

8 x 120 Gb/s Unrepeated Transmission over 444 km (76.6 dB) using Distributed Raman Amplification and ROPA without Discrete Amplification

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Abstract: Unrepeated transmission of 8 x 120 Gb/s PM-NRZ-QPSK signal over standard effective-area pure silica core fiber of 444.2 km (76.6 dB) is achieved using only forward and backward distributed Raman amplification and remotely-pumped erbium fiber. Multi-rate transmission of 8 x 120 Gb/s and 9 x 10.7 Gb/s over 75.4 dB span is also demonstrated.

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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 needed in unrepeated 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 unrepeated cables consists of pure silica core (PSC) fiber with $76 \mu\text{m}^2$ effective 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 120 Gb/s over long unrepeated 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 ($> 5\text{W}$) 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 unrepeated system. Here we report 8 x 120 Gb/s unrepeated transmission over 444.2 km (76.6 dB) of standard PSC fiber, 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 demonstrate mixed transmission of interleaved 8 x 120 Gb/s and 9 x 10.7 Gb/s over a 75.4-dB span, which is, to our knowledge, the first experimental result of multi-rate channels with 100 Gb/s transmission in an unrepeated system.

2. Experiment description

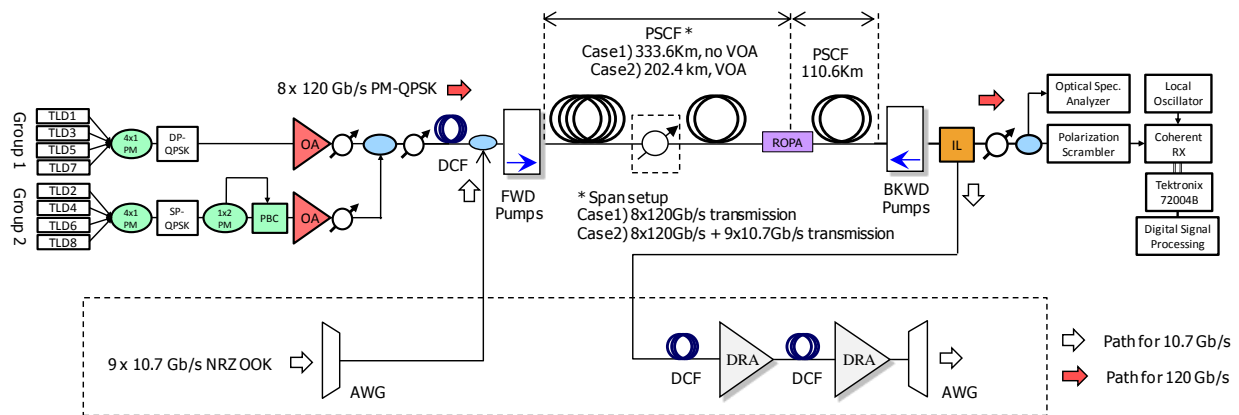


Figure 1. System configuration. Equipment in dashed boxes is used for case 2 (mixed 10 Gb/s and 100 Gb/s transmission).

The experimental system setup is shown in Fig. 1. To generate 120 Gb/s 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 and 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 1.9×10^{-2} to less than 10^{-15} . The Optical Amplifiers (OA) in this configuration are used 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. 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 (-500 ps/nm), widely-tunable transponders with enhanced forward error correction (E-FEC, 7% overhead) 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 link consists of standard PSC fiber (SEI “Z” fiber) with $76 \mu\text{m}^2$ 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. 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 1.4 W for the forward and 1.3 W 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 PSCF fiber with a VOA in the middle of the span. 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 3dB coupler at transmit side and separated using an interleaver (IL) at the receiver side. Dispersion compensation fiber (DCF) and two discrete Raman amplifiers (DRA) are used at the receiver side to compensate for chromatic dispersion of the 10.7 Gb/s channels.

3. Transmission Results

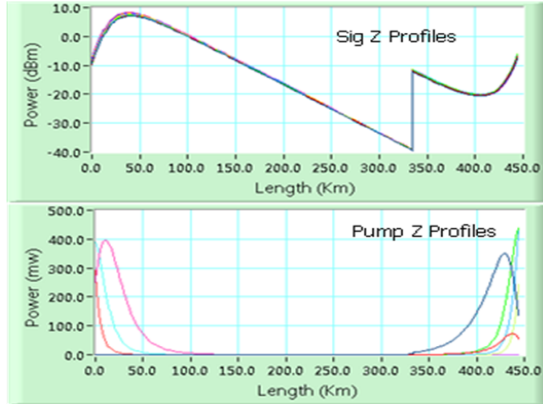


Figure 2. Power distribution of signals and pumps

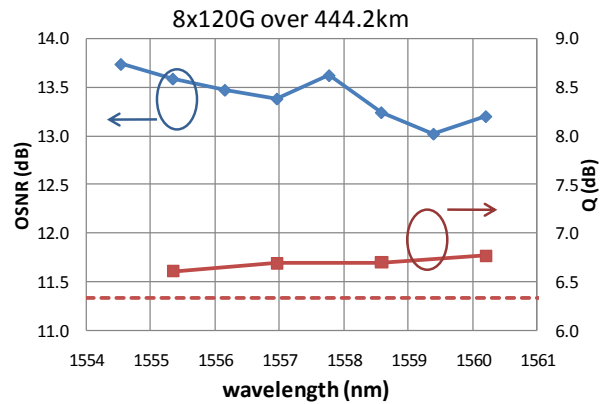


Figure 3. Measured OSNR (0.1 nm RBW) and Q

Fig. 2 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 (on-off) and backward pumps provide 28 dB from the ROPA and 25 dB from distributed Raman gain (on-off) resulting in an overall gain of 78 dB (1.2dB 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 is normally needed to compensate for DCF loss. Measured OSNR and Q values are shown in Fig. 3; the average OSNR of 8 channels is 13.4 dB. The Q could be measured for only 4 channels at a time, but these channels could be tuned to any of the 8 wavelengths used and thus all 8 channels are above the (pre-SD-FEC) Q threshold of 6.4 dB.

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. 4 (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. 4a) are adjusted to keep the forward Raman gain constant. Fig. 4 (b) shows the Q versus relative 10.7 Gb/s signal power at different channel spacings. 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 120 Gb/s channel.

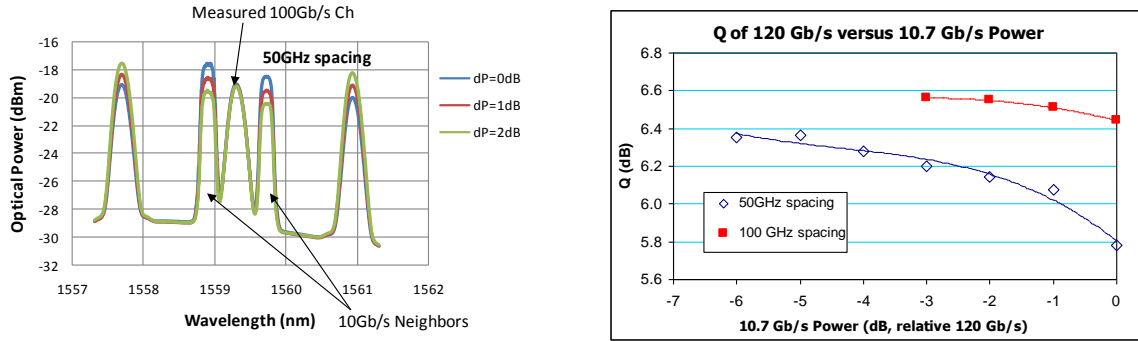


Figure 4 (a) spectra of mixed 10.7 and 120 Gb/s signals, (b) Q of 120 Gb/s versus relative signal power of adjacent 10.7 Gb/s channels

Fig. 5 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 dB less than the 120 Gb/s channels. All 9 channels at 10.7 Gb/s have Q value above the E-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.

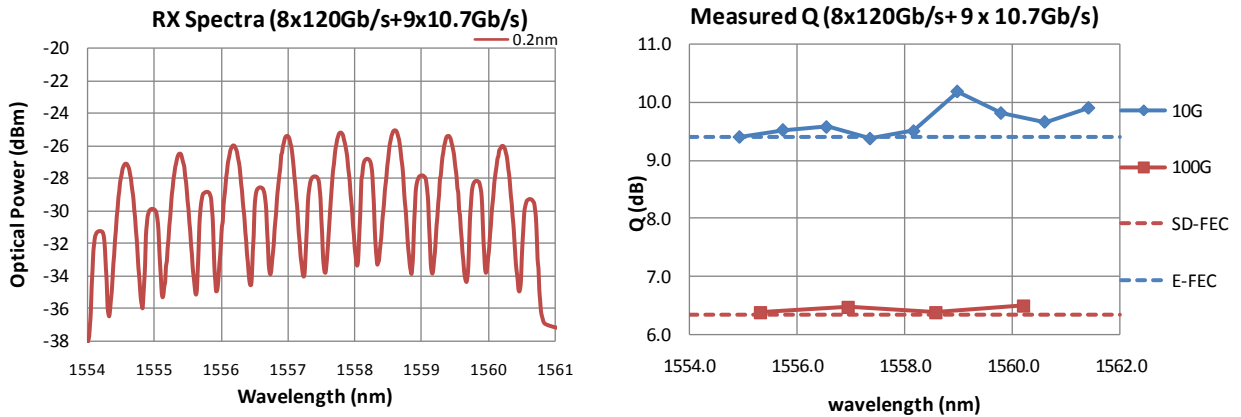


Fig. 5 (a) WDM spectrum of the multi-rate transmission and (b) measured OSNR and Q (8 x 120 Gb/s and 9 x 10.7 Gb/s).

4. Conclusion

Unrepeated 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 also demonstrated to show that coherent 100 Gb/s channels can co-exist with legacy 10 Gb/s OOK channels.

5. References

- [1] John D. Downie, Jason Hurley, John Cartledge, Sergey Ten, Scott Bickham, Snigdharaj Mishra, Xianming Zhu, and Andrey Kobaykov, "40 x 112 Gb/s Transmission over an Unrepeated 365 km Effective Area-Managed Span Comprised of Ultra-Low Loss Optical Fibre," in Proc ECOC' 2010, Paper We.7.C.5.
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