40 × 112 Gb/s Transmission over an Unrepeatered 365 km Effective Area-Managed Span Comprised of Ultra-Low Loss Optical Fibre

John D. Downie, Jason Hurley, John Cartledge, Sergey Ten, Scott Bickham, Snigdharaj Mishra, Xianming Zhu, and Andrey Kobyakov

Corning Incorporated SP-AR-02-1, Corning, NY 14831, USA, downiejd@corning.com

Abstract *We experimentally demonstrate transmission of 40 × 112 Gb/s PM-QPSK channels over a 365 km unrepeatered span enabled by ultra-low loss fibres in an effective area-managed configuration using only backward-pumped Raman with 25 dB gain and EDFA amplification.*

Introduction

Long unrepeatered spans are commonly found in submarine networks connecting islands to the mainland, one island to another, and mainland points to each other in a festoon arrangement. In these systems, it is desirable to achieve span distances as long as possible with no underwater active electronics, including powered amplifiers. To date, almost all such networks operate at bit rates of 10 Gb/s, with interest recently moving toward 40 Gb/s[1-3]. To attain the span lengths necessary, system designers often resort to advanced technologies including bidirectional or higher-order pumped Raman amplifiers, remote optically pumped amplifiers (ROPAs), and strong forward error correction (FEC) coding[4,5]. With long-haul transmission systems rapidly moving toward 100 Gb/s channel bit rates, it is clear that eventually 100 Gb/s channels will be also needed in festoon and other unrepeatered systems. In that case, the span distances required (>350 km) will not change during the move to 100 Gb/s, and so the high bit rate systems must be able to support transmission over such lengths with good performance and with minimal system complexity and cost. Recent work has demonstrated a 401 km span system with 26 × 100 Gb/s channels over long unrepeatered spans but relied on a complex ROPA and third order Raman pumping scheme with 39 dB total gain[6]. In this paper, we demonstrate transmission of 4 Tb/s with 40 channels modulated at 112 Gb/s with the polarization multiplexed quadrature phase-shift keying (PM-QPSK) modulation format over a 365 km unrepeatered span using an effective area-managed fibre configuration[7] with only EDFA amplification at the transmitter and backward-pumped Raman/EDFA amplification at the receiver. The span is comprised of 3 types of ultra-low loss fibre with effective areas ranging from 76 μm^2 to 128 μm^2 in an arrangement designed to maximize nonlinear tolerance and overall effectiveness of the Raman amplifier. The total capacity-distance product of the system is 40 × 100 Gb/s × 365 km = 1460 Tb/s-km, which we believe to be a record for an unrepeatered system.

Experimental set-up

The experimental system set-up is shown in Fig. 1. Forty DFB lasers spaced by 50 GHz and ranging from 1542.9 nm to 1558.6 nm were multiplexed together and modulated by a QPSK modulator. The modulator was driven by two 2^{15}-1 PRBS patterns at 28 Gsymbol/s. The output from the QPSK modulator was then polarization multiplexed by splitting the signal, orthogonalizing the polarization states, de-correlating by hundreds of symbols with a relative delay, and combining with a polarization beam combiner to produce the final PM-QPSK

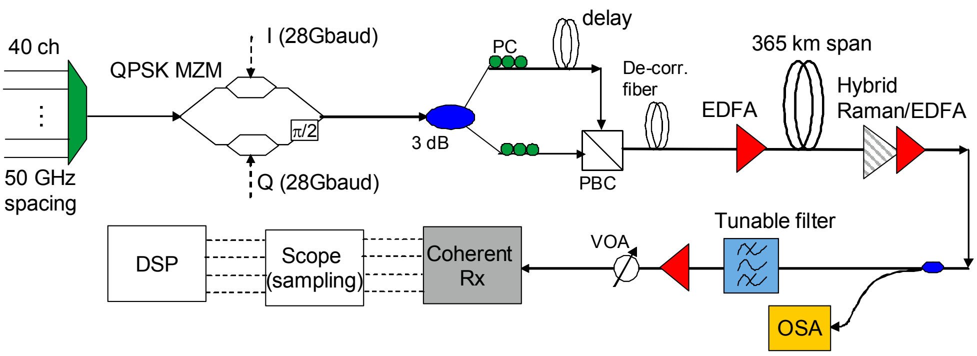

Fig. 1: Experimental set-up.

signals modulated at 112 Gb/s. The 40 channels were launched into the 365 km span with a nominally flat launch spectrum after de-correlation using a short piece of standard single-mode fibre and amplification with a high-power EDFA.

The fibre span was comprised of 3 types of ultra-low loss fibres with different effective areas (Aeff). The fibres used were Corning® Vascade® EX1000 fibre with 76 μm^2 effective area, Vascade® EX2000 fibre with about 112 μm^2 effective area, and a developmental fibre with an effective area of 128 μm^2. The average attenuation values of the 3 fibre types used in this experiment were 0.162 dB/km, 0.162 dB/km, and 0.164 dB/km, respectively. The total fibre span loss including splices was about 59.6 dB, giving an average span attenuation of 0.163 dB/km. The span configuration is shown in Fig. 2 and consisted of about 40 km of the 128 μm^2 effective area fibre, followed by 155 km of Vascade® EX2000, 160 km of Vascade® EX1000, and then another 10 km of Vascade® EX2000 fibre at the end of the span. The length of the largest Aeff fibre at the beginning was chosen to balance nonlinear tolerance and OSNR. The Raman gain primarily occurred in the 76 μm^2 effective area fibre, while the addition of 10 km of the fibre with 112 μm^2 Aeff at the end of the span was predicted by modelling to maximize the overall system OSNR at the receiver while minimizing nonlinear penalties.

The Raman amplifier had 3 pump wavelengths at 1427 nm, 1443 nm, and 1462 nm. The total aggregate output power of the pumps was approximately 725 mW in each polarization which produced a total Raman gain of about 25 dB. Immediately following the Raman amplifier was an EDFA. A tuneable optical filter with 0.4 nm bandwidth was then used to select a channel for measurement.

The measurement channel was amplified before detection in a polarization- and phase-diverse digital coherent receiver that used a free-running local oscillator laser with nominal linewidth of 100 kHz. The four signals from the balanced photodetectors were digitized by analog-to-digital converters operating at 50 Gsamples/s using a real-time oscilloscope with 20 GHz electrical bandwidth. The sampled waveforms were processed off-line in a computer, with the digital signal processing steps including (i) quadrature imbalance compensation, (ii) up-sampling to 56 Gsamples/s and chromatic dispersion (~7000 ps/nm) compensation using a fixed time-domain equalizer (filter coefficients determined from the impulse response), (iii) digital square and filter clock recovery, (iv) polarization recovery, polarization mode dispersion compensation and residual dispersion compensation using an adaptive butterfly equalizer (filter coefficients determined using the constant modulus algorithm), (v) carrier frequency and phase recovery, and (vi) bit decisions[8,9]. The bit error rate (BER) was determined for each of the 28 Gb/s tributary signals by direct error counting.

Experimental results

We first determined the optimal channel launch power into the span. The BER was measured for a channel in the middle of the channel plan at 1550.92 nm as a function of launch power. The results from these measurements are shown in Fig. 3a, which has the data for the 50 GHz, 40 channel system, and for sake of comparison, data for a 100 GHz, 16 channel system. The optimal channel launch power for the 40 channel system is seen to be between 13 and 14 dBm. In Fig. 3b, the OSNR sensitivity of the measured channel using the DFB signal laser through the 365 km span is compared to measured back-to-back OSNR sensitivity data using an external cavity signal laser.

Based on the results shown in Fig. 3a, the optimal launch power was set to be about 13.5 dBm per channel. The output spectrum at the end of the 365 km span is shown in Fig. 4a. The range of received channel powers was less than 3 dB. The BER and OSNR values of all 40 channels were measured, based on 1,000,000 samples for each of the four tributary signals. The calculated Q values based on the measured BER data and OSNR data are shown in Fig. 4b. All 40 channels were determined to have Q values above the enhanced FEC (eFEC) threshold [6] of 8.5 dB. The average Q value was 9.6 dB and the average OSNR value was 14.7 dB.

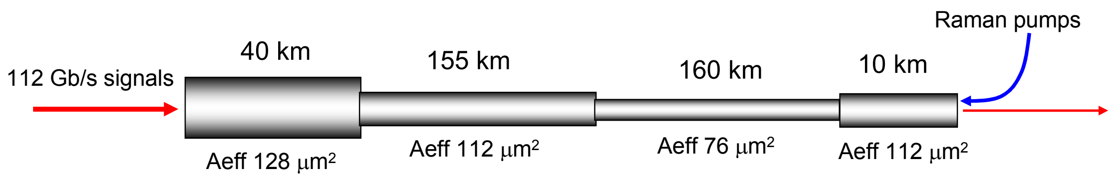

Fig. 2: Schematic representation of the optical fibre span configuration.

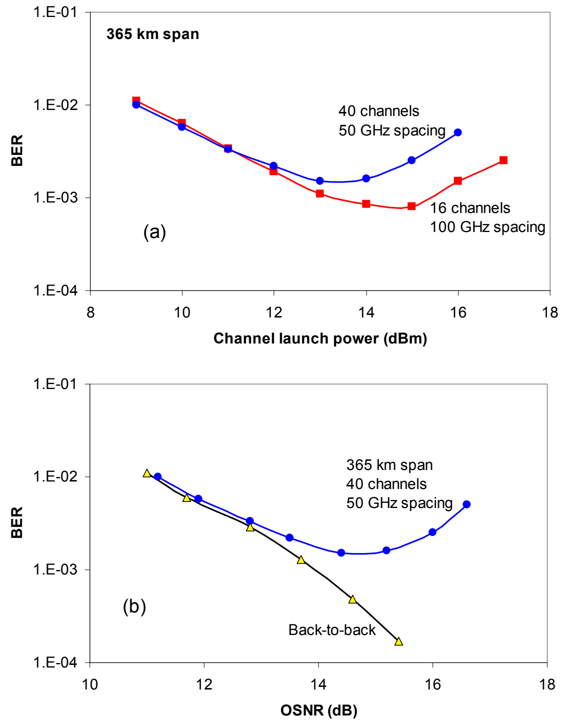

Fig. 3: For 1550.92 nm channel, (a) BER vs. channel launch power for 50 GHz and 100 GHz systems, and (b) BER vs. OSNR/0.1nm for 40 channel system and in back-to-back.

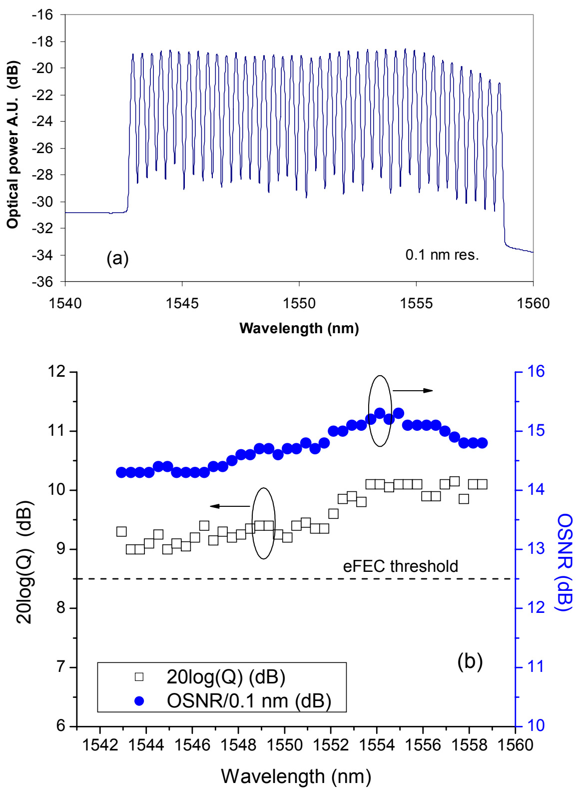

Fig. 4: (a) System spectrum at the end of the 365 km span, (b) 20log(Q) and OSNR values for all 40 channels.

Conclusions

We have experimentally demonstrated transmission of 40 × 112 Gb/s PM-QPSK channels over an unrepeatered span of length 365 km. The span was an effective area-managed configuration and was comprised of three types of ultra-low loss fibre with effective areas ranging from 76 μm^2 to 128 μm^2. The average attenuation for the total fibre span was 0.163 dB/km. Only high-power EDFA amplification at the transmitter and simple hybrid Raman/EDFA amplification at the receiver were used. All channels were measured to have Q values greater than the enhanced FEC threshold, and the average Q was 1.1 dB higher than the threshold. We believe the capacity-distance product of 1460 Tb/s-km is a record for an unrepeatered span.

Acknowledgments

The authors would like to thank Stuart Gray and Boh Ruffin for helpful discussions and assistance.

References

1 J.-X. Cai, B. Bakhshi, and M. Nissov, *OFC/NFOEC 2008*, San Diego, CA,, paper OMQ5 (2008).
2 T. Mizuochi, K. Kinjo, S. Kajiya, T. Tokura, and K. Motoshima, J. Lightwave Technol., **20**, pp. 2079-2085, (2002).
3 H. Bissessur, F. Boubal, S. Gauchard, A. Hugbart, L. Labrunie, P. Le Roux, J-P. Hebert and E. Brandon, *ECOC 2003*, Rimini, Italy, paper Tu1.6.3, (2003).
4 L. Labrunie, F. Boubal, P. Le Roux, and E. Brandon, Electron. Lett., **39**, pp.1394-1395, (2003).
5 T. Mizuochi, *et al*, IEEE J. Sel. Topics in Quantum Electron., **10**, pp. 376-386, (2004).
6 D. Mongardien, P. Bousselet, O. Bertran-Pardo, P. Tran, and H. Bissessur., *ECOC 2009*, Vienna, Austria, paper 6.4.3, (2009).
7 K. Shimizu *et al*, *OFC 2001*, Anaheim, CA, paper TuU2-1 (2001).
8 M. Kuschnerov, F. N. Hauske, K. Piyawanno, B. Spinnler, M. S. Alfiad, A. Napoli, and B. Lankl, J. Lightwave Technol., **27**, pp. 3614-3622, (2009).
9 S. J. Savory, to appear in IEEE J. Sel. Topics in Quantum Electron.