43Gbit/s NRZ-DPSK and RZ-DQPSK transmission over 1000km of G.652 ultra-low-loss fibre with 200km amplifier spans

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Abstract: We demonstrate 40x43Gbit/s NRZ-DPSK and RZ-DQPSK transmission over 1000km of ultra-low-loss G.652 fibre with 200km amplifier spacing. Hybrid contra-directional Raman-EDFA amplification and lumped dispersion management enables simple, cost-effective link design.

OCIS codes: (060.2330) Fiber optics communications; (060.4510) Optical communications; (190.4370) Nonlinear optics

1. Introduction

Raman amplification is a key technology for enabling long distance, high-speed, and high-capacity optical transmission [1]. Although all-Raman amplification offers extended bandwidth [2], in many cases a more cost-effective and energy-efficient design approach is based on hybrid Raman-EDFAs [3,4]. WDM systems using hybrid Raman-EDFAs have been used to demonstrate ultra-long-haul transmission with standard amplifier spans of 100km [4], and to promote "hut-skipped" link design, in which the greater OSNR margin available due to Raman amplification enables savings via increased amplifier spacing [5,6]. To date, demonstrations of WDM transmission with ultra-long amplifier spacing on standard G.652 fibre have shown the feasibility of 160km spans for 43Gbit/s carrier-suppressed return-to-zero transmission over 640km, using backward Raman pumping only [6].

Another key enabling technology to emerge in recent years has been pure silica core, ultra-low-loss G.652 fibre, which offers the potential for cabled fibre losses below 0.17dB/km that improves OSNR of the link [4,7-9]. Moreover, the effective nonlinearity of G.652 ultra-low-loss fibre is comparable to standard G.652 fibre, so it delivers approximately the same power tolerance and Raman gain. Recently, WDM systems combined with ultra-low-loss G.652 fibre have produced numerous impressive demonstrations including a record distance of 4400km over 100km spans at 43Gbit/s using hybrid Raman-EDFAs [4], 100Gbit/s-based, 32Tbit/s transmission over 7x80km using EDFA-only amplification [7], 8x10.7Gbit/s transmission over 500km using remote and high power Raman pumping [8], and even quantum key distribution over 250km [9].

In this paper, we extend previous demonstrations of 43Gbit/s transmission with ultra-long amplifier spacing to investigate a cost-effective link design based on Corning SMF-28® ULL G.652 fibre for terrestrial, inter-capital transport over 1000km [10]. We present a systematic performance evaluation of full C-band 43Gbit/s WDM transmission, combining hybrid Raman-EDFA amplifiers with relatively high Raman gain, today's leading 43Gbit/s modulation formats (NRZ-DPSK and RZ-DQPSK), and lumped dispersion management [11], deploying dispersion compensating modules (DCMs) at the transmit and receive terminals only. We demonstrate that 40x43Gbit/s transmission can be supported over 1000km using 200km amplifier spans, with sufficient performance margin for terrestrial deployments.

2. Experimental setup

The test system, Figure 1, operates in a configuration utilizing Corning SMF-28 ULL fiber with contra-directional Raman amplification and single-stage, in-line Erbium amplifiers. The transmit terminal is equipped with 40×43Gbit/s wavelength tuneable transponder units arranged across the C- band on a 100GHz grid. The modulation formats of NRZ-DPSK and RZ-DQPSK are represented in an approximate 1:1 ratio, with each of the transponder units independently modulated by a 2^{31}-1 PRBS pattern mapped into an STM-256 SDH frame and G.709 digital wrapper with a 7% FEC overhead. No polarization management is performed during the multiplexing of the transponder units resulting in a complete de-correlation of the polarization states of adjacent channels and a random exploration of polarization space during the course of the experiment. No optical pre-emphasis is applied at the transmitter and the transponder output powers are actively controlled to maintain an equal launch power for all channels, whilst the total fibre-based dispersion pre-compensation of -7035ps/nm corresponds to approximately 45% of the total system requirement.

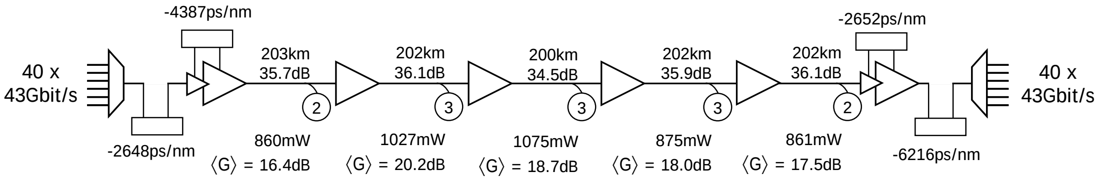
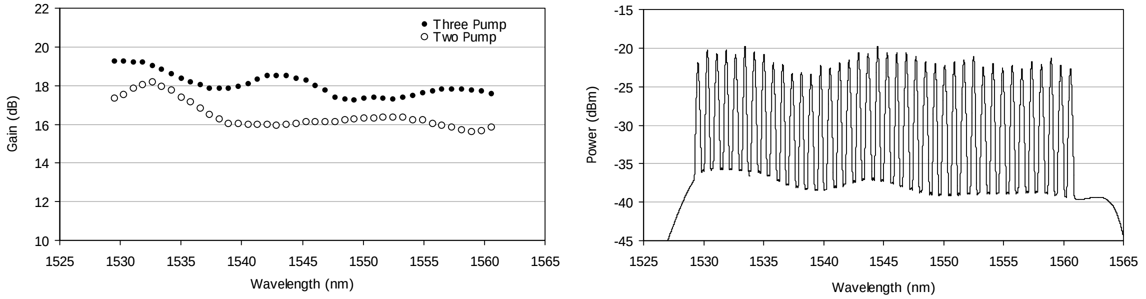


Fig.1: Schematic of experimental setup. The Tx/Rx terminals contain DCMs with a total dispersion of -7035ps/nm and -8868ps/nm at 1550nm, respectively.

The transmission link of 5×200km spans, is constructed with Corning SMF-28 ULL fiber on the shipping spools with intrinsic fiber attenuation < 0.17dB/km at 1550 nm. After patching, splicing and connector losses associated with their concatenation, span losses ranging from 34.5dB to 36.1dB are achieved, thereby yielding a more realistic representation of installation practice.. The average fibre dispersion at 1550nm is 16.0ps/(nm.km). Each in-line amplifier node combines a variable gain, single-stage EDFA, capable of up to 20.5dBm total output power, and either a dual-wavelength (1425nm and 1452nm), or triple wavelength (1424nm, 1435nm, and 1459nm) contra-directional Raman pump unit. At the receiving terminal, the channels are de-multiplexed with each transponder unit independently performing active tuneable chromatic dispersion compensation (fully tuneable over ±700ps/nm), and optimization of its delay line interferometer and decision threshold settings to optimize the pre-FEC BER. Post dispersion compensation of -8868ps/nm at 1550nm is split between dispersion compensating fibre of -2652ps/nm and concatenated fibre Bragg gratings totaling -6216ps/nm.

3. Results and discussion

Figure 2(a) shows sample Raman gain spectra from the dual and triple-wavelength Raman pumps on the first and fourth span respectively, with the two and three gain peaks characteristic of the multi-wavelength Raman pumping evident. Average on-off Raman gains of 16.4dB and 18.0dB were measured for these spans, with peak-to-peak variations of 2.6dB and 2.1dB respectively. The individual pump wavelengths are powered appropriately to generate a gain tilt to compensate both for the fibre attenuation tilt across the C-band and the intra C-band Raman power transfer. The Raman pumps output up to 430mW of depolarized pump power at each wavelength and details of the total pump powers used and the average gains achieved for each of the five spans are illustrated in Figure 1. The distributed amplification efficiency of a given span is seen to vary due to localised point losses along the span introduced by connectors, splicing and patching. The Raman gain per span was also controlled to ensure that the associated EDFA was operating optimally within its designed input power and gain ranges. The 40×43Gbit/s optical spectrum at the receiver terminal is shown in Fig. 2(b), demonstrating a gain variation < 4dB over 1000km.



(a) (b)

Fig.2: (a) Example Raman gain spectra for dual-wavelength and triple-wavelength Raman pumps from spans 1 and 4 for pump powers of 430mW and 430mW, and 297mW, 198mW and 330mW respectively, (b) resultant spectrum at the receive terminal.

Figure 3 presents the composite OSNR and pre-FEC BER measurements for the 43Gbit/s NRZ-DPSK and RZ-DQPSK transponders each averaged over a 5 minute gating period, although excellent BER stability was observed over much longer time periods. No post-FEC errors on an STM-256 test set were observed during the course of these measurements. The EDFA per-channel launch power was set to 3dBm and the received OSNR is better than 18dB (measured integrated signal power over measured noise power in a 0.1nm bandwidth). The OSNR shows a 3.2dB variation, reflecting both the Raman gain variations and the fibre attenuation tilt across the C-band, which although only 0.005dB/km, results in a 1dB difference over 200km. This tilt is further emphasized by intra C-band stimulated Raman scattering. Despite the spectral tilt in the OSNR, the pre-FEC BERs were all lower than 10^{-5}, indicating more than 3dB Q-margin with respect to the enhanced FEC threshold of 2×10^{-3} for post-FEC performance $< 10^{-15}$. It is also notable that, in this configuration, the RZ-DQPSK transponders outperform their NRZ-DPSK counterparts on average by approximately 1dB, and we attribute this to spectral narrowing due to the concatenation of the FBG DCMs in the receive terminal [12].

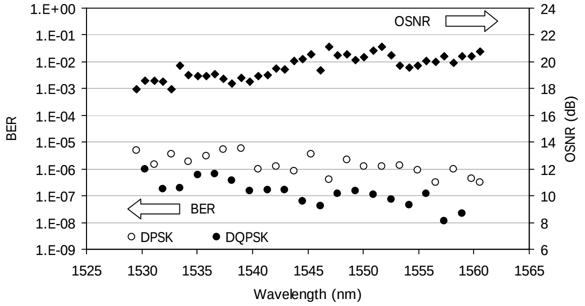


Fig.3: Receive OSNR and pre-FEC BER for 43Gbit/s NRZ-DPSK and RZ-DQPSK transponders after 1000km.

We expect the link design described in this paper to be potentially attractive to operators considering the replacement of existing ITU-T G.652 fibre infrastructure adversely affected by PMD and seeking to deploy 43Gbit/s transport using the minimum number of amplifier sites. Moreover, the DCM-free, inter-terminal optical path is well-suited to the requirements of first generation 100Gbit/s interfaces based on dual-polarization QPSK with coherent detection and DSP, whose OSNR requirements are similar to those of the 43Gbit/s line cards used here, but for which optimum performance is achieved with complete electronic-domain dispersion compensation [13].

4. Conclusions

We have demonstrated 40x43Gbit/s NRZ-DPSK and RZ-DPSK transmission over 1000km of Corning SMF-28 ULL fibre with 200km amplifier spacing. Using hybrid Raman-EDFA amplification, inter-amplifier losses over 34.5dB are traversed using contra-directional Raman pumping only, enabling 43Gbit/s over 1000km with only 4 intermediate amplifier sites. 43Gbit/s NRZ-DPSK and RZ-DQPSK modulation supports the adoption of a simple, lumped dispersion map with DCMs deployed at terminals only. These combined technologies enable a simple and cost-effective WDM system design for 43Gbit/s transport, and establish a suitable optical path for future upgrade to 100Gbit/s.

5. References

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