Optimization of NRZ data transmission at 10Gbit/s over G.652 without in-line EDFA's

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Abstract

Performance limits of NRZ data transmission at 10Gbit/s over standard single mode fibre (SSMF, G.652) without the deployment of in-line erbium-doped fibre amplifiers (EDFA's) are evaluated by means of numerical simulation. The fibre system was modelled using the standard split-step Fourier algorithm for the solution of non-linear Schröedinger equation. The effect of group velocity dispersion (GVD) compensation scheme, degree of GVD compensation of the SSMF, input optical powers to SSMF and to the dispersion compensating fibre (DCF) has been investigated with the aim to maximize the distance between transmitter and receiver. We have found that post-compensation scheme performs better than the pre-compensation scheme and that, by careful selection of input powers and degree of GVD compensation, it should be possible to keep the bit-error-ratio (BER) bellow 10^{-15} for SSMF length of 270 km.

Keywords– Optical communications, dispersion compensation, optical fiber nonlinearity, optical fiber amplifiers.

I. Introduction

Most of the embedded fibre cables contain standard single mode fibres (SSMF, G.652) with zero group velocity dispersion (GVD) at 1300 nm. At the 1550 nm wavelength range the accumulated GVD in these fibres is so large that dispersion compensation is necessary to reduce inter-symbol interference (ISI) and to achieve error-free transmission at bit rates higher than 2.5 Gbit/s. The most effective and practical strategy for upgrading already installed 1550 nm transmission systems based on SSMF is the periodical insertion of dispersion compensating fibre (DCF) for suppression of ISI due to linear distortion caused by GVD.

Systematic theoretical and experimental investigation of dispersion managed non-return to zero (NRZ) single and multi-channel links at transmission rates of 10 Gbits/s and higher using the DCF has received considerable attention in the last few years. When power capabilities of commercially available erbium-doped fibre amplifiers (EDFA's) are utilized, non-linear effects such as self-phase modulation (SPM) and cross-phase modulation (XPM), cause signal distortion that cannot be fully suppressed by simple insertion of DCF. The generation of non-linear phase modulation and signal distortion through GVD is distributed along the fibre during signal propagation. 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 fibre amplifiers. Because of the non-linear nature of signal propagation, system performance depends on power levels at the input of different types of fibres (SSMF, DCF), on the position of the DCF with respect to SSMF, and on the amount of residual dispersion. In [1], the effect of SPM and the dispersion map in periodically amplified 10 Gbits/s SSMF links have been investigated. Each span consisted of 50 km of SSMF and 8.5 km of DCF to fully compensate the GVD of the SSMF. One erbium-doped fibre amplifier has been assumed in each span, the effect of mutual position of SSMF and DCF (pre-, post-compensation scheme) has been investigated. The effect of dispersion compensation ratio or residual dispersion has been investigated in [2]. Link composed of five spans of 100 km of SSMF and variable length L of DCF has been analyzed by numerical simulation. It has been found that the post-compensation with certain positive residual dispersion is the most performing scheme. Compared with [1] and [2], another degree of freedom has been taken into account in [3], where the input powers to the SSMF and the DCF have been varied independently to find transmission optima. Spans consisting of 80 km of SSMF and variable length of DCF have been considered. Results for links containing 10, 20, 30, and 40 spans were shown.

In some cases the application of in-line amplification is inconvenient. For example, in Academic networks where dark fibres 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. Similar situation occurs in coast-island links where the application of in-line amplifiers should preferably bee avoided.

Little attention has so far been paid to extension of SSMF transmission distance at 10 Gbit/s without the application of in-line amplifiers. In [4], experimental results of 10 Gbit/s, 16 channel unrepeated WDM transmission over 340 km of standard single mode fibre has been reported. 18 dBm/channel power has been 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 [5] 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 seem to be too complicated for practical applications.

In this contribution we present results of comprehensive numerical simulation of NRZ data transmission at 10 Gbit/s over standard single mode fibre with GVD compensation by means of DCF without application of in-line EDFA's and deployment of booster EDFA's, only. The analysis has been performed with the aim to find out the limits of the transmitter - receiver distance and to optimize input powers to SSMF and DCF fibres and the degree of GVD dispersion compensation. To author's best knowledge, results of such an analysis has net been published so far.

II. Simulation parameters and results

Schematic representation of the system under investigation is shown in Fig. 1. Continuous wave of the DFB laser (output power $P_{out} = 0\,\mathrm{dBm}$, $FWHM = 10\,\mathrm{MHz}$) is externally modulated by zero-chirp Mach-Zehnder modulator (extinction ratio 15 dB) with NRZ $2^{10}-1$ pseudo random bit sequence (PRBS). Booster EDFA amplifies the modulated signal before it is transmitted through a link consisting either of the SSMF, another booster amplifier and the receiver (post-compensation scheme), or the DCF, the second EDFA and the SSMF followed by the receiver (pre-compensation scheme). Such a scheme enables us to place the DCF and EDFA's either at the transmitter or at the receiver site so that no active components are placed between the link end points. Fiber attenuation, dispersion, dispersion slope, non-linear coefficient, and effective area of 0.22 dB/km, 16 ps/nm/km, 0.06 ps/nm^2/km, $2.7 \cdot 10^{-20}\,\mathrm{m^2/W}$, and $80\,\mu m^2$, respectively, for SSMF, and 0.55 dB/km, −80 ps/nm/km, 0.09 ps/nm^2/km, $2.6 \cdot 10^{-20}\,\mathrm{m^2/W}$, and $22\,\mu m^2$ for DCF have been considered. In order to independently set input powers to both the SSMF and the DCF, two EDFA's with noise figure of 4.5 dB operating in output power controlled regime has been simulated. The optical receiver consists of an optical band-pass Gaussian filter with $FWHM = 40\,\mathrm{GHz}$, PIN photodiode with a responsivity of 1 A/W and single-sided thermal noise density of $15\,\mathrm{pA}/\sqrt{\mathrm{Hz}}$ followed by a fifth-order low-pass Bessel filter with $FWHM = 7\,\mathrm{GHz}$. Non-linear Schröedinger equation describing propagation in optical fibres has been solved using the standard split-step Fourier method [6].

First we will demonstrate the limits of 10 Gbit/s transmission without the compensation of GVD. Figure 2 plots the dependence of Q-factor on the length of the SSMF, L_{SSMF}, for three values of input power to the SSMF, P_{SSMF}. The Q factor is 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. BER is calculated under the assumption of Gaussian statistics as

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

where $erfc()$ is the complementary error function and V_{th} is the decision threshold level. The corresponding diagram displaying the dependence of BER on L_{SSMF} is shown in Fig. 3. It is seen from these two figures that $BER < 10^{-12}$ cannot be achieved without dispersion compensation for $L_{SSMF} > 125\,\mathrm{km}$ and that the optimum input power to the SSMF is about $P_{SSMF} = 17\,\mathrm{dBm}$. Zoomed part of the SRBS at the input and at the output port of 100 km long SSMF is plotted in Fig. 4 and 5, respectively.

A. Post-compensation scheme

We will now present results for post-compensation scheme shown in the upper part of Fig. 1. We have performed a comprehensive analysis by increasing the length of the SSMF from 230 to 290 km in steps of 10 km. The effect of DCF length, input power to SSMF and to DCF fibre has been investigated with the aim to find out the limits in which the $BER < 10^{-15}$. We have found that the maximum SSMF length for which this criterion is fulfilled with reasonable margin is $L_{SSMF} = 270$ km. Moreover, the best performance for this scheme can be achieved when the GVD of the SSMF is not 100 % compensated by the DCF, but some residual positive dispersion proved to have beneficial effect. The degree of GVD compensation will be expressed by means of dispersion compensation ratio (DCR) defined as

$$DCR = \frac{|L_{DCF} \cdot D_{DCF}|}{L_{SSMF} \cdot D_{SSMF}} \tag{3}$$

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. Figure 6 depicts the dependence of Q factor on DCR for several values of SSMF input power. The corresponding contour plots displaying the dependence of Q-factor and BER on P_{SSMF} and DCR are shown in Fig. 7 and 8, respectively. It is seen from these three figures that there is a certain range of P_{SSMF} and DCR where $BER < 10^{-14}$. The highest Q factor has been calculated for $P_{SSMF} = 19$ dBm and $DCR = 0.85$. In [3], optimal performance of the post compensation scheme for spans consisting of 80 km of SSMF and variable length of DCF has been achieved for SSMF and DCF input powers in the range from 1 to 3 dBm and from -9 to -6 dBm, respectively.

Simulations have been performed to optimize the DCF input power for different length of DCF. Optimal value of DCF input power has been found to be $P_{DCF} = 0$ dBm. The maximum Q factor has been obtained for $DCR = 0.85$. For the optimal value of $DCR = 0.85$, the SSMF and DCF input powers have been varied in the range from 16 to 21 dBm and -15 to 12 dBm, respectively, in steps of 0.5 dB. The results are summarized in Fig. 9 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. Corresponding BER contour plot is shown in Fig. 10.

B. Pre-compensation scheme

In this GVD compensation scenario the maximum SSMF length at which the $BER < 10^{-15}$ can be guaranteed with reasonable margin is about 220 km. Figure 11 plots the BER as a function of DCF input power for $DCR = 1.0$ and $P_{SSMF} = 14$ dBm. For $L_{SSMF} = 230$ km the BER limit cannot be achieved. The effect of GVD compensation ratio has been investigated in the same way as in the case of post-compensation scheme. Figure 12 shows the dependence Q-factor on DCR for $L_{SSMF} = 220$ km, $P_{DCF} = 2$, 6, 10, 14, and 16 dBm and $P_{SSMF} = 8$ dBm. In comparison with the post-compensation scheme, the sensitivity to DCR is not so pronounced, the optimum value of DCR is slightly shifted to higher values, see Fig. 6, 7, and 8. Corresponding contour plot demonstrating the dependence of Q factor on DCF input power and DCR is shown in Fig. 13. It is seen that in contrast to post-compensation scheme, optimum performance is reached for $0.85 < DCR < 0.95$. The optimal value of DCF input power is much higher than in the case of post-compensation scheme and ranges from 10 to 16 dBm. Optimal value of SSMF input power ranges from 7 to 9 dBm. In the next two figures we summarize the analysis of SSMF and DCF input powers for the case of optimal GVD compensation ratio, $DCR = 0.85$, ($L_{SSMF} = 220$ km, $L_{DCF} = 37.4$ km). Figure 14 shows the BER as a function of DCF and SSMF input powers, the corresponding Q factor contour plot is displayed in Fig. 15.

III. Conclusion

Results of an extensive numerical simulations have been presented showing the distance limits of NRZ data transmission at 10 Gbit/s over standard single mode fibre (G.652) with GVD compensation by means of DCF without the deployment of in-line erbium-doped fibre amplifiers. We have found, that the post-compensation scheme performs better than the pre-compensation one when the SSMF and DCF input power levels and the dispersion compensation ratio are carefully optimized. Bit-error-ratio less than 10^{-15} can be expected with reasonable margin when the SSMF length is 270 and 220 km for post- and pre-compensation scheme, respectively. Optimal ratio of GVD dispersion compensation was found to be $0.75 < DCR < 0.90$ and $0.85 < DCR < 0.95$, for post- and pre-compensation scheme, respectively. The pre-compensation scheme is less sensitive to DCR than the post-compensation one.

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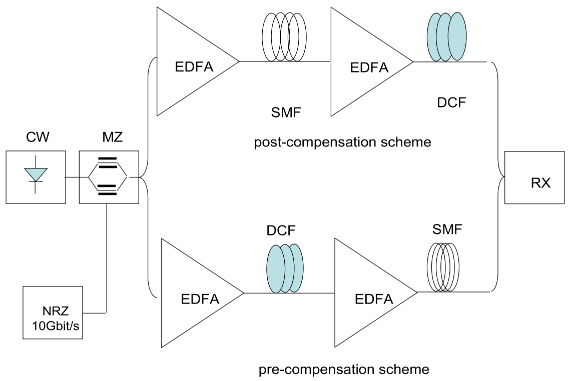

Fig. 1. Schematic diagram of post- and pre-compensation scheme under investigation.

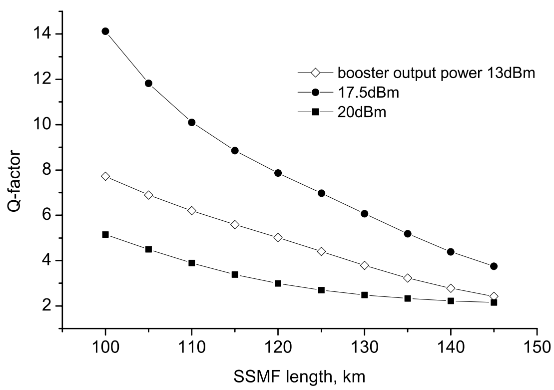

Fig. 2. Q-factor as a function of SSMF length: no GVD compensation, $P_{SSMF} = 13$, 17.5, and 20 dBm.

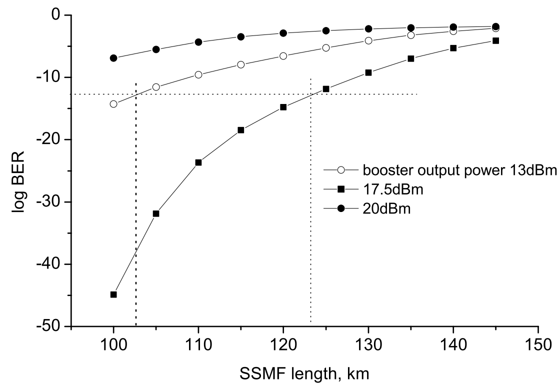

Fig. 3. Logarithm of BER as a function of SSMF length: no GVD compensation, $P_{SSMF} = 13$, 17.5, and 20 dBm.

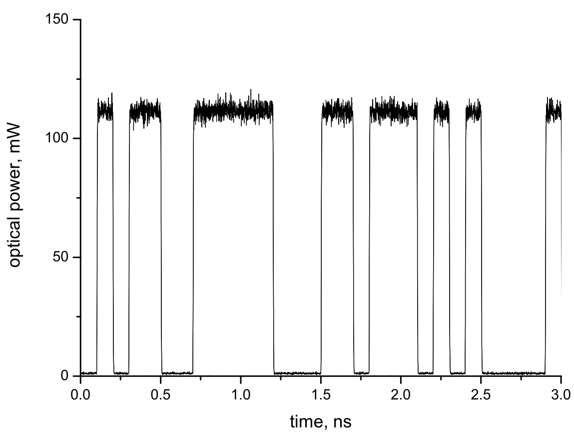

Fig. 4. Pulse shape at the input of 100 km of SSMF: $P_{SSMF} = 17.5$ dB.

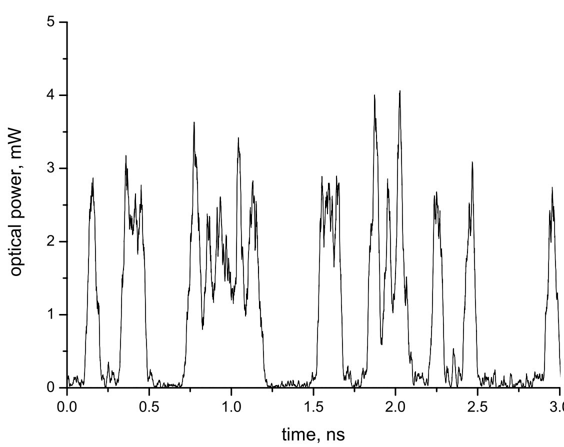

Fig. 5. Pulse shape after 100 km of SSMF: no GVD compensation, $P_{SSMF} = 17.5$ dBm.

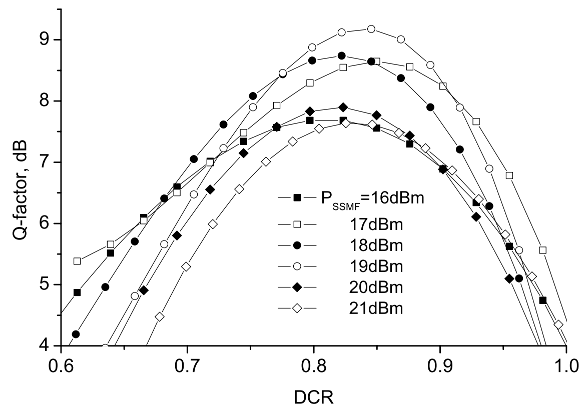

Fig. 6. Q-factor as a function of DCR for post-compensation scheme: $L_{SSMF} = 270\,\mathrm{km}$, $P_{SSMF} = 16$, 17, 18, 19, 20, and 21 dBm, $P_{DCF} = 0\,\mathrm{dBm}$.

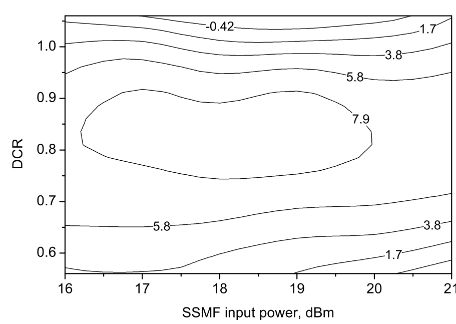

Fig. 7. Q-factor as a function of P_{SSMF} and DCR for post-compensation scheme: $L_{SSMF} = 270\,\mathrm{km}$, $P_{DCF} = 0\,\mathrm{dBm}$.

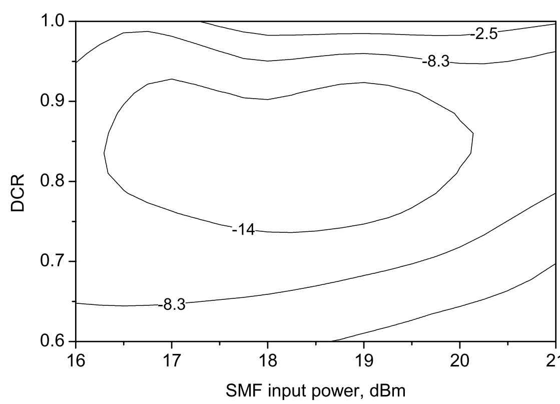

Fig. 8. Logarithm of BER as a function of P_{SSMF} and DCR for post-compensation scheme: $L_{SSMF} = 270\,\mathrm{km}$, $L_{DCF} = 45.9\,\mathrm{km}$, $(DCR = 0.85)$.

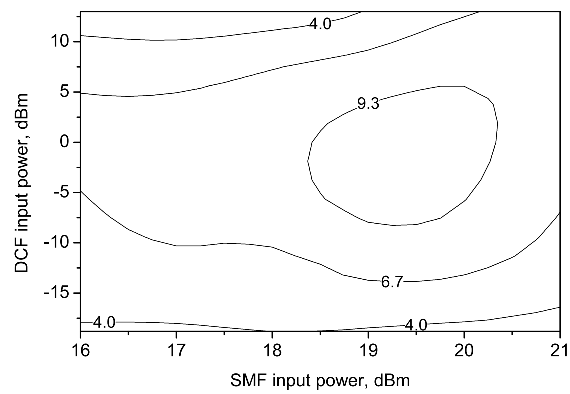

Fig. 9. Q-factor as a function of P_{SSMF} and P_{DCF} for post-compensation scheme: $L_{SSMF} = 270\,\mathrm{km}$, $L_{DCF} = 45.9\,\mathrm{km}$, $(DCR = 0.85)$.

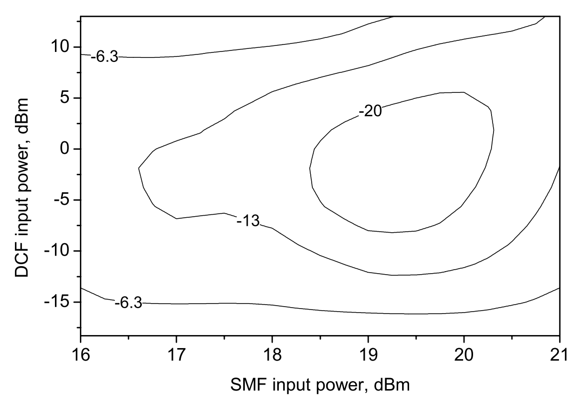

Fig. 10. Logarithm of BER as a function of P_{SSMF} and P_{DCF} for post-compensation scheme: $L_{SSMF} = 270\,\mathrm{km}$, $L_{DCF} = 45.9\,\mathrm{km}$, $(DCR = 0.85)$

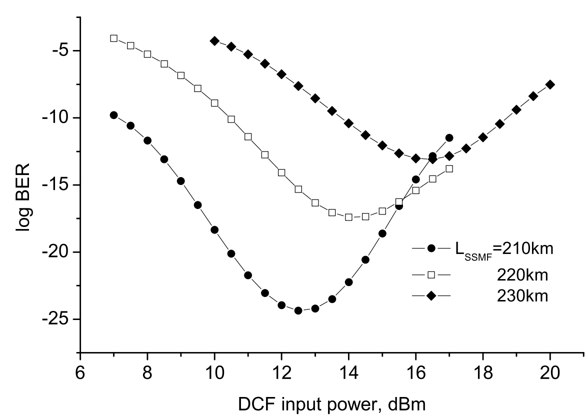

Fig. 11. Logarithm of BER as a function of P_{DCF} for pre-compensation scheme: $L_{SSMF} = 210$, 220, and $230\,\mathrm{km}$, $P_{SSMF} = 14\,\mathrm{dBm}$, $DCR = 1.0$.

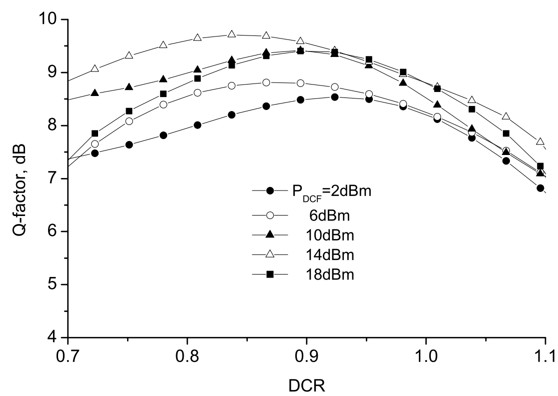

Fig. 12. Q factor as a function of DCR for pre-compensation scheme: $L_{SSMF} = 220\,\mathrm{km}$, $P_{SSMF} = 8\,\mathrm{dBm}$, $P_{DCF} = 2$, 6, 10, 14, and 18 dBm.

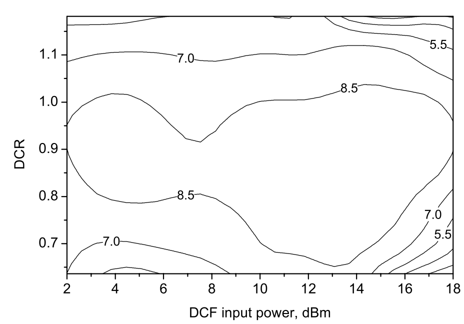

Fig. 13. Q factor as a function of P_{DCF} and DCR for pre-compensation scheme: $L_{SSMF} = 220\,\mathrm{km}$, $P_{SSMF} = 8\,\mathrm{dBm}$.

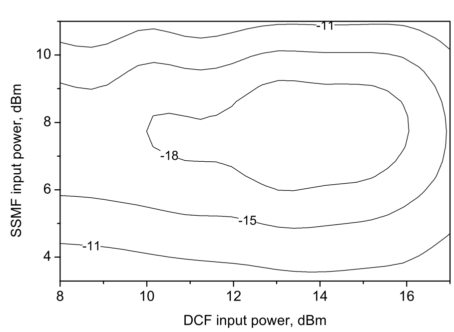

Fig. 14. Logarithm of BER as a function of P_{DCF} and P_{SSMF} for pre-compensation scheme: $L_{SSMF} = 220\,\mathrm{km}$, $L_{DCF} = 37.4\,\mathrm{km}$, ($DCR = 0.85$).

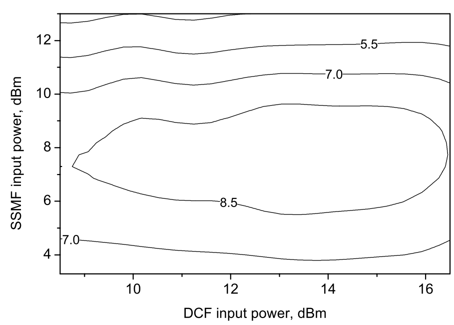

Fig. 15. Q factor as a function of P_{DCF} and P_{SSMF} for pre-compensation scheme: $L_{SSMF} = 220\,\mathrm{km}$, $L_{DCF} = 37.4\,\mathrm{km}$, $(DCR = 0.85)$.