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202 km repeaterless transmission of 2 × 10 GE plus 2 × 1 GE channels over standard single mode fibre

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Abstract

In this article, we present experimental results on transmission of two 10 gigabit ethernet channels (10 GE) plus two 1 gigabit ethernet channels (1 GE) over 202 km of standard single mode fibre (SSMF, ITU-T Recommendation G.652) without deployment of in-line amplifiers. Standard Cisco Catalyst 6503 line-cards with one 10 GE port and one 1 GE port in the 1550 nm, high power booster erbium-doped fibre amplifiers (EDFA) and low noise EDFA have been used in the experimental set-up. All the active components were placed either at the transmitter, or at the receiver side of the link. Group velocity dispersion (GVD) of the SSMF has been compensated by dispersion compensating fibre (DCF).

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1. Introduction

Majority of already-embedded fibre plants are mainly composed of standard single model fibres (SSMF, G.652) with zero group velocity dispersion (GVD) at 1310 nm. Various techniques have been investigated how to overcome the GVD of the SSMF at 1550 nm wavelength window when transmitting data with rates 10 GHz and higher. They include the use of dispersion compensating fibre (DCF), [1], chirped fibre Bragg gratings, [2], pre-chirp control [3] and different bandwidth reduction schemes [4–6].

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 Gbit/s, [7–9]. In [7], experimental results of 16 channel unrepeated WDM transmission over 340 km of standard single mode fibre has been reported. 18 dBm/channel power has been

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launched into the pure-silica core SMF (PS-SMF) with average loss of 0.17 dB/km. Remotely pumped EDFA pre-amplifier located 80 km away from the receiver has been used. To excite this amplifier remotely, 400 mW at 1480 nm was coupled to PS-SMF from the receiver end. Similar experimental configuration has been reported in [9] with the exception that the transmitted signal (32 channels at 10 Gbit/s) was amplified by a remotely pumped post-amplifier located 72 km away from the transmit terminal. This amplifier was pumped by 4 W at 1480 nm through a dedicated pumping fibre and by 1 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 km away from the receiver terminal and was pumped by 4 W at 1480 nm through a dedicated pumping fibre. The second stage was 43 km away from the first stage and was pumped with 1.2 W at 1480 nm. The above described configurations are devoted to maximize the repeaterless distances and not to low-cost applications. Moreover, in all the above experiments, pseudo-random non-return-to-zero (NRZ) bit sequence was artificially produced by a pattern generator. The c.w. signals were split into odd and even channels and two Mach–Zehnder modulators were used.

In this contribution, we present theoretical and experimental results of error-free transmission of two 10 GE plus two 1 GE channels over 202 km of G.652 fibre without deployment of in-line amplifiers. In our experimental set-up we have used 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 and low noise EDFA preamplifier. Group velocity dispersion of the SSMF has been compensated by two modules of dispersion compensating fibre. Raman amplification of the DCF modules has been achieved by counter-directional pumping by Raman fibre laser at 1455 nm. In comparison with Raman pumping of the SSMF, this configuration saves us one EDFA which will otherwise be necessary for amplification after the second DCF module. All the active components and the DCF modules were placed either at the transmitter, or at the receiver side of the link. The experimental results are encouraging especially for operators of national research and educational networks (NREN) who rely on leased dark fibres and prefer as long repeaterless transmission as possible.

2. Theoretical analysis

For the theoretical analysis, the non-linear Schröedinger equation describing light propagation in optical fibres is solved by the standard split-step Fourier method [10]. It is well known that the post-compensation scheme (where the DCF follows the SSMF) performs better than the pre-compensation one provided that the SSMF and DCF input power levels and the dispersion compensation ratio ($\mathrm{DCR} = |L_{\mathrm{DCF}} \cdot D_{\mathrm{DCF}}|/(L_{\mathrm{SSMF}} \cdot D_{\mathrm{SSMF}})$, where L_{DCF} and L_{SSMF} are the length of the DCF and SSMF, respectively, and D_{DCF} and D_{SSMF} are the dispersion parameters of the DCF and SSMF, respectively are carefully optimized. Schematic representation of the system under investigation is shown in Fig. 1. It is the same as our experimental set-up and all the parameters of this set-up have been used in numerical simulations. Wavelengths of the 10 GE transmitters are $\lambda_1 = 1544.98$ and $\lambda_2 = 1545.97$ nm, of the two 1 GE ports $\lambda_3 = 1550.76$ and $\lambda_4 = 1553.73$ nm, respectively. Noise figure of EDFA_1 and EDFA_2 at 1550 nm were 5.5 dB (at $P_{\mathrm{in}} = 0$ dBm) and 4.5 dB (at $P_{\mathrm{in}} = -35$ dBm), respectively. Fibre attenuation, dispersion, dispersion slope, non-linear coefficient, and effective area of 0.201 dB/km, 16.5 ps/nm/km, 0.06 ps/nm^2/km, 2.7×10^{-20} m^2/W, and 80 μm^2, respectively, for the SSMF, and 0.55 dB/km, −80 ps/nm/km, 0.09 ps/nm^2/km, 2.6×10^{-20} m^2/W, and 22 μm^2 for the DCF have been considered. The peak value of Raman gain coefficient, $g_{\mathrm{R}}(\nu - \xi)$, between waves with frequency ν and ξ divided by the $A_{\mathrm{eff}}(\nu)$ of the DCF is 2.384×10^{-3} (1/W/m) at 1420 nm and 1.961×10^{-3} [1/W/m] at 1510 nm.

The simulation software evaluates the Q-factor defined as

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0}, \tag{1}$$

where μ_1, σ_1 (μ_0, σ_0) are the mean and the standard deviation of the received signal at the sampling instant when a logical “1” (“0”) is transmitted and

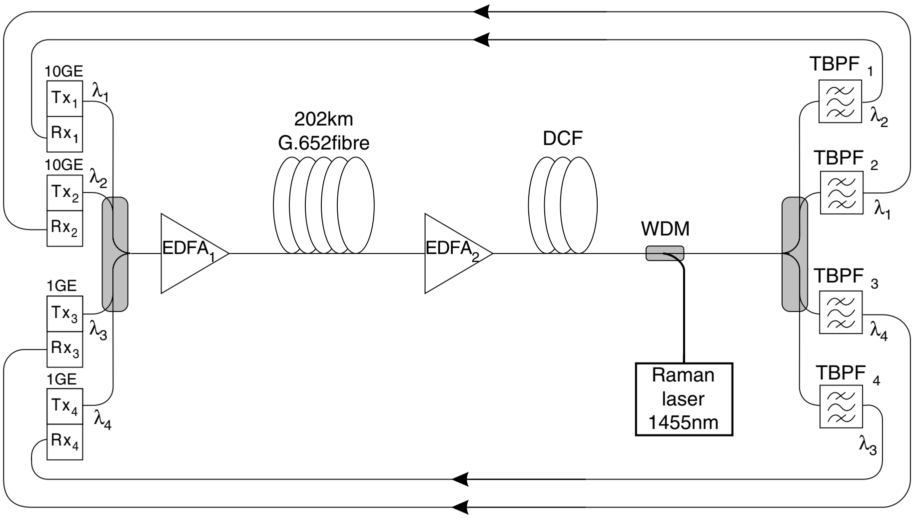

Fig. 1. Schematic diagram of our experimental set-up: GE gigabit ethernet optical transceiver, EDFA erbium doped fibre amplifier, DCF dispersion compensating fibre module, WDM wavelength division multiplexer to combine the Raman pump into the signal fibre, TBPF tunable band-pass filter.

the bit-error-rate (BER) is calculated under the assumption of Gaussian statistics as

$$\mathrm{BER} = \frac{1}{2}\left\{ erfc\left(\frac{|V_{\mathrm{th}} - \mu_1|}{\sigma_1}\right) + erfc\left(\frac{|V_{\mathrm{th}} - \mu_0|}{\sigma_0}\right)\right\}, \tag{2}$$

where $erfc()$ is the complementary error function and V_{th} is the decision threshold level. We have performed a comprehensive numerical analysis with the aim to find out the optimum input power to the SSMF, P_{SSMF}, and the DCF, P_{DCF}, optimal Raman pump power, P_{RP}, and the optimal degree of chromatic dispersion compensation that will guarantee the BER $< 10^{-15}$. We have found that minimum Raman pump power was ≈250 mW and that, as can be expected, the 1 GE data streams are less sensitive to input powers and do not need GVD compensation. The results of input power optimization for 10 GE transmission channels are

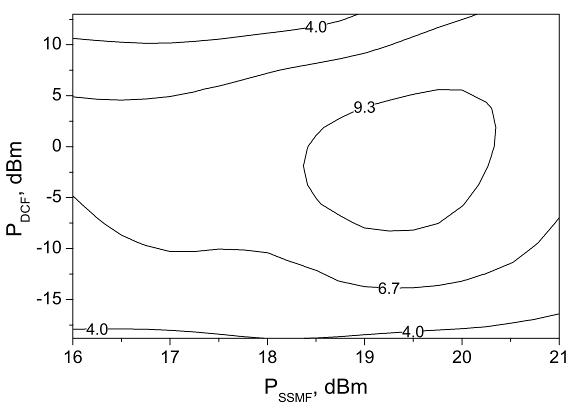

Fig. 2. Q-factor of the 10 GE transmission channel as a function of P_{SSMF} and P_{DCF}: $P_{\mathrm{Raman}} = 300$ mW, DCR = 0.80, results of numerical simulation.

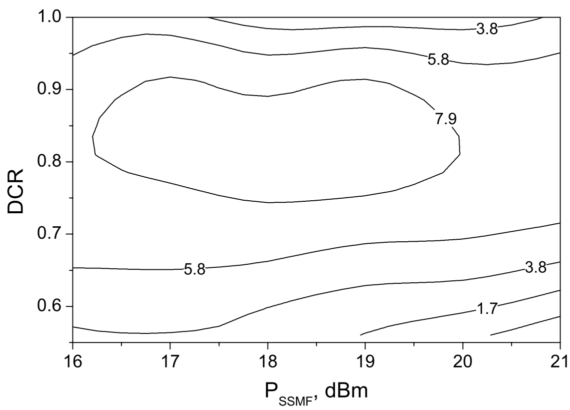

Fig. 3. Q-factor of the 10 GE transmission channel as a function of DCR and P_{SSMF}: $P_{\mathrm{Raman}} = 300$ mW, $P_{\mathrm{DCF}} = 0.0$ dBm, results of numerical simulation.

summarized in Fig. 2 which shows the contour plot of the Q-factor. The existence of transmission optimum for certain sets of powers is clearly seen in this contour plot. Fig. 3 demonstrates the dependence of the Q-factor on P_{SSMF} and DCR. The highest Q-factor has been calculated for $P_{SSMF} = 19$ dBm and DCR $= 0.85$. However, total dispersion of the two DCF modules available for our experiments is −2727.7 ps/nm which, for the 202 km of SSMF, corresponds to dispersion compensation ratio DCR $= 0.80$.

3. Experimental results

Signals from the two 10 and the two 1 GE transmitters were combined via conventional 4:1 directional coupler, amplified in $EDFA_1$ and launched into the 202 km of the SSMF. Fig. 4 shows optical power at the input port of $EDFA_1$ (resolution bandwidth of the optical spectrum analyzer was 0.033 nm). Wavelengths of individual channels have already been mentioned in the paragraph on theoretical analysis. Low noise pre-amplifier, $EDFA_2$, picks-up the signals from the level of ≈ -30 dBm as is shown in Fig. 5. The DCF modules are counter-directionally pumped by Raman fibre laser at 1455 nm, optical power at the output of DCF is plotted in Fig. 6. Individuals channels, after splitting by conventional 1:4 directional coupler and filtering by tunable band-pass filters, TBPF, (−3 dB bandwidth 0.3 nm) are fed to respective receivers (sensitivity of the 10 GE receiver is ≈ -15 dBm, of the 1 GE receiver ≈ -28 dBm).

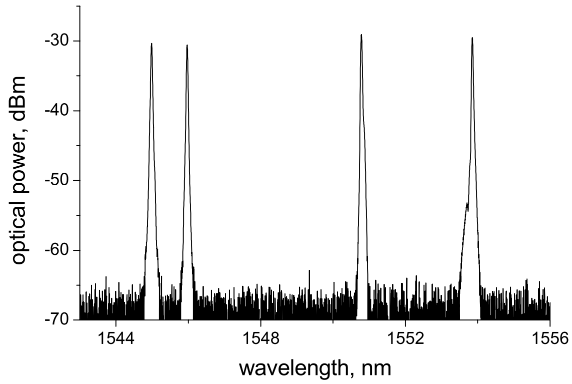

Fig. 5. Optical power at the input to $EDFA_2$: $P_{SSMF} = 20$ dBm, experiment.

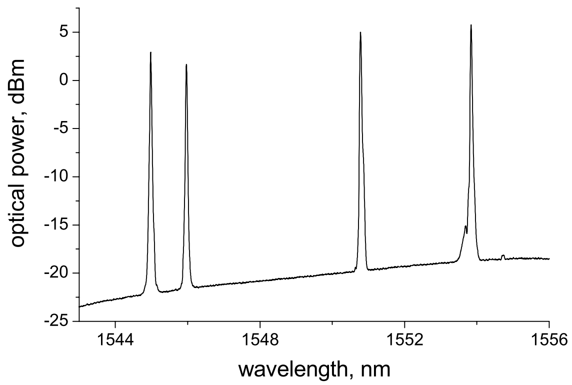

Fig. 6. Optical power at the output of DCF: $P_{SSMF} = 20$ dBm, $P_{DCF} = 0$ dBm, $P_{RL} = 400$ mW, experiment.

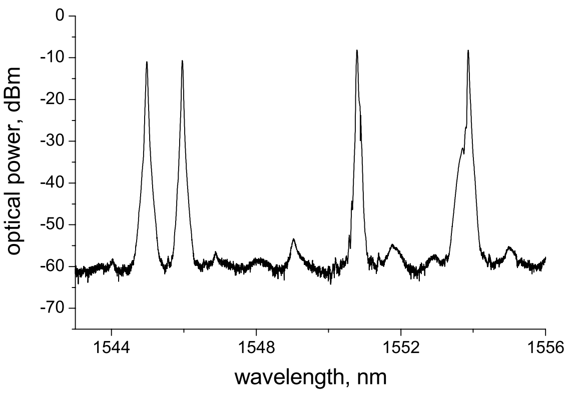

Fig. 4. Optical power at the input to $EDFA_1$: experiment.

We measured the BER using either the PING utility, or by ACTERNA, ONT-50 Optical Network Tester. Using the PING utility, we transmitted 10^7 of 1500 Bytes long packets and evaluated the drop-outs. The 1 GE channels were rather insensitive to P_{SSMF}, P_{DCF} and P_{RL} with the exception that when P_{RL} was increased above ≈ 600 mW, distributed Rayleigh reflections in the DCF resulted in gain instability and lasing action, [11]. Fig. 7 plots the percentage of successfully received packets as a function of $EDFA_1$ output power for the 10 GE channel at $\lambda_2 = 1545.97$ nm. It is seen that even at the maximum available output power of 21.5 dBm, 100% of launched

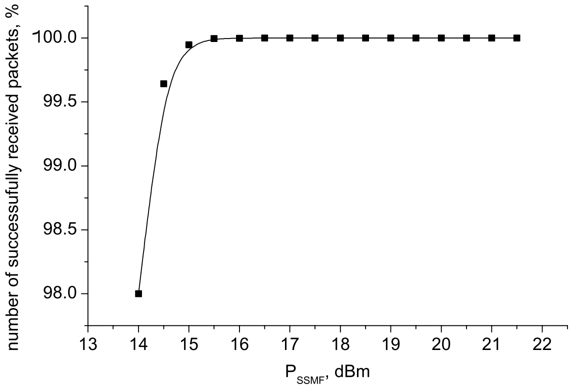

Fig. 7. Number of successfully received packets as a function of P_{SSMF}: $P_{DCF} = 0$ dBm, $P_{RL} = 400$ mW, experiment.

packets was successfully received. The dependence of Q-factor measured by the ONT-50 Optical Network Tester is shown in Fig. 8 and the logarithm of BER is plotted in Fig. 9. It is seen that the maximum Q-factor and the lowest BER is achieved for $P_{SSMF} = 20$ dBm. The results presented in Figs. 7–9 were recorded for $P_{DCF} = 0$ dBm and $P_{RL} = 400$ mW. Sensitivity to P_{DCF} and P_{RL} was investigated with the PING utility for $P_{SSMF} = 20$ dBm. 100% transmission was achieved for -1 dBm $< P_{DCF} < 10$ dBm and 250 mW $< P_{RL} < 550$ mW. The same results were obtained for the other 10 GE channel at $\lambda_2 = 1544.98$ nm.

Although accurate information concerning the frequency chirp of the 10 GE transmitters was not available, it is seen that our numerical simulations

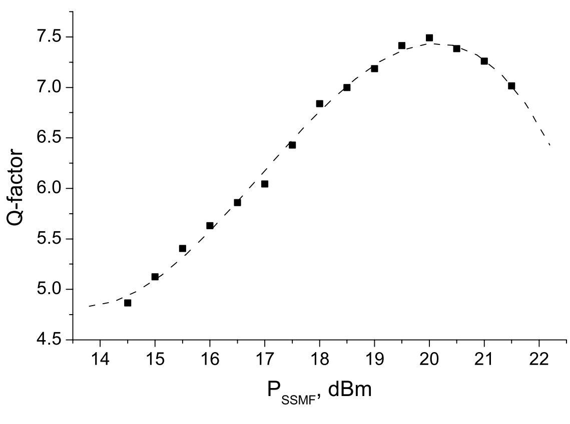

Fig. 8. Q-factor as a function of P_{SSMF}: $P_{DCF} = 0$ dBm, $P_{RL} = 400$ mW, experiment.

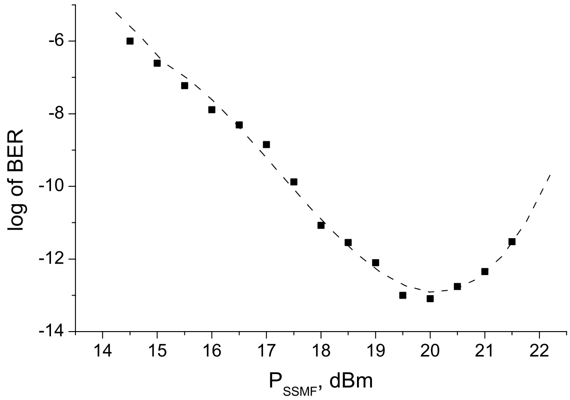

Fig. 9. Logarithm of BER as a function of P_{SSMF}: $P_{DCF} = 0$ dBm, $P_{RL} = 400$ mW, experiment.

predict with reasonable accuracy the range of acceptable optical powers to be launched into the SSMF and the DCF and the necessary degree of DCR.

4. Conclusion

We have demonstrated that using commercially available and relatively cheap optical communication systems and components, repeaterless transmission of two 10 GE channels and two 1 GE channel over 202 km of standard single mode fibre 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. It can be concluded that when all nominal values (i.e. channel power at the SSMF and the DCF inputs, Raman pump power and the DCR) were used, the span length can even be extended beyond 202 km. In our experiment we were limited by the available DCF modules. Our results are encouraging especially for operators of national research and educational networks who rely on leased dark fibres and prefer as long repeaterless transmission as possible.

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