8 x 120 Gb/s unrepeatered transmission over 444 km (76.6 dB) using distributed Raman amplification and ROPA without discrete amplification

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Abstract: Unrepeatered transmission of 8 x 120 Gb/s over 444.2 km (76.6 dB) and multi-rate transmission of 8 x 120 Gb/s and 9 x 10.7 Gb/s over a 75.4 dB span have been demonstrated with off-line digital processing for the coherent 120 Gb/s channels. Transmission of 2 x 120 Gb/s with 7 x 12.5Gb/s over 78 dB is also demonstrated with a real-time ASIC processor. All transmission results have been achieved using standard effective-area pure-silica-core fiber using forward and backward distributed Raman amplification and remotely-pumped erbium fiber. ASIC real-time processed results match well with off-line processing.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.1660) Coherent communications.

References and links

1. John D. Downie, Jason Hurley, John Cartledge, Sergey Ten, Scott Bickham, Snigdharaj Mishra, Xianming Zhu, and Andrey Kobyakov, "40 × 112 Gb/s Transmission over an Unrepeatered 365 km Effective Area-Managed Span Comprised of Ultra-Low Loss Optical Fibre," Proc. ECOC 2010, Paper We.7.C.5.
2. D. Mongardien, P. Bousselet, O. Bertran-Pardo, P. Tran, H. Bissessur , "2.6Tb/s (26 x 100 Gb/s) Unrepeatered Transmission Over 401km Using PDM-QPSK with a Coherent Receiver " Proc. ECOC 2009, Paper 6.4.3.
3. A. Puc, D. Chang, W. Pelouch, P. Perrier, D. Krishnappa, S. Burtsev, "Novel Design of Very Long, High Capacity Unrepeatered Raman Links" Proc. ECOC 2009, Paper 6.4.2.

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1. Introduction

Following the trend in terrestrial transmission systems toward 100 Gb/s channel bit rates, it is clear that 100 Gb/s channels will also be required in unrepeatered systems. Upgrades of legacy optical networks are typically preferable to green field installations and thus the addition of 100 Gb/s services will often occur over existing fiber types. The majority of unrepeatered cables consists of pure-silica-core (PSC) fiber with 76 μm^2 effective core area and often includes a remote optically pumped amplifier (ROPA) for longer spans. In addition, it is desirable that the high bit rate systems be able to support simultaneous transmission of legacy 10 Gb/s OOK channels. Recent work has demonstrated a 365 Km span system with 40 x 112 Gb/s over long unrepeatered spans, but relied on a complex span configuration which required 3 different types of fiber [1]. Other work has achieved transmission of 26 x 100 Gb/s over 401 km with a ROPA and a third-order Raman pumping scheme [2], however it required very strong pump power (> 5W) into large effective area line fiber. At the time of this writing, there have been no demonstrations of multi-rate 10 Gb/s and 100 Gb/s transmission together in an unrepeatered system.

Here we report 8 x 120 Gb/s unrepeatered transmission over 444.2 km (76.6 dB) of standard PSC fiber and mixed transmission of interleaved 8 x 120 Gb/s and 9 x 10.7 Gb/s over a 75.4 dB span by combining bi-directional distributed Raman amplification with a ROPA. This configuration does not require any discrete amplifier for 100 Gb/s transmission which simplifies system operation and maintenance. We also report unrepeatered transmission results using 100G modules with a real-time ASIC processor. 2 x 120 Gb/s transmission over 79.7 dB span and multi-rate 2 x 120Gb/s and 7 x 12.5 Gb/s transmission over a 78.0 dB span have been demonstrated.

2. Experiment Description

2.1 System with off-line processing 100G setup.

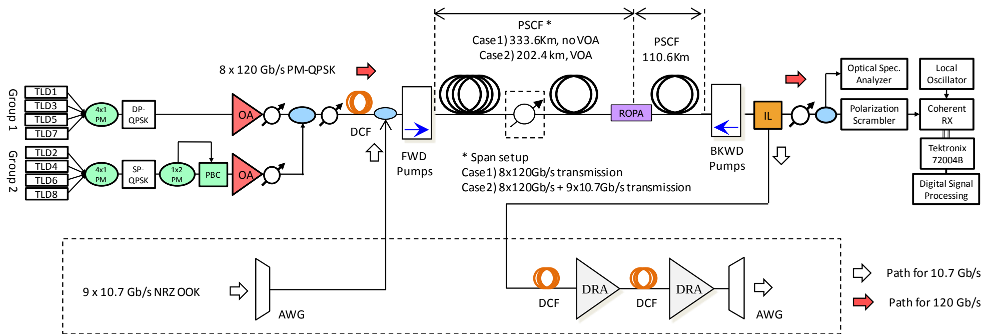

Fig. 1. System configuration with off-line processing 100G setup. Equipment in dashed boxes is used for mixed 10 Gb/s and 100 Gb/s transmission.

The first experimental system setup is depicted in Fig. 1. To generate 120 Gb/s PM-NRZ-QPSK signals, 8 Tunable Laser Diodes (TLD) with a wavelength range from 1554.5 nm to 1560.2 nm (100 GHz spacing) are separated into two groups and combined by 1x4 PM coupler. The channels in group 1 are modulated by PM-QPSK modulator and group 2 is modulated by single-polarization QPSK modulator and then split, combined by PBC to emulate PM-QPSK signals. All the channels are modulated at 120 Gb/s. This bit rate accounts for the 15% overhead of the Soft Decision Forward Error Correction (SD-FEC), which corrects a BER of 1.9 x 10^{-2} to less than 10^{-15}. The Optical Amplifiers (OA) are used in this configuration to compensate the loss of the 1x4 PM combiner and 3dB coupler (which will not be required in a commercial system). At the receiver end, 120 Gb/s channels are routed through a polarization scrambler at 2000 rad/s before the polarization-diverse coherent receiver to test the capability to track the polarization. The resulting electrical waveforms are digitized by analog-to-digital converters operating at 50 G-samples/s with a 16-GHz electrical bandwidth and stored for off-line digital processing. The 10 Gb/s signals are negatively chirped widely-tunable transponders with enhanced forward error correction (E-FEC, 7% overhead, Q threshold of 9.4 dB) at 10.7 Gb/s. The forward and backwards Raman pumps are both commercially available high power distributed pump modules. The pump lasers were polarization balanced for low polarization dependent gain and wavelength multiplexed into the line using a standard high power connector (Diamond E2000PS). The typical Relative Intensity Noise (RIN) of the pump laser diodes is -105 dB/Hz. The pumps ranged in wavelength from 1420 to 1500 nm.

The link consists of standard PSC fiber (SEI “Z” fiber) with 76 μm^2 effective area. For the 8 channels x 120 Gb/s transmission, a total length of 444.2 km of PSC fiber is used with a span loss of 76.6 dB (including high power connectors, corresponding to a mean fiber attenuation of 0.171 dB/km including fiber splices). The cumulated chromatic dispersion is close to 8400 ps/nm at the signal wavelengths. The ROPA is designed to provide high gain (> 25dB) and consists of 21 m of erbium-doped fiber placed at 110.6 km from the receiver end. To provide more gain and remove the requirement for a discrete amplifier, the ROPA has a longer fiber length and is located closer to the backward pumps compared to the previous experiment [3]. The configuration was optimized with approximately -650 ps/nm of dispersion pre-compensation (at the transmit side of the span), a signal launch power of -9 dBm/ch (average), and with distributed pump power of 1400 mW for the forward and 1350 mW for the backward Raman pumps.

For mixed 8 x 120 Gb/s and 9 x 10.7 Gb/s transmission, the link consists of 313 km PSC fiber with a VOA. The VOA is used to provide a flexible span loss change and is located at the middle of the span where the signal and pump powers are very low to prevent any nonlinear penalty or Raman gain change. Total insertion loss of VOA is set to be 21.3 dB, making the total span loss 75.4 dB. The ROPA and backward Raman pumps remain the same as the 8 x 120 Gb/s transmission experiment, while the forward pump power is increased by 50 mW to offset the decrease in forward Raman gain caused by the additional 10 Gb/s channels. The 9 channels x 10.7 Gb/s are combined with the 120 Gb/s channels using a 3 dB coupler at transmit side and separated using an interleaver (IL) at the receiver side. Dispersion compensation modules (DCM) and two discrete Raman amplifiers (DRA) are used at the receiver side to compensate for chromatic dispersion of the 10.7 Gb/s channels.

2.2 System with real-time ASIC processing 100G module.

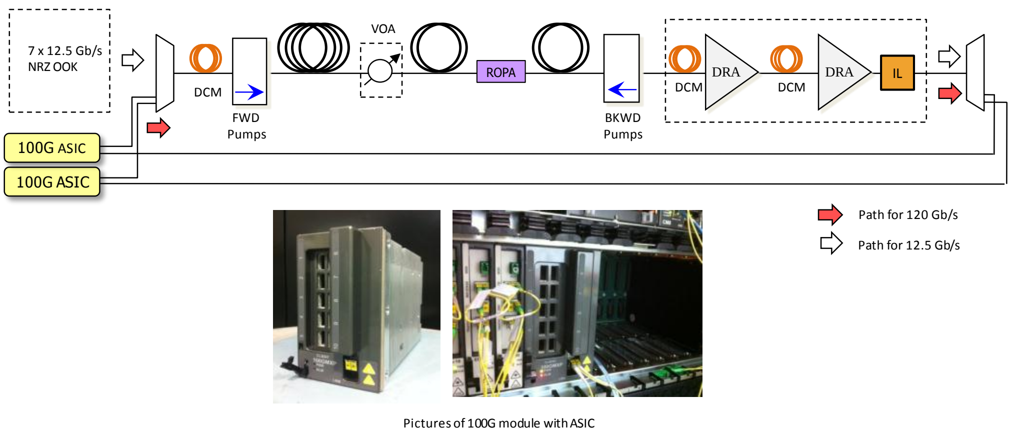

Fig. 2. System configuration with real-time ASIC processing 100G module. Equipment in dashed boxes is used for mixed 10 Gb/s and 100 Gb/s transmission. Insert pictures show ASIC 100G module under test.

The second experimental system setup with real-time processing 100G modules is shown in Fig. 2. The same span with VOA and forward and backward distributed Raman pumps is used to make a direct comparison with the off-line processed results. For mixed 2 x 100 Gb/s and 7 x 12.5 Gb/s transmission, dispersion compensation modules (DCM) and two discrete Raman amplifiers (DRA) are used. In this setup, the 100G channels travel the exact same path as the 10G channels with dispersion compensation optimized for the 10 Gb/s channels. The 10 Gb/s channels are widely-tunable transponders with 25% forward error correction (UFEC, Q threshold of 7.4 dB) at 12.5 Gb/s line rate (not available in the earlier measurements). The insert in Fig. 2 shows pictures of the OIF compliant 100G card which has a real-time ASIC processor and soft-decision FEC. The configuration was re-optimized with -680 ps/nm of dispersion pre-compensation (at the transmit side of the span), a signal launch power of -9.3 dBm/ch (average) for the 120 Gb/s channels and -12.4 dBm/ch (average) for the 12.5 Gb/s channels, and with distributed pump power of 1453mW for the forward and 1370 mW for the backward Raman pumps. This amount of dispersion pre-compensation was approximately optimal for both the 10G and 100G channels.

3. Transmission Results

3.1 Transmission results with off-line processing 100G setup.

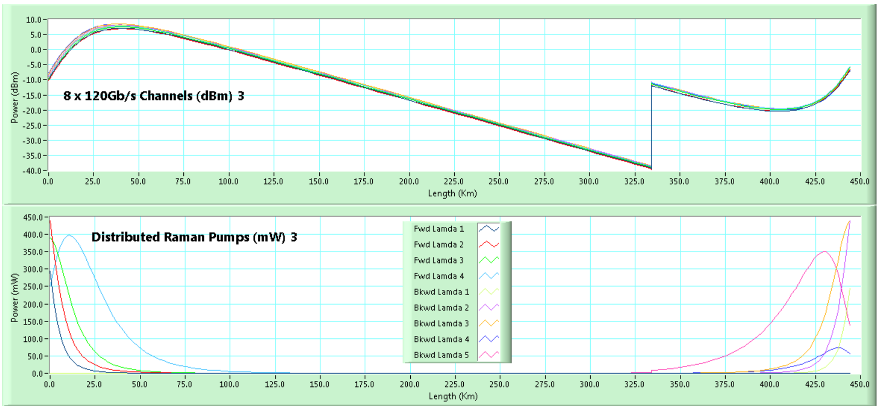

Fig. 3. Power distribution of signals and pumps

Fig. 3 shows the simulated power profiles for 8 channels x 120 Gb/s and associated Raman pump power distribution along the line fiber. Forward pumps provide 25 dB distributed Raman gain and backward pumps provide 28 dB from the ROPA and 25 dB from distributed Raman gain resulting in an overall gain of 78 dB (1.2 dB more than the span loss). Since the coherent detection of the 120 Gb/s channels does not require any optical dispersion compensation, the system can operate without any discrete amplifier which would normally be needed to compensate for DCM loss.

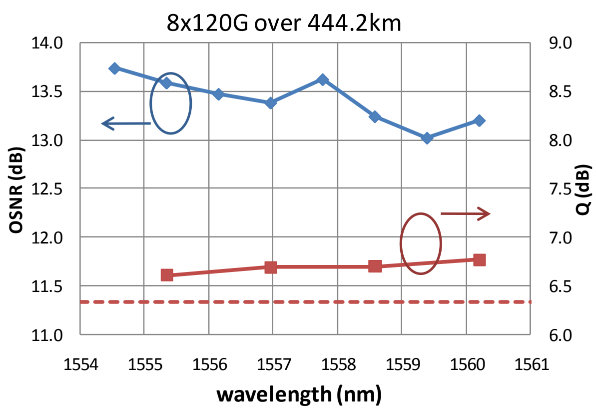

Fig. 4. Measured OSNR (0.1 nm RBW) and Q.

Measured OSNR and Q values are shown in Fig. 4; the average OSNR of 8 channels is 13.4 dB. The Q could be measured for only 4 channels in group 1 at a time since the high speed MUX of the modulator in group 2 has to operate beyond the specified MUX's rating to generate 120 GB/s data (which causes Q measurement instability). However, the group 1 channels were tuned to all of the 8 wavelengths used and thus all 8 channels are above the (pre-SD-FEC) Q threshold of 6.4 dB. There is no performance difference with and without the polarization scrambler before the receiver.

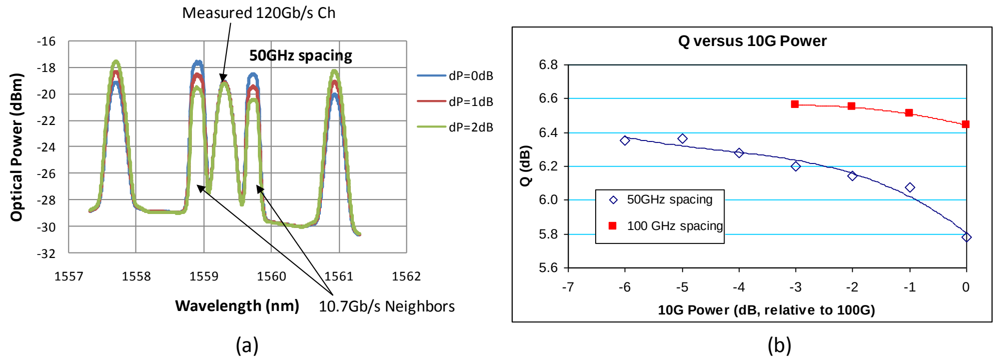

Fig. 5. (a) spectra of mixed 10.7 and 120 Gb/s signals,
(b) Q of 120 Gb/s versus relative signal power of adjacent 10.7 Gb/s channels.

For the transmission of a mixed 120 Gb/s and 10.7 Gb/s, we have analyzed the influence of relative signal power of neighboring 10.7 Gb/s channels to the Q value of 120 Gb/s channels. Fig. 5 (a) shows the spectra measured for several cases. The power of the adjacent 10.7 Gb/s signals (separated by 50GHz) has been changed while keeping the power of 120 Gb/s channel in the middle same. Since the gain by forward Raman pumping varies with total signal power, the power of two additional 120 Gb/s channels (outside channels in Fig. 5a) are adjusted to keep the forward Raman gain constant. Fig. 5 (b) shows the Q versus relative 10.7 Gb/s signal power at different channel spacing. For the 50-GHz channel spacing case, the cross-talk penalty becomes negligible when the signal power of 10.7 Gb/s channels is 4dB less than 120 Gb/s channel. When the 10.7 Gb/s channels are separated by 100 GHz, cross-talk penalty is measured to be less than 0.2 dB even when the signal power of 10.7 Gb/s channels is same as the 120 Gb/s channel.

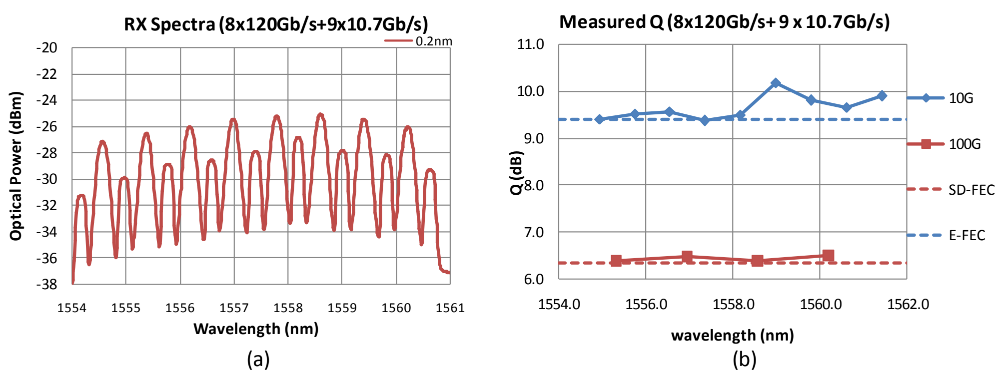

Fig. 6. (a) WDM spectrum of the multi-rate transmission and
(b) measured Q (8 x 120 Gb/s and 9 x 10.7 Gb/s).

Fig. 6 shows the results of multi-rate transmission (8 x 120 Gb/s and 9 x 10.7 Gb/s) with 50-GHz spacing over a 75.4 dB PSC fiber span. The signal power of the 10.7 Gb/s channels is about 4.5 dB less than the 120 Gb/s channels. All 9 channels at 10.7 Gb/s have Q value above the FEC threshold of 9.4 dB and the selected 4 channels at 120 Gb/s have a Q value more than the SD-FEC threshold of 6.4 dB.

3.2 Transmission results with real-time ASIC processing 100G module.

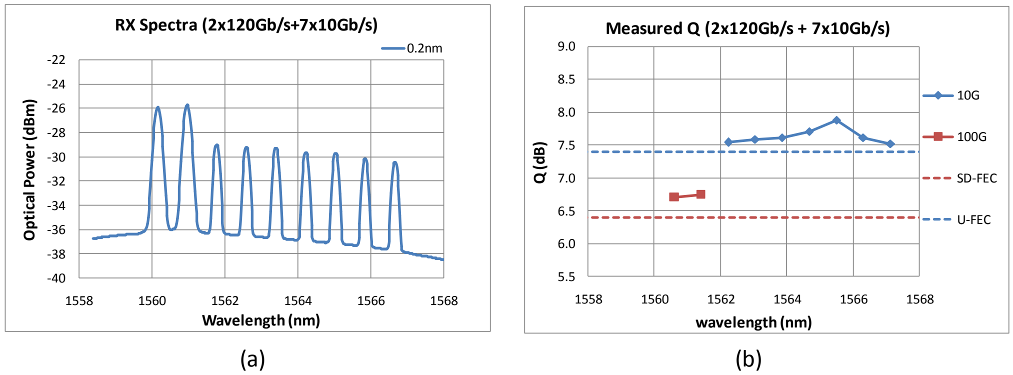

Fig. 7. (a) WDM spectrum of the multi-rate transmission and (b) measured OSNR and Q (8 x 120 Gb/s and 9 x 10.7 Gb/s).

Fig. 7 shows the results of multi-rate transmission (2 x 120 Gb/s and 7 x 10.7 Gb/s) over a 78.0 dB PSC fiber span. All the channels are spaced at 100 GHz. The signal power of the 12.5 Gb/s channels is about 4.5 dB less than the 120 Gb/s channels. Measured OSNR and Q values are shown in Fig. 7 (b): the 2 x 120 Gb/s channels have an average OSNR of 14.0 dB and minimum Q of 6.7 dB; the 7 x 12.5 Gb/s channels have an average OSNR of 9.4 dB and minimum Q of 7.6 dB. All the channels are error free after FEC.

3.3 Max span loss supported versus 100G capacity.

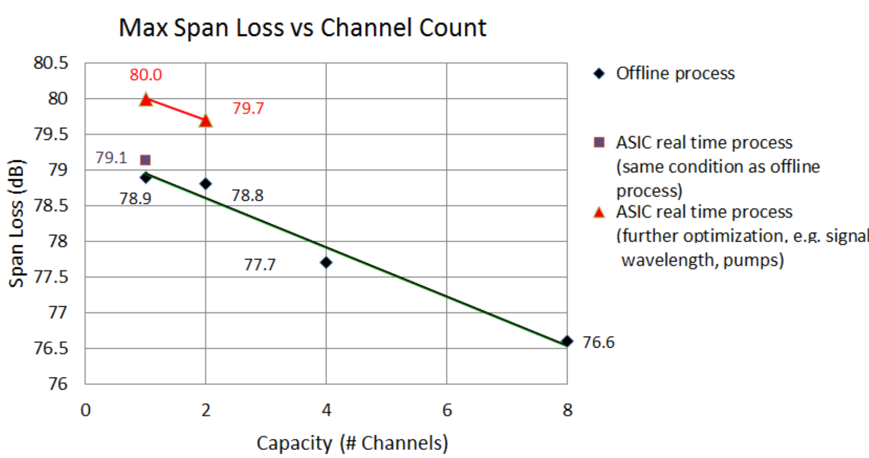

Fig. 8. Max Span loss vs. 100G Channel Count.

Fig. 8 plots the maximum span loss supported versus 100G capacity over the span consisting of 313 km PSC fiber with a VOA. A span loss of 78.9 dB can be supported with a single off-line processed 100 Gb/s channel. A single channel with real-time ASIC processing module using the same signal and pump conditions results in a span loss of 79.1 dB, in excellent agreement with the off-line processing result. Thanks to the wider tuning range of the real-time ASIC 100G module, further improvement in performance was achieved by using longer signal wavelengths and re-optimized pump powers (red triangle symbols in Fig. 8).

4. Conclusion

Unrepeatered transmission of 8 x 120 Gb/s PM-NRZ-QPSK signal over 444.2 km (76.6dB) of standard PSC fiber has been achieved using commercially available distributed Raman pump modules and a ROPA without any discrete amplification. Multi-rate transmission of interleaved 8 x 120 Gb/s and 9 x 10.7 Gb/s is demonstrated to show that coherent 100 Gb/s channels can co-exist with legacy 10 Gb/s OOK channels. Unrepeatered 120Gb/s transmission with real-time ASIC digital processing validates previous off-line processing results. Multi-rate of 2 x 120 Gb/s (real-time processing) and 7 x 12.5 Gb/s over a 78.0 dB span has been also successfully transmitted.