the average BER of the four 10.7 Gbit/s tributaries.

Experimental results: The uncorrected-BER and received optical-signal-to-noise ratio (OSNR) (in 0.1 nm resolution) for 10 and 40 Gbit/s channels after 3000 and 1600 km, respectively, of TWRS fibre are shown in Fig. 3 for randomly selected channels across the transmission band. We observed that 10 Gbit/s performance with DP maps is slightly worse compared to uniform maps, while it is similar for 40 Gbit/s (the reader is referred to [1] for a complete set of results of experiments with uniform maps for both 10 and 40 Gbit/s).

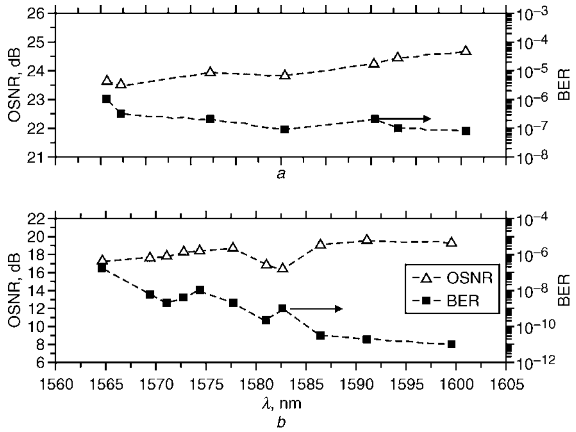

Fig. 3 *Doubly periodic dispersion map performance. Received OSNR (in 0.1 nm resolution) and BER for 128 × 10.7 Gbit/s, and 64 × 42.7 Gbit/s, after propagation of 3000 and 1600 km of TWRS fibre, respectively, and for randomly selected channels across transmission band*

a 40 Gbit/s *b* 10 Gbit/s

Performance is quantified using OSNR-based system margin and transmission penalty, as detailed in several papers [1, 5]. For 40 Gbit/s transmission, and after 1600 km, the measured system margin was 4.5 dB on average and the transmission penalty was less than 1 dB. As shown in Fig. 2, for a DP map the spread in accumulated dispersion across the band against distance is reduced by almost 40%. Although wavelengths at the extremes of the transmission band do not show such an ideal DP behaviour with the components used in our experiments, it is possible to optimise the map to further reduce the spread for each wavelength. Irrespective of transmission distance, this key improvement is significant in two ways: it simplifies TDC design for end terminals as well as OADM sites, and provides a means of predicting a fixed pre-compensation for the 'add' channels to match the residual dispersion of the 'through' channels at any OADM site. Also, the periodicity of the DP map can be made to vary according to OADM distance requirements, allowing for tremendous flexibility in network design. Furthermore, we have shown that a DP map does not preclude ultra-long-haul 10 Gbit/s transmission, thus allowing the migration from 10 to 40 Gbit/s and/or transmission of hybrid data rates.

Conclusions: We have presented an investigation of DWDM transmission performance of 128 × 10.7 Gbit/s and 64 × 42.7 Gbit/s over 3000 and 1600 km of TWRS fibre, respectively, using DP dispersion maps. Transmission performance is comparable to that obtained with the more traditional uniform maps. In this context, the real advantage of DP maps is in TDC design for 40 Gbit/s systems and on the added degree of flexibility in designing networks with multiple OADM sites and/or hybrid data rates.

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References

1 Grosz, D.F., *et al.*: 'All-Raman ultra-long-haul single-wideband DWDM transmission systems with OADM capability', *J. Lightwave Technol.*, 2004, **22**, (2), pp. 423–432

2 Killey, R.I., *et al.*: 'Reduction of intrachannel nonlinear distortion in 40-Gb/s-based WDM transmission over standard fiber', *IEEE Photonics Technol. Lett.*, 2000, **12**, (12), pp. 1624–1626

3 Ito, T., Sekiya, K., and Ono, T.: 'Study of 10G/40G hybrid ultra long haul transmission systems with reconfigurable OADMs for efficient wavelength usage'. Proc. ECOC 2002, Copenhagen, Denmark, 2002, Paper 1.1.4.

4 Banerjee, S., *et al.*: 'Long-haul 64 × 40 Gbit/s transmission over commercial fibre types with large operating margins', *Electron. Lett.*, 2003, **39**, (1), pp. 92–94

5 Agarwal, A., *et al.*: 'Ultra long-haul transmission of 40 Gb/s RZ-DPSK in a 10/40 G hybrid system over 2500 km of NZDSF', *IEEE Photonics Technol. Lett.*, 2003, **15**, (12), pp. 1779–1781