Unrepeatered 256 Gb/s PM-16QAM transmission over up to 304 km with simple system configurations

John D. Downie,* Jason Hurley, Ioannis Roudas, Dragan Pikula, and Jorge A. Garza-Alanis

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

Abstract: We study unrepeatered transmission of 40x256 Gb/s systems with polarization-multiplexed 16-quadrature amplitude modulation (PM-16QAM) channels using simple coherent optical system configurations. Three systems are investigated with either a homogeneous fiber span, or simple two-segment hybrid fiber designs. Each system relies primarily on ultra-low loss, very large effective area fiber, while making use of only first-order backward pumped Raman amplification and no remote optically pumped amplifier (ROPA). For the longest span studied, we demonstrate unrepeatered 256 Gb/s transmission over 304 km with the additional aid of nonlinear compensation using digital backpropagation. We find an average performance improvement in terms of the Q-factor of 0.45 dB by using digital backpropagation compared to the case of using chromatic dispersion compensation alone for an unrepeatered span system.

OCIS codes: (060.2330) Fiber optics communications; (060.2360) Fiber optics links and subsystems.

References and links

1. J. D. Downie, J. Hurley, J. Cartledge, S. Ten, S. Bickham, S. Mishra, X. Zhu, and A. Kobyakov, "40 x 112 Gb/s transmission over an unrepeatered 365 km effective area-managed span comprised of ultra-low loss optical fibre," in *Proceedings of European Conf. Opt. Commun.* (2010), paper We.7.C.5.
2. D. Mongardien, P. Bousselet, O. Bertran-Pardo, P. Tran, and H. Bissessur, "2.6Tb/s (26 x 100Gb/s) unrepeatered transmission over 401km using PDM-QPSK with a coherent receiver," in *Proceedings of European Conf. Opt. Commun.* (2009), paper 6.4.3.
3. H. Bissessur, P. Bousselet, D. Mongardien, G. Boissy, and J. Lestrade, "4 x 100Gb/s unrepeatered transmission over 462km using coherent PDM-QPSK format and real-time processing," in *Proceedings of European Conf. Opt. Commun.* (2011), paper Tu.3.B.3.
4. D. Chang, W. Pelouch, and J. McLaughlin, "8 x 120 Gb/s unrepeatered transmission over 444 km (76.6 dB) using distributed Raman amplification and ROPA without discrete amplification," in *Proceedings of European Conf. Opt. Commun.* (2011), paper Tu.3.B.2.
5. S. Oda, T. Tanimura, Y. Cao, T. Hoshida, Y. Akiyama, H. Nakashima, C. Ohshima, K. Sone, Y. Aoki, M. Yan, Z. Tao, J. C. Rasmussen, Y. Yamamoto, and T. Sasaki, "80x224 Gb/s unrepeated transmission over 240 km of large-A_{eff} pure silica core fibre without remote optical pre-amplifier," in *Proceedings of European Conf. Opt. Commun.* (2011), paper Th.13.C.7.
6. D. Mongardien, C. Bastide, B. Lavigne, S. Etienne, and H. Bissessur, "401 km unrepeatered transmission of dual-carrier 400 Gb/s PDM-16QAM mixed with 100 Gb/s channels," in *Proceedings of European Conf. Opt. Commun.* (2013), paper Tu.1.D.2.
7. A. H. Gnauck, P. J. Winzer, S. Chandrasekhar, X. Liu, B. Zhu, and D. W. Peckham, "Spectrally efficient long-haul WDM transmission using 224-Gb/s polarization-multiplexed 16-QAM," J. Lightwave Technol. **29**(4), 373–377 (2011).
8. F. Chang, K. Onohara, and T. Mizuochi, "Forward error correction for 100 G transport networks," IEEE Commun. Mag. **48**(3), S48–S55 (2010).
9. I. Fatadin, D. Ives, and S. J. Savory, "Blind equalization and carrier phase recovery in a 16-QAM optical coherent system," J. Lightwave Technol. **27**(15), 3042–3049 (2009).
10. T. Pfau, S. Hoffmann, and R. Noe, "Hardware-efficient coherent digital receiver concept with feedforward carrier recovery for M-QAM constellations," J. Lightwave Technol. **27**(8), 989–999 (2009).

11. Y. Gao, A. P. T. Lau, C. Lu, Y. Dai, and X. Xu, "Blind cycle-slip detection and correction for coherent communication systems," in *Proceedings of European Conf. Opt. Commun.* (2013), paper P.3.16.
12. J. D. Downie, J. Hurley, D. Pikula, S. Ten, and C. Towery, "Study of EDFA and Raman system transmission reach with 256 Gb/s PM-16QAM signals over three optical fibers with 100 km spans," Opt. Express **21**(14), 17372–17378 (2013).
13. E. Ip and J. M. Kahn, "Compensation of dispersion and nonlinear impairments using digital backpropagation," J. Lightwave Technol. **26**(20), 3416–3425 (2008).
14. E. Ip, "Nonlinear compensation using backpropagation for polarization-multiplexed transmission," J. Lightwave Technol. **28**(6), 939–951 (2010).
15. C. Behrens, R. I. Killey, S. J. Savory, M. Chen, and P. Bayvel, "Nonlinear transmission performance of higher-order modulation formats," IEEE Photon. Technol. Lett. **23**(6), 377–379 (2011).
16. G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed. (Academic, 1995).
17. J. Rodrigues Fernandes de Oliveira, U. C. de Moura, G. E. Rodrigues de Paiva, A. Passos de Freitas, L. H. Hecker de Carvalho, V. E. Parahyba, J. C. Rodrigues Fernandes de Oliveira, and M. Araujo Romero, "Hybrid EDFA/Raman amplification topology for repeaterless 4.48 Tb/s (40 x 112 Gb/s DP-QPSK) transmission over 302 Km of G.652 standard single mode fiber," J. Lightwave Technol. **31**(16), 2799–2808 (2013).
18. A. Puc, D. Chang, W. Pelouch, P. Perrier, D. Krishnappa, and S. Burtsev, "Novel design of very long, high capacity unrepeatered Raman links," in *Proceedings of European Conf. Opt. Commun.* (2009), paper 6.4.2.

1. Introduction

Long point-to-point unrepeatered spans of several hundred kilometers are found in submarine and terrestrial networks connecting islands, mainland points in a festoon configuration, or cities with desert or otherwise forbidding landscape between them. In these systems, the primary objective is to achieve a single-span system between the points of interest with no active equipment between terminals. There have been a number of recent research experiments with this type of system using a data rate of 100 Gb/s and polarization-multiplexed quadrature-phase-shift keying (PM-QPSK) signals. In one experiment, the feasibility of unrepeatered transmission over a span of 365 km was demonstrated with backward pumped Raman amplification and a hybrid fiber span configuration [1]. Even longer span lengths have been shown by employing more complex amplification schemes including ROPAs, forward and backward Raman pumping, and higher order Raman pumps [2–4]. To date, there has been less activity in unrepeatered span transmission at the 200 Gb/s net data rate, but 80x224 Gb/s was demonstrated over 240 km without a ROPA using a large effective area (A_{eff}) fiber with a silica core [5]. More recently, 401 km transmission was demonstrated for one dual-carrier 400 Gb/s channel (2x200 Gb/s), but this system also used a ROPA and higher order forward and backward Raman pumping using high pump powers [6].

In this paper, we investigate 40x256 Gb/s transmission of PM-16QAM signals over unrepeatered spans with minimal complexity comprised solely or primarily of an ultra-low loss, very large effective area fiber. The systems investigated use first-order backward pumped Raman amplification combined with a discrete erbium-doped fiber amplifier (EDFA) at the receiver and no ROPA. We begin with a homogeneous span and demonstrate 286 km transmission for all 40 channels with at least 0.5 dB margin over the forward error correction (FEC) threshold. We next show transmission over a 292 km span with a simple hybrid fiber configuration that allows higher Raman gain and better performance. Finally, we extend the hybrid span length to 304 km and demonstrate successful transmission with the aid of nonlinear compensation using digital backpropagation. To the authors' knowledge, this is the longest unrepeatered span transmission demonstrated for 200 Gb/s data rate, PM-16QAM signals using a simple first-order backward pumped Raman amplification scheme.

2. Experimental set-up

The general experimental set-up is shown in Fig. 1. A total of 40 channels spaced by 50 GHz were multiplexed together and modulated by a quadrature modulator with the 16QAM format. The channel under measurement was encoded on the output of a tunable external cavity laser (ECL) and the other 39 channels were encoded on fixed wavelength DFB lasers. The optical 16QAM signals were generated by driving the modulator with four-level electrical signals in

#207821 - $15.00 USD Received 6 Mar 2014; revised 3 Apr 2014; accepted 5 Apr 2014; published 21 Apr 2014

the two quadrature arms, each of which were created by combining pairs of shifted (>600 symbols offset) binary 2^{15}-1 PRBS signals at 32 Gbaud with 6 dB amplitude difference [7]. The resulting bit rate was 256 Gb/s for the PM-16QAM signals, with a 28% total overhead above the nominal 200 Gb/s data rate. The assumed soft-decision FEC (SD-FEC) has a raw BER threshold of $2x10^{-2}$ corresponding to a Q-factor threshold of 6.25 dB [8]. After polarization multiplexing with 286 symbols delay between polarizations, the channels passed through a continuously varying polarization scrambler and then a piece of fiber with total chromatic dispersion of 800 ps/nm to de-correlate adjacent channels by more than 10 symbols prior to amplification and launch. The number of channels was limited to about 40 by the gain bandwidth of our high output power fiber amplifier at the span input.

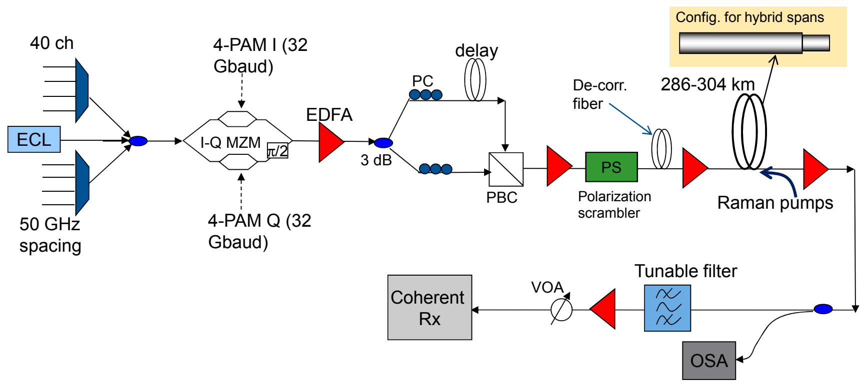

Fig. 1. Experimental system set-up. PS: polarization scrambler, PBC: polarization beam combiner, PC: polarization controller, OSA: optical spectrum analyzer, PAM: pulse amplitude modulation, Rx: receiver.

In the first experiment, the fiber span was comprised entirely of Corning® Vascade® EX3000 fiber. This fiber had average effective area of just under 152 μm² and the average fiber attenuation was 0.154 dB/km. The fiber dispersion was about 21 ps/nm/km at 1550 nm. For the second and third experiments, simple hybrid fiber span configurations were employed with some of the Vascade EX3000 fiber replaced at the end of the span by Vascade® EX2000 fiber, having an effective area of just over 110 μm² and attenuation of about 0.158 dB/km. These configurations were investigated to increase the Raman gain in the span and thus increase the achievable span length.

Channels were selected for detection in a polarization- and phase-diverse digital coherent receiver with a free-running local oscillator with 100 kHz linewidth. The four signals from the balanced photodetectors were digitized by analog-to-digital converters operating at 50 Gsamples/s using a real-time sampling oscilloscope with 20 GHz electrical bandwidth. BER values were calculated via direct error counting of at least $2.5x10^{6}$ bits with offline digital signal processing steps including quadrature imbalance compensation, up-sampling to 64 Gsamples/s, chromatic dispersion compensation using a frequency-domain equalizer, digital square-and-filter clock recovery, polarization demultiplexing and equalization using a 21-tap adaptive butterfly structure with filter coefficients determined by a radius-directed constant modulus algorithm (CMA) [9] following pre-convergence using a standard CMA, carrier frequency offset using a spectral domain algorithm, and blind search carrier phase recovery [10]. We also employed a blind cycle-slip detection and correction technique that is helpful in conditions with high BER values [11].

The characteristics and back-to-back performance of the PM-16QAM transmitter and coherent receiver were described more fully in a previous publication [12]. In ref. 12, we also demonstrated that modulation of all channels with a single modulator has negligible effect on performance since adjacent channels are de-correlated (by more than 10 symbols here) before launch and are then quickly de-correlated further during transmission. Furthermore, the optical spectrum of the 16QAM signal generated was sufficiently narrow such that the transmitter configuration incurred insignificant penalty from linear crosstalk.

3. Experimental transmission results

As mentioned above, the fiber span in the first experimental configuration was 286 km long and was comprised homogeneously of Vascade EX3000 fiber. The total span loss of this system was about 44.5 dB including 19 splices. The maximum Raman ON/OFF gain achievable with three Raman pump wavelengths at 1427 nm, 1443 nm, and 1461 nm was just over 14 dB. The pumps had polarization diversity and the maximum total pump power available was a little over 1 W. For the second configuration studied, we adopted a simple two-part hybrid fiber span construction in which 50 km of Vascade EX2000 was spliced at the end of 242 km of Vascade EX3000 fiber for a total span length of 292 km. This system had a total span loss of about 45.5 dB including 14 splices. Splice loss between the two fiber types was ≤0.2 dB. With this configuration the maximum Raman gain increased to a little over 21 dB due to the higher Raman gain coefficient of the Vascade EX2000 fiber with smaller effective area on the receiver side of the span. In both spans, the maximum Raman gain was limited by the available pump power. The 50 km length of the second fiber segment was calculated to produce nearly all of the additional Raman gain possible within a fraction of a dB. In general, the Raman gain ratio of two fibers with the same material should scale as the ratio of pump wavelength effective length L_{eff} and the inverse ratio of A_{eff} for the two fibers, respectively. The relative effective areas of the two fiber types accounts for most of the difference in maximum Raman gain observed in the two span configurations.

With maximum Raman gain set in each system, we first measured the BER of a central channel in the middle of the channel plan as a function of channel launch power to find the optimal power. The 40 channels were launched into the span from the high-power amplifier output with a nominally flat spectrum. The optimal channel power for both systems was about 8.5 dBm. With the optimal channel power thus set, we also evaluated the system performance in terms of Q-factor value and the effective equivalent noise figure (NF) of the hybrid Raman/EDFA amplifier combination in the receiver as a function of Raman ON/OFF gain for the central channel. The Q-factor values were calculated from direct BER measurement and the effective equivalent NF was calculated from OSNR measurements. These results are shown in Fig. 2. As expected, the results show that both systems produced best performance operating with the maximum Raman gain available. The lowest effective NF at maximum Raman gain for the homogeneous span was about 0 dB, while it was about 1.4 dB for the hybrid fiber span system. Combined with the additional 1 dB extra loss from the extra 6 km of fiber, the longer span had a Q-factor advantage of about 0.2 dB compared to the shorter span.

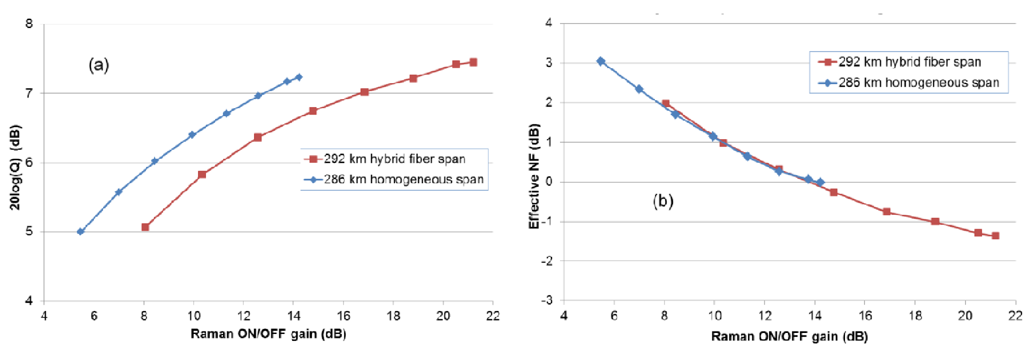

Fig. 2. (a) 20log(Q) as function of Raman ON/OFF gain for 286 km and 292 km systems. (b) Effective hybrid Raman/EDFA amplifier noise figure as function of Raman ON/OFF gain.

All 40 channels were measured for both systems with maximum Raman gain. The OSNR and Q-factor values are shown in Fig. 3. The average OSNR and Q-factor values for the 286 km homogeneous span were 21.8 dB and 7.1 dB, respectively, while they were 22.1 dB and 7.3 dB for the 292 hybrid fiber span, respectively. The minimum Q-factor margin over the FEC threshold for the 292 km span system was 0.7 dB. The larger Raman gain afforded by the simple hybrid fiber span produced overall better performance for the longer 292 km span system due to the lower effective NF of the hybrid amplifier which more than offset the higher span loss.

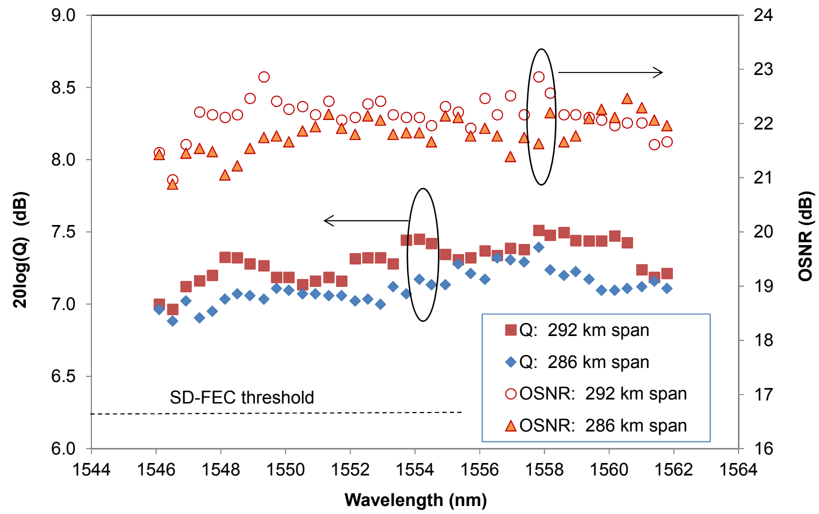

Fig. 3. OSNR and Q-factor values of all 40 channels for two 256 Gb/s unrepeatered span systems.

Finally, we extended the hybrid fiber span length to 304 km by adding another 12 km of Vascade EX2000 fiber at the span end. This increased the total span loss to about 47.4 dB. The maximum measured Raman ON/OFF gain was less than 0.4 dB higher than for the 292 km span, thus confirming that the second configuration did in fact achieve nearly all of the potential Raman gain possible. Modeling also showed that virtually all of the Raman gain occurred in the 62 km segment of Vascade EX2000 fiber at the span end.

To achieve successful transmission of all 40 channels over 304 km with Q values at least 0.5 dB above the FEC threshold, we employed a digital backpropagation (DBP) technique to mitigate intra-channel nonlinear impairments [13,14]. The algorithm was based on solving the Manakov equation in the absence of polarization mode dispersion (PMD) and polarization dependent loss (PDL) [15], using the split-step Fourier method with a symmetrized operator scheme [16]. Each WDM channel was processed separately to compensate for chromatic dispersion and self-phase modulation accrued in the transmission fiber. The Q-factor values for a central channel as a function of channel power over this span, with and without the nonlinear compensation, are shown in Fig. 4(a). The optimal channel power with the DBP was close to 10 dBm for this system. Figure 4(b) shows the performance improvement in terms of the Q-factor as a function of the number of spatial steps in the split-step Fourier method for a middle channel. The point at zero steps corresponds to linear compensation alone. We observe that almost all potential improvement can be obtained by solving the Manakov equation with 10 or fewer equal segments, although a single step appears to provide essentially no improvement.

The Q-factor values for all 40 channels launched at the optimal power are shown in Fig. 5 along with the Q-factor improvement (ΔQ) provided by the DBP. The average ΔQ was 0.45 dB. With DBP, the average Q-factor value was 7.0 dB, and the minimum margin above the FEC threshold for all channels was 0.5 dB. The improvement ΔQ from the DBP appears to be greater for shorter wavelengths. This may be due to increasing dispersion and decreasing

#207821 - $15.00 USD Received 6 Mar 2014; revised 3 Apr 2014; accepted 5 Apr 2014; published 21 Apr 2014

nonlinear coefficient γ as a function of wavelength. We note that the benefit of using DBP in an unrepeatered coherent optical communication system was briefly studied previously [17]. In that particular experiment, 40 WDM channels carrying 112 Gb/s PM-QPSK were transmitted over 302 km of SSMF using hybrid EDFA/Raman amplification but the DBP was not found to improve the average system performance.

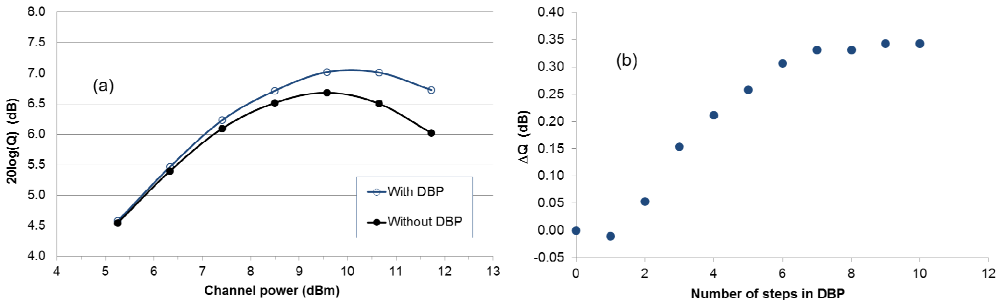

Fig. 4. 304 km span transmission: (a) Q-factor vs. channel power for a center channel. (b) Q improvement ΔQ as a function of number of steps in DBP algorithm for a central channel.

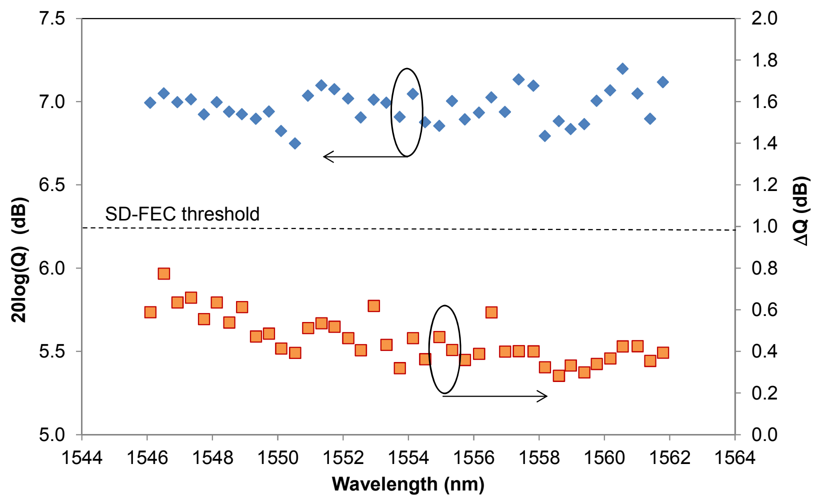

Fig. 5. Q-factor values and ΔQ produced by DBP algorithm for all 40 channels in 304 km span transmission system.

4. Summary and conclusions

We have demonstrated 40x256 Gb/s PM-16QAM transmission over unrepeatered spans of length 286 km (homogeneous span), 292 km (hybrid fiber span), and 304 km (hybrid span and DBP). The simple two-segment hybrid span configurations enabled a reduction in the overall effective noise figure of the Raman/EDFA amplifier combination by about 1.5 dB compared to the homogeneous fiber span. Some further improvement may have been possible with a hybrid span including more fiber segments [1,18], but the focus of these experiments was on system and span simplicity. These reach lengths attained were enabled by advanced optical fiber and used only simple first-order backward-pumped Raman and EDFA amplification. The longest link studied was also enabled by the use of DBP nonlinear compensation in the receiver which produced an average Q improvement of about 0.45 dB.

Acknowledgment

The authors would like to thank Michal Mlejnek for helpful modeling and discussions.