Transmission of 2x10 GE Channels over 252 km without In-Line EDFA.

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Abstract—**In this letter, we present experimental results on optical packet transmission of two 10 gigabit ethernet channels (10 GE) over 252 km of standard single mode fibre (SSMF, ITU-T Recommendation G.652) and single $10\,\mathrm{GE}$ channel over $287\,\mathrm{km}$ of a link comprising NZ-DSF (TW^{+}) and G.652 fibre without deployment of in-line erbium-doped fiber amplifiers (EDFAs). Two commercially available Cisco Catalyst 6503 line-cards in the 1550 nm wavelength range, high power booster EDFA and low noise EDFA have been used in the experimental set-up. The transmission fiber was counter-directionally pumped at 1455 nm to generate Raman amplification. All the active components and optical band-pass filters were placed at the transmitter and at the receiver side of the link. Group velocity dispersion (GVD) of the SSMF has been compensated by dispersion compensating fibre (DCF).**

I. INTRODUCTION

In the last few years, systematic theoretical and experimental investigation of dispersion managed non-return to zero (NRZ) single and multi-channel links consisting of the standard single mode fibre (SSMF, ITU-T Recommendation G.652) at transmission rates of $10\,\mathrm{Gbits/s}$ and higher using the dispersion compensating fiber (DCF) to eliminate group velocity dispersion (GVD) of the SSMF has received considerable attention [1]–[3]. The main reason was that at these transmission rates and relatively high input powers required, the generation of non-linear phase modulation and signal distortion due to GVD is distributed along the fiber during signal propagation which makes the design of communication system rather complicated. In these studies, the GVD was periodically compensated and the signals amplified by in-line EDFAs every 80 to $100\,\mathrm{km}$. Signal degradation in such systems is due to the combined effects of GVD, Kerr non-linearity and accumulation of amplified spontaneous emission (ASE) noise generated in optical fiber amplifiers. Because of the non-linear nature of signal propagation, system performance depends on power levels at the input of individual types of fibers (SSMF, DCF), on the position of the DCF with respect to SSMF (post-pre-compensation schemes), and on the amount of residual chromatic dispersion. It has been found that if no pre-distortion is used, the post-compensation scheme with certain positive residual dispersion is the most performing one [3].

In some cases the application of in-line amplification is inconvenient. For example, in National Research and Educational Networks (NREN) where dark fibers are extensively deployed the utilization of in-line EDFA's has many drawbacks. In-line EDFA's demand electric power supplies, they increase the probability of network breakdown and require regular maintenance in remote sites which do not belong to ARN operator. Similar situation occurs in coast-island links where the application of in-line amplifiers should preferably be avoided. Due to the commercial availability of high-power erbium-doped fibre amplifiers (EDFA), the span of repeaterless links has substantially increased. This has also enabled transmission of wavelength-division-multiplexed (WDM) channels at $10\,\mathrm{Gbit/s}$, [4]–[6]. In [4], experimental results of 16 channel unrepeated WDM transmission over $340\,\mathrm{km}$ of standard single mode fibre has been reported. $18\,\mathrm{dBm}$/channel power has been launched into the pure-silica core SMF (PS-SMF) with average loss of $0.17\,\mathrm{dB/km}$. Remotely pumped EDFA pre-amplifier located $80\,\mathrm{km}$ away from the receiver has been used. To excite this amplifier remotely, $400\,\mathrm{mW}$ at $1480\,\mathrm{nm}$ was coupled to PS-SMF from the receiver end. Similar experimental configuration has been reported in [6] with the exception that the transmitted signal (32 channels at $10\,\mathrm{Gbit/s}$) was amplified by a remotely pumped post-amplifier located $72\,\mathrm{km}$ away from the transmit terminal. This amplifier was pumped by $4\,\mathrm{W}$ at $1480\,\mathrm{nm}$ through a dedicated pumping fibre and by $1\,\mathrm{W}$ through the signal fibre. At the receiver side, the signal was amplified by a two-stage remotely pumped pre-amplifier. The first stage was located $143\,\mathrm{km}$ away from the receiver terminal and was pumped by $4\,\mathrm{W}$ at $1480\,\mathrm{nm}$ through a dedicated pumping fibre. The second stage was $43\,\mathrm{km}$ away from the first stage and was pumped with $1.2\,\mathrm{W}$ at $1480\,\mathrm{nm}$. The above described configurations seem to be too complicated for practical applications. Moreover, the PS-SMF is not the most widely installed type of fibre and in all the above experiments, pseudo-random non-return-to-zero (NRZ) bit sequence was artificially produced by pattern generator. The c.w. signals

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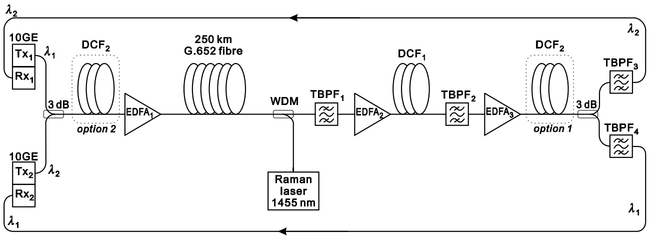


Fig. 1. Schematic diagram of our experimental set-up: 10 GE gigabit ethernet optical transceiver, EDFA erbium doped fibre amplifier, DCF dispersion compensating fibre module, WDM wavelength division multiplexer to combine the Raman pump into the signal fibre, TBPF tunable band-pass filter.

were split in odd and even channels and two Mach-Zehnder modulators were used. Recently, we successfully transmitted two 10 GE plus two 1 GE channels over 252 km of G.652 fibre without deployment of in-line amplifiers [7]. In this experiment we used live traffic generated by standard Cisco Catalyst 6503 line-cards with one 10 GE port and one 1 GE port in the 1550 nm wavelength range, high power EDFA and low noise EDFA preamplifier. Two DCF modules (with total dispersion of -2727.7 ps/nm) was counter-directionally pumped at 1455 nm to achieve Raman amplification.

In this contribution, we present experimental results of error-free transmission of two 10 GE channels over 252 km of G.652 fibre and single 10 GE channel over 287 km of a link comprising NZ-DSF (TW^+) and G.652 fibre without deployment of in-line amplifiers. Two commercial Cisco Catalyst 6503 line-cards with one 10 GE port and one 1 GE port in the 1550 nm wavelength range, high power EDFA (Keopsys BT2-C-27) and low noise EDFA preamplifier (Keopsys BT2-C-10) have been used in our experimental set-up. The transmission fibre has been counter-directionally pumped at 1455 nm by a Raman fibre laser (Keopsys RFL-1455-30-SA /WDM). Group velocity dispersion of the SSMF has been compensated by dispersion compensating fibre. All the active components and the DCF were placed either at the transmitter, or at the receiver side of the link.

II. EXPERIMENTAL RESULTS

Schematic representation of the system under investigation is shown in Fig. 1. Wavelengths of the 10 GE transmitters are $\lambda_1 = 1544.98$ nm and $\lambda_2 = 1545.97$ nm. Noise figure of the $EDFA_1$ at 1550 nm was 5.5 dB (at $P_{in} = 0$ dBm), of the $EDFA_2$ and $EDFA_3$ was 4.5 dB (at $P_{in} = -35$ dBm). The DCF_1 represents two modules with total GVD of -2727.7 ps/nm, the DCF_2 module has a GVD of -946 ps/nm, DCF attenuation is 0.37 dB/km at 1550 nm. Fiber attenuation and dispersion of the SSMF are 0.202 dB/km and 16.5 ps/km/nm, respectively. Two dispersion compensation schemes are depicted in Fig. 1: post-compensation scheme where both the DCF_1 and the DCF_2 are placed at the receiver site, option 1, and the pre- and post-compensation scheme where DCF_2 is placed in front of the high-power $EDFA_1$, option 2. Dispersion compensation ratio ($DCR = |L_{DCF} \cdot D_{DCF}|/(L_{SSMF} \cdot D_{SSMF})$) of the span is $DCR = 0.88$. Signals from the two 10 GE transmitters were combined via conventional 50 : 50 directional coupler, amplified in $EDFA_1$ and launched into the 202 km of the SSMF. The transmission fibre was counter-directionally pumped at 1455 nm via WDM coupler by Raman fiber laser with maximum output power of $P_{RL} = 3$ W. In order to improve optical signal-to-noise ratio (OSNR) and to avoid saturation of subsequent EDFAs by spontaneous emission generated by the previous EDFAs and by the Raman amplifier, two tunable optical band-pass filter ($TBPF_1$, $TBPF_2$) with full width at half maximum (FWHM) of 1 nm were used. Their central wavelength was set with the aid of optical spectrum analyzer at ≈ 1545.48 nm, so that both data channels exhibit the same optical power after the filters. Before the 10 GE receivers, the optical power was split by conventional 50 : 50 directional coupler and individual channels separated by $TBPF_3$ and $TBPF_4$ with FWHM of 0.3 nm. Back-to back sensitivity of the 10 GE receivers was measured to be -19 dBm for zero loss of transmitted packets.

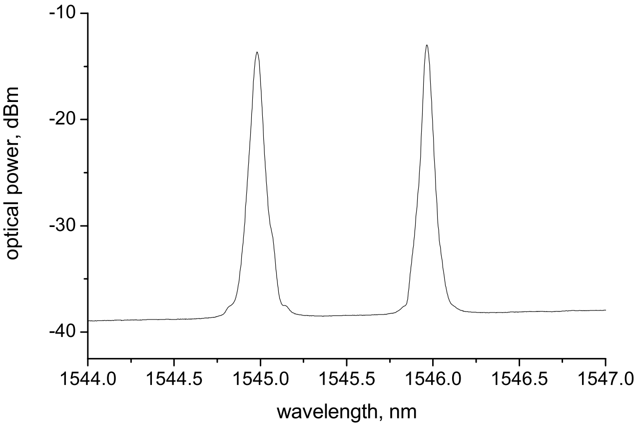


Fig. 2. Optical power at the output of the WDM coupler: $P^{out}_{EDFA_1} = 15.8\,\mathrm{dBm}$, $P_{RL} = 1.1\,\mathrm{W}$.

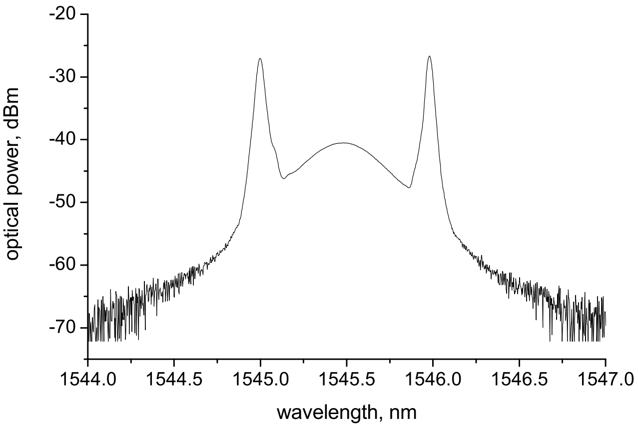


Fig. 3. Optical power at the output of the WDM coupler: $P^{out}_{EDFA_1} = 15.5\,\mathrm{dBm}$, $P_{RL} = 1.1\,\mathrm{W}$.

Next 3 figures show the optical spectrum at different points

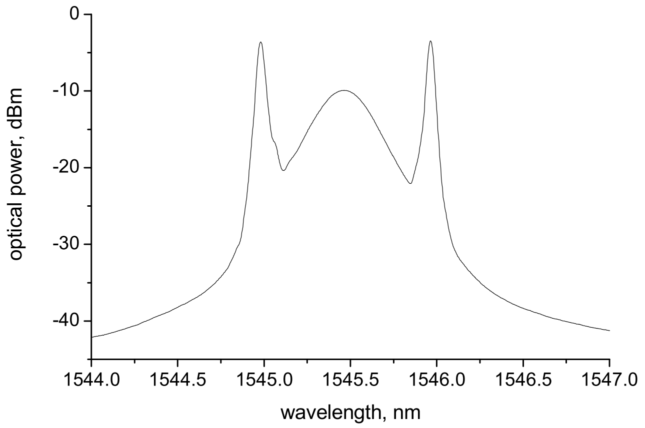


Fig. 4. Optical power at the output of DCF_2: $P^{out}_{EDFA_1} = 15.5\,\text{dBm}$, $P_{RL} = 1.1\,\text{W}$, $P^{out}_{EDFA_2} = 6.1\,\text{dBm}$, $P^{out}_{EDFA_3} = 1.5\,\text{dBm}$.

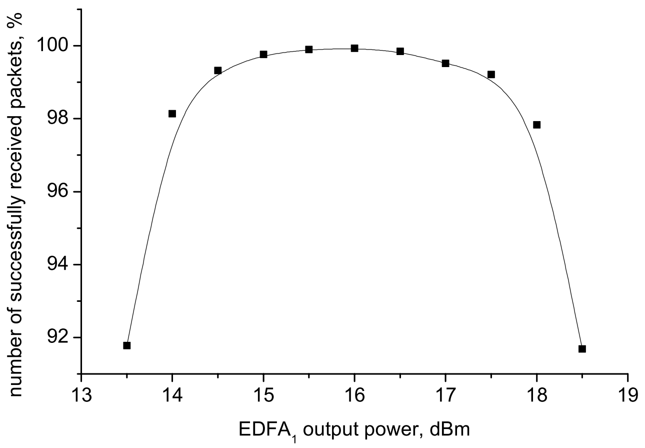


Fig. 5. Number of successfully received packets for λ_1 channel as a function of $P^{out}_{EDFA_1}$: $P_{RL} = 1.1\,\text{W}$, $P^{out}_{EDFA_2} = 6.1\,\text{dBm}$, $P^{out}_{EDFA_3} = 1.5\,\text{dBm}$.

of the link in case of post-compensation scheme and were recorded with resolution bandwidth of the optical spectrum analyzer $0.033\,\text{nm}$. Figure 2 depicts the spectrum after the WDM coupler, optical powers are -13.5 and $-12.95\,\text{dBm}$ at $\lambda_1 = 1544.98\,\text{nm}$ and $\lambda_2 = 1545.97\,\text{nm}$, respectively. The OSNR is $\approx 24.5\,\text{dB}$. Figure 3 shows the spectrum after $TBPF_1$. It is seen that due to careful tuning of the filter the channels remain symmetric, the optical powers are -27 and $-26.8\,\text{dBm}$ at λ_1 and λ_2, respectively. Spectrum at the output port of the DCF_2 is shown in Fig. 4. After careful tuning of $TBPF_2$ the power of both 10 GE channels is approximately the same and equal to $-3.7\,\text{dBm}$. We measured the BER using either the PING utility, or by ACTERNA, ONT-50 Optical Network Tester which also measures Q-factor of the link. Using the PING utility, we transmitted 10^7 of 1500 Bytes long packets and evaluated the number of drop-outs. Figure 5 plots the percentage of successfully received packets as a function of $EDFA_1$ output power for the 10 GE channel at $\lambda_1 = 1544.98\,\text{nm}$. It is seen that for $15\,\text{dBm} < P^{out}_{EDFA_1} < 17\,\text{dBm}$, $100\,\%$ of launched packets was successfully received. The dependence of the the logarithm of BER and the Q-factor on the $EDFA_1$ output power measured by the ONT-50 Optical Network Tester is shown in Fig. 6 and 7, respectively. It is seen that the maximum Q-factor and the lowest BER is achieved for $P^{out}_{EDFA_1} = 16.5\,\text{dBm}$. The results presented in Fig. 5, 6, and 7 for post-compensation scheme were recorded for $P_{RL} = 1.1\,\text{W}$, $P^{out}_{EDFA_2} = 6.1\,\text{dBm}$, $P^{out}_{EDFA_3} = 1.5\,\text{dBm}$. Sensitivity to $P^{out}_{EDFA_2}$ and P_{RL} was investigated with the PING utility for $P^{out}_{EDFA_1} = 16.5\,\text{dBm}$. $100\,\%$ transmission was achieved for $5.5\,\text{dBm} < P^{out}_{EDFA_2} < 7.5\,\text{dBm}$ and $950\,\text{mW} < P_{RL} < 1150\,\text{mW}$. When the P_{RL} was increased above $\approx 1300\,\text{mW}$, distributed Rayleigh reflections in the SSMF resulted in gain instability and lasing action, [8]. The same results were obtained for the other 10 GE channel at $\lambda_2 = 1545.97\,\text{nm}$. Slightly lower BER and higher Q-factor were obtained for the pre- and post-compensation scheme, where the DCF_2 module was placed directly after the conventional $50 : 50$ coupler, see option 2 in the set-up schematic, Fig. 1. Results for this compensation scheme

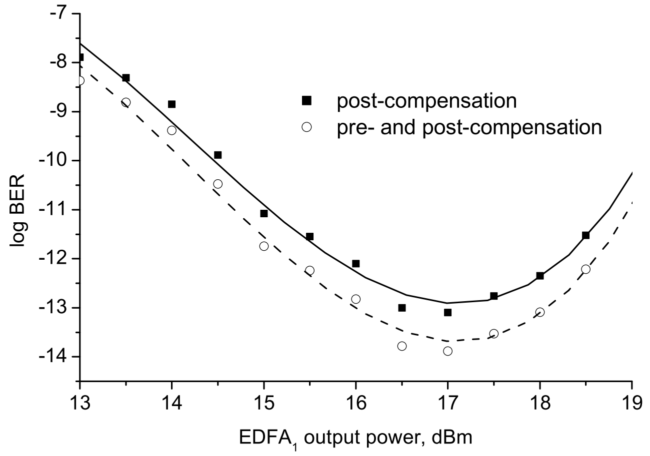


Fig. 6. Logarithm of BER for λ_1 channel as a function of $P^{out}_{EDFA_1}$.

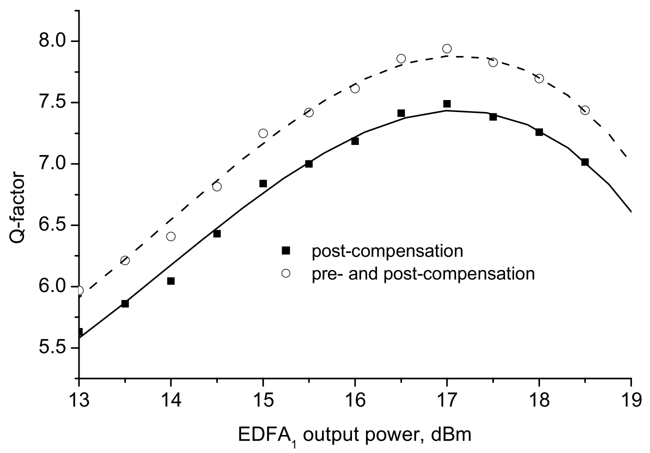


Fig. 7. Q-factor for λ_1 channel as a function of $P^{out}_{EDFA_1}$.

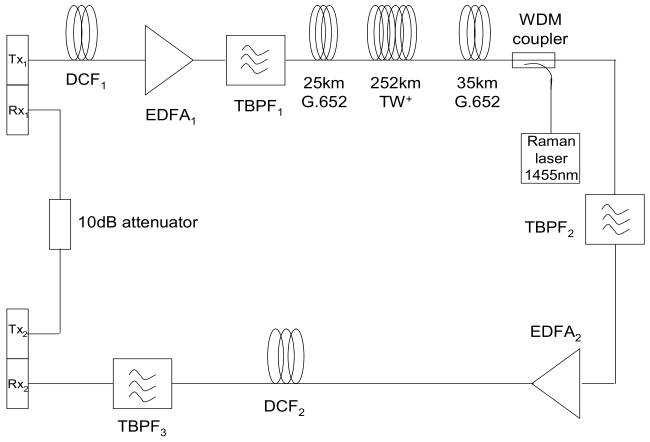


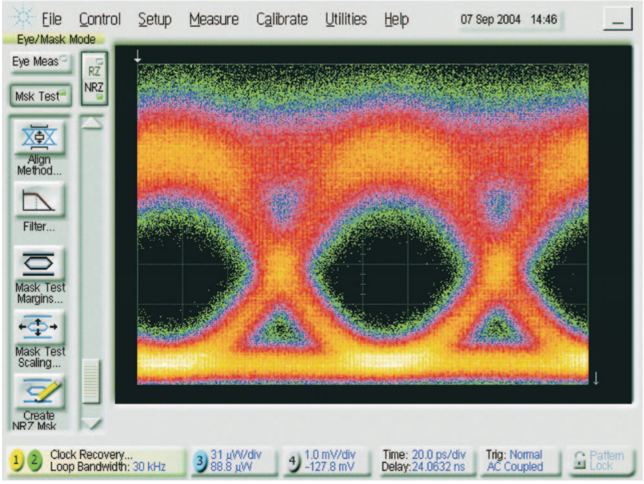
Fig. 8. Schematic diagram of our experimental set-up of the 287 km link.

shown in Fig. 6 and 7 were recorded for $P_{RL} = 1.1\,\mathrm{W}$, $P^{out}_{EDFA_2} = 6.5\,\mathrm{dBm}$, $P^{out}_{EDFA_3} = 3.0\,\mathrm{dBm}$.

Some dark fibre links in the Czech Republic contain not only the G.652 fibres, but also non-zero dispersion-shifted fibres. To be prepared for potential exploitation of such dark fibre links, we have also experimented with links composed of G.652 and TW^+ fibres. We have extended the link length to 287 km for single-channel 10 GE transmission. Schematic diagram of the link is shown in Fig. 8. The transmitter Tx_1 is followed by DCF_1 module with $GVD = -690$ ps/nm, EDFA booster. Output signal is filtered by $TBPF_1$ and launched in the link composed of to $25\,km$ of G.652, 202 km of TW^+ followed by 60 km of G.652. The link is counter-directionally pumped at 1455 nm by Raman fibre laser. Output power is filtered by $TBPF_2$ and amplified by a low noise EDF preamplifier. Post-compensation of GVD is performed in DCF_2 module with $GVD = -960$ ps/nm. Using the PING utility, we transmitted 10^7 of 1500 Bytes long packets and evaluated the number of drop-outs. 100 % of packets has been successfully received under the following values of the power launched into the link, P_{launch}, (measured after $TBPF_1$), pumping power of the Raman laser and output power of the EDF preamplifier, $P^{out}_{EDFA_2}$. One of the amplification parameters was fixed and the acceptable range of the other two parameters was investigated. For $P_{RL} = 1000\,\mathrm{mW}$ the ranges were: $15.5\,\mathrm{dBm} < P_{launch} < 17.5\,\mathrm{dBm}$, $5.5\,\mathrm{dBm} < P^{out}_{EDFA_2} < 7.5\,\mathrm{dBm}$. For $P_{launch} = 16\,\mathrm{dBm}$ the Raman amplifier pump power and $EDFA_2$ output power were: $P_{RL} > 800\,\mathrm{mW}$, $5.5\,\mathrm{dBm} < P^{out}_{EDFA_2} < 7.5\,\mathrm{dBm}$. Eye diagram recorded at the end of the link is shown in Fig. 9.

III. CONCLUSION

We have demonstrated that using commercially available and relatively inexpensive optical communication systems and components, repeaterless error-free transmission of two 10 GE channels over 252 km of standard single mode fibre and 287 km long link composed of G.652 and TW^+ fibres is possible. Moreover, the error-free transmission is not very sensitive to optical powers launched into the SSMF and DCF, neither to Raman pump power. These results are encouraging especially for operators of national research and educational networks who rely on leased dark fibres and prefer to have no active components located along the link and at the same time to have as long the link length as possible.



1 2 Clock Recovery...
Loop Bandwidth: 30 kHz
3 31 μW/div
88.8 μW
4 1.0 mV/div
-127.8 mV
Time: 20.0 ps/div
Delay: 24.0632 ns
Trig: Normal
AC Coupled

Fig. 9. Eye diagram of the 10GE signal at the end of 278 km long link.

ACKNOWLEDGMENT

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