TRANSMISSION OVER UNREPEATERED 85 dB FIBER LINK USING ADVANCED MODULATION FORMAT

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Abstract: Unrepeatered transmission of 6 x 50 Gb/s over 85 dB large area core fiber, using co-propagating Raman amplification and a Rx Remote Optically Pumped Amplifier (Rx ROPA) with a 3rd order cascaded pumping, is reported. An advanced modulation format, Matrix-enhanced BPSK (ME-BPSK), has been used in the test and shows more than 1 dB gain on reach over BPSK.

1. INTRODUCTION

Unrepeatered transmission is a cost-effective solution to target communication between two sites where it is not desirable, and may not be possible, to add in-line active elements. In some applications, it shows great value even as the systems trade off capacities for reach (overall loss of the link) such as subsea connections between sparsely-populated islands or terrestrial links through hostile areas. As technology continues to progress, the loss of propagation possible for commercial operation without active elements continues to improve. Recent developments in large core fiber [1], high power Raman amplification [2,3,4], enhanced ROPA amplification configuration [3,5,6] and advanced coherent technologies [7] all play important roles to benefit unrepeatered transmission and further extend reach. In this paper, we report a 6 x 50 Gb/s transmission over an 85 dB unrepeatered link with large area core fiber using co-propagating Raman pumping amplification and ROPA with 3rd order Raman pumping [2,3]. In the experiment, we demonstrate an advanced modulation format, Matrix-Enhanced BPSK (ME-BPSK), which provides the same spectral efficiency of BPSK with the same baud rate and channel spacing, but with more than 1dB reach improvement.

Capacity calculation indicated that BPSK modulation with 20% overhead soft decision FEC can still be on the order of 2.5 dB away from the Shannon bound. One method of obtaining some of that performance gap is to expand constellation size to QPSK by way of Trellis Coded Modulation as an example [7]. With the use of soft decision FEC with large net coding gain, convolutional inner code is viewed as inconvenient and cumbersome in implementation. A more preferred approach is through a short length block code in what is referred to as ME-BPSK. This inner code when decoded with maximum likelihood decoding can provide significant performance gain even near the soft decision FEC threshold. This translates into increased reach and performance of channels at a lower optical signal-to-noise (OSNR) than BPSK. It is worth noting that ME-BPSK utilizes eight dimensions of the optical field. The performance comparison is shown in

Figure 1, against BPSK modulation in additive white Gaussian noise (AWGN) channel.

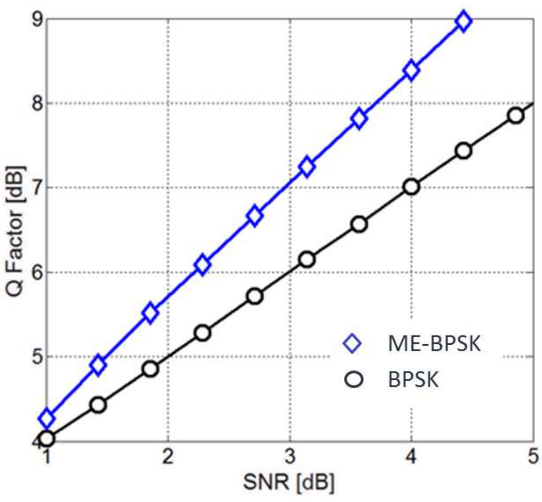


Figure 1: Performance comparison of ME-BPSK and BPSK in AWGN

2. EXPERIMENTAL SETUP

The testing setup is shown in **Erreur ! Source du renvoi introuvable.**. Fiber used in the tests is TeraWave large area core fiber, which features 130 µm^2 effective area and 0.184 dB/km attenuation. In the tested link, signals from transmitting terminal through a booster amplifier launched into 110 km TeraWave fiber, with a 4-wavelength multiplexed laser diode co-pump providing co-propagating Raman amplification. The signals then pass through an Rx ROPA, followed by 100 km of TeraWave fiber before a pre-amplifier at the receiving terminal. The ROPA is counter-directionally pumped by a 3rd order cascaded Raman pump [3]. Two VOAs used to emulate and optimize spans are placed just before (VOA1) and after Rx ROPA (VOA2), where the co-pump and counter Raman pumps are depleted and the signal powers are low enough to have negligible nonlinearities. In the experiments, the reach in dB is quoted as from co-pump output to ROPA input including VOA1 as 1st section loss, and from ROPA output to counter pump input including VOA2 as ROPA section loss. All the losses were calibrated and measured at 1550 nm.

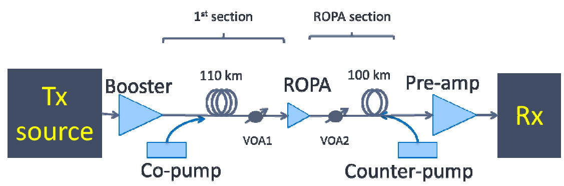
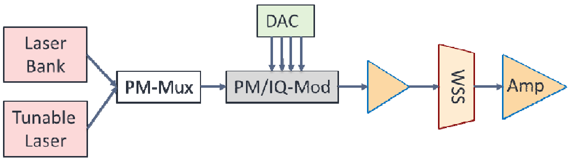
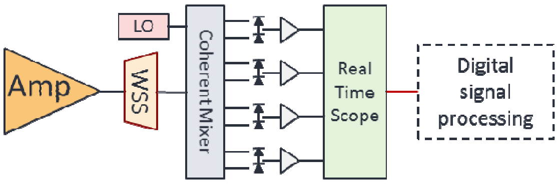


Figure 2: Link setup

The transmitter of the test setup is shown in Figure 3(a). The light source consisted of a laser bank and a tunable laser. Six lasers from the laser bank at frequencies from 191.75625 THz to 192.74375 THz with about 187.5 GHz spacing were selected to construct the testing spectrum. The tunable laser was used for bit error ratio (BER) measurement. During the tests, the tunable laser was switched to the testing frequency and the corresponding laser in the laser bank was turned off. All the lasers were combined through a polarization-maintained mux, then routed to a dual polarization 32 GHz IQ modulator with linear driver driven by a high-speed digital-to-analog convertor (DAC), where both 50 Gb/s ME-BPSK and BPSK with overhead was applied. Then the modulated signals were amplified to compensate most mux and modulator insertion losses and passed through a wavelength selective switch (WSS), where the proper filtering and pre-emphasis was applied for optimizing channel performance. Before entering the booster, another optical amplifier was used to set to the proper power level.



(a) Transmitter



(b) Receiver

Figure 3 Transmitter/Receiver setup

At the receiver end, as shown in Figure 3(b), the amplified signals were filtered by a WSS to select the testing channel into the coherent receiver with off-line processing. The coherent receiver consists of a typical coherent mixer with a tunable local oscillator and four balanced detectors. The resulting electrical waveforms were digitalized by a 50 GSample/s real-time scope with 16 GHz bandwidth for offline signal processing.

3. EXPERIMENTAL RESULTS

The link was optimized for best minimum Q among 6 testing channels with suitable margin from FEC limit for operation by means of adjusting booster launch power, power of co-pumps, seed power and pump power of the 3rd order counter-pump and pre-emphasis at Tx end WSS. At final testing, the booster had 11.5 dBm total power at input of the multiplexed laser diode Raman co-pump module, which worked with pump wavelengths of 1400 nm, 1410 nm, 1426 nm and 1454 nm, respectively, at total launch power of 2 W. The 3rd order counter pump Raman was set as 70 mW for the seed and 5300 mW for the main output. The simulated power profiles of the experiment is shown in Figure 4. Propagation of the Raman co-pumping pump wavelengths (propagating from left to right) and those of the 3rd order ROPA pumps (right to left), along with one of the signal channels are illustrated. The distance shown in the chart is the equivalent distance translated from span loss at 0.184 dB/km. The 1485 nm pump power delivered to the ROPA was 8.2 dBm which provided a ROPA gain of 22 dB and Noise Figure of 5.33 dB. The On/Off Raman gain provided by the ROPA pump was 17.5 dB for the shortest signal wavelength and 18.5 dB for the longest. The co-propagating Raman gain was ~18 ± 0.3 dB.

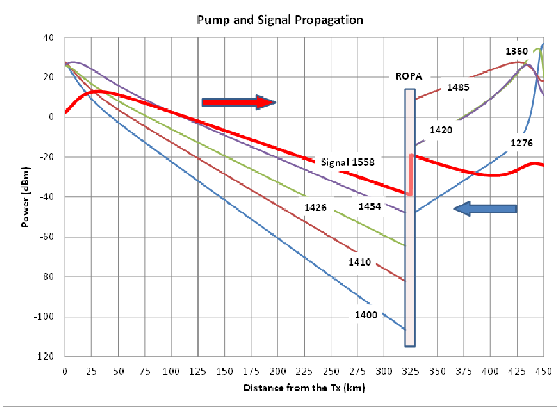


Figure 4 Simulated Power Profile

To compare performance in the experiments, both ME-BPSK and BPSK formats were tested with similar Tx launch profile. The only variables in the tests were 1st section loss and ROPA section loss. With more than 2 dB Q margin for the worst channels with ME-BPSK format, the 1st section loss was set to 59 dB and ROPA section loss was 25 dB, a total 84 dB link loss. A similar but slightly worse Q margin was obtained for the BPSK format, while 1st section loss at 58 dB and ROPA section loss at 25 dB, a total 83 dB link loss. Both relative Qs to the FEC limit are presented in the Figure 5. It clearly shows that the ME-BPSK outperforms the BPSK for more than 1 dB reach with suitable margin above FEC limit. Furthermore, with the same link settings (including Tx pre-emphasis and amplification across link), we extended the 1st section loss to 60 dB and ROPA section loss remained 25 dB, which gave total span loss of 85 dB. We measured both Qs and OSNRs for all six channels with ME-BPSK format, and the results are shown in Figure 6. All Qs were above FEC limit by at least 1 dB except the channel at 191.94375 THz, which was 0.8 dB above FEC limit. Since the Qs and OSNRs hold similar trend across frequency, it is possible to improve the worst channel Q by adjusting pre-emphasis at Tx WSS, and then the system could have all 6 channels above FEC limit by at least 1 dB after 85 dB transmission loss.

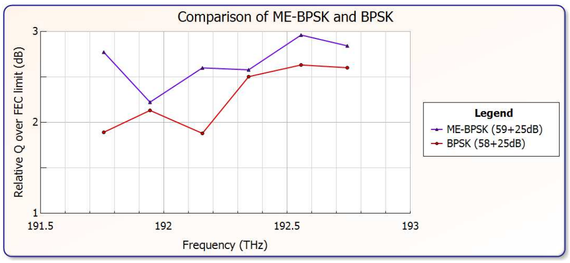


Figure 5. Performance Comparison of ME-BPSK and BPSK

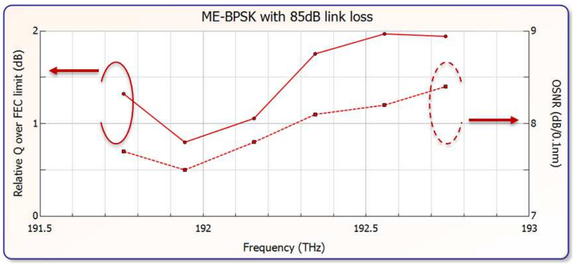


Figure 6. Q and OSNR of ME-BPSK in 85dB Link

4. CONCLUSIONS

Transmission of 6 x 50 Gb/s ME-BPSK over 85 dB unrepeatered link with large core fiber has been demonstrated using both a multiplexed laser diode pump for co-propagating Raman amplification and Rx ROPA with a 3rd order cascaded pumping. Performance of ME-BPSK and BPSK have also been compared. With suitable operational margin, ME-BPSK shows more than 1 dB gain over BPSK on reach in this unrepeatered link.

5. ACKNOWLEDGEMENTS

We would like to thank MPB Communications for allowing us to demonstrate the advantages of ME-BPSK on unrepeatered link by using their equipment.

6. REFERENCES

[1] B. Zhu, P. Borel, K. Carlson, X. Jiang, D. Peckham, R. Jr. Lingle., “Unrepeatered transmission of 3.2-Tb/s (32 × 120-Gb/s) over 445-km fiber link with Aeff managed span,” Proc. OFC 2013, OTu2B.2. (2013)

[2] S.Papernyi, V.Karpov, W.Clements, “Third-Order Cascaded Raman Amplification,” Proc. OFC 2002, Post deadline FB4 (2002).

[3] V.Karpov, S.Papernyi, V.Ivanov, W.Clements, T.Araki, Y.Koyano, “Cascaded pump delivery for remotely pumped Erbium doped amplifiers,” Proc. SubOptic 2004, We.8.8. (2004).

[4] H. Bissessur, S. Etienne, P. Bousselet, S. Ruggeri, D. Mongardien, “6 Tb/s Unrepeatered Transmission of 60 x 100 Gb/s PDM-RZ QPSK channels with 40 GHz Spacing over 437km”, Proc. ECOC’12, Mo.1.C.3 (2012).

[5] S.B.Papernyi “Inline Pump Sharing Architecture for Remotely-Pumped Pre-

and Post-Amplifiers” Proc. OFC 2007, OThL4. (2007).
[6] D. Chang, P. Perrier, H. Fevrier, T. Xia, D. Peterson, G. Wellbrock, S. Ten, C. Towery, G. Mills, “Unrepeatered 100G Transmission Over 520.6 km of G.652 Fiber and 556.7 km of G.654 Fiber With Commercial Raman DWDM System and Enhanced ROPA”, IEEE J of Lightwave Tech., VOL. 33, NO. 3, FEBRUARY, 2015
[7] P. Mertz, X. Yang, E. Burmeister, H. Sun, S. Grubb, S. Papernyi, “TCM-QPSK Provides 2dB Gain Over BPSK In Festoon Links”, Proc. SubOptic 2013, TH2C-3, (2013)