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Optical signal quality improvement due to nonlinear interaction between spectral channels

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Abstract. **This paper examines stimulated Brillouin scattering (SBS) suppression in multichannel DWDM systems owing to nonlinear cross interaction between the channels and its effect on optical signal quality (1/OSNR$_R$) in a communication link. We present an experimental study of single-, three- and five-channel systems with 10 Gbit s^{-1} NRZ channels. The optical signal quality in the three- and five-channel systems is shown to be better than that in the single-channel system. The reason for this is that cross-phase modulation broadens the spectrum of the signal and raises the SBS threshold. This in turn ensures a more pronounced optical signal quality improvement due to self-phase modulation.**

Keywords: *multichannel DWDM systems, nonlinear interaction between channels, optical signal quality, cross-phase modulation, self-phase modulation.*

1. Introduction

The transmission capacity of optical fibre communication systems (OFCS's) is limited by Kerr effect-induced nonlinear distortions. Nonlinear signal distortions in OFCS's generally lead to an increase in bit error rate and limit their maximum transmission range and capacity [1–13]. In single-span links, the lowest threshold nonlinear effect degrading the quality of their operation is stimulated Brillouin scattering (SBS) [14]. To reduce nonlinear effects, special fibres have been designed, with low Kerr nonlinearity [15] and an increased SBS threshold [16].

It is important to note that, as shown earlier [17–19], nonlinear self-phase modulation (SPM) in amplitude modulation OFCS's may improve signal quality. This phenomenon originates from a combined effect of SPM and chromatic dispersion. It was also shown earlier that cross-phase modulation (XPM) in multichannel DWDM systems may extend the spectrum of the signal and increase its Q-factor through SBS suppression [20]. This effect was studied in detail by Downie and Hurley [21] for a multichannel single-span DWDM system with a channel bit rate of 10.7 Gbit s^{-1} (NRZ signal), and they determined the bit error rate (BER) as a function of the number of channels and channel frequency spacing. Their study focused predominantly on Corning Vascade EX1000 G.654-compliant fibre with a shifted cutoff wavelength. Their results demonstrate that, in the case of a combination of several nonlinear effects, the influence of some nonlinear effects may eliminate a negative influence of others.

In the above-mentioned studies [18–21], signal quality was quantified by the BER or Q-factor (which are uniquely related to each other). At the same time, a more important parameter for practical issues in communication network design is the required OSNR (OSNR$_R$)[*]. In particular, it was shown that the optimisation of communication networks by maximising the OSNR margin (OSNR$_M$ ≡ OSNR$_L$/OSNR$_R$) makes it possible to build more reliable communication networks than does the optimisation by minimising the BER [6].

Moreover, as distinct from Q, which is proportional to the signal power in the linear transmission regime, the OSNR$_R$ is independent of signal power in the linear regime. Owing to this, the latter is more convenient to employ in assessing the influence of nonlinear effects on the signal, because the variation of the OSNR$_R$ with signal power demonstrates the influence of nonlinear effects in pure form. In other words, the OSNR$_R$ more accurately gauges the signal quality, not obscured by the varying signal-to-noise ratio, than does the BER or Q-factor. Because of this, optical signal quality will hereafter be gauged by 1/OSNR$_R$. Lower OSNR$_R$ values correspond to higher optical signal quality, and an increase in OSNR$_R$ suggests a reduction in optical quality. Note that we consider Q as a parameter gauging information signal quality.

In previous studies [20, 21], no direct measurements of optical signal quality as a function of input signal power or other parameters in the nonlinear regime were performed. BER values cannot be converted to OSNR$_R$ without knowing additional experimental parameters[**], and no such conversion was made in Refs [20, 21]. Thus, previous experimental

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[*] The minimum optical signal-to-noise ratio required for a transponder to receive a signal in an OFCS at a particular bit error rate (e.g. BER = 10^{-12}).

[**] The Q-factor is uniquely related to the BER, and the calibration curve of the transponder uniquely relates the BER to OSNR$_{BER}$. In turn, 1/OSNR$_{BER}$ = 1/OSNR$_L$ + 1/OSNR$_{NL}$, and 1/OSNR$_R$ = 1/OSNR$_{BTB}$ – 1/OSNR$_{NL}$ [6]. Thus, experimental BER data can in principle be converted to OSNR$_R$, but only if OSNR$_L$ was measured during experiments and if OSNR$_{BTB}$ and the calibration curve of the transponder are known.

data [20, 21] demonstrate that cross modulation in multichannel systems eliminates the negative effect of SBS but provide no evidence that this is accompanied by optical signal quality improvement.

For practical application of previously found information signal quality improvement effects in multichannel systems, direct investigation of the effect of XPM on the optical signal quality 1/OSNR$_\mathrm{R}$ is needed. Such investigation was carried out in this work for high-power single-span DWDM systems with a channel bit rate of 10 Gbit s^{-1}. Our experimental data demonstrate that, in a single-span OFCS with a 10 Gbit s^{-1} OOK NRZ signal, optical signal quality in a given DWDM channel can be improved by adding one or a few neighbouring DWDM channels. This can be accounted for by the fact that cross-phase modulation extends the spectrum of the signal and raises the SBS threshold. This in turn allows the optical signal quality improvement effect to show up to a higher degree owing to self-phase modulation.

2. Anomalous behaviour of 10 Gbit s^{-1} channels

Figure 1 shows a schematic of the experimental setup. The required OSNR was measured as a function of channel power in a 50-km length of SSMF (Fig. 2). Broadband amplified spontaneous emission (ASE) noise from a noise source was mixed to the system through a variable optical attenuator (VOA). To measure the OSNR$_\mathrm{R}$ at a particular input power level, the ASE noise power was gradually raised using the VOA until failure of the line (loss of matching). Next, the ASE noise power was slightly reduced to restore the performance of the system with the required bit error rate (BER = 10^{-12}). The OSNR value at this moment was recorded as OSNR$_\mathrm{R}$. The OSNR was determined using an optical spectrum analyser (OSA). Failure of the line and performance restoration were traced using a BER tester (BERT).

At the end of the line, we used a Teraxion tunable dispersion compensation module (TDCM) for tuning the dispersion at the transponder input to the optimal value (~700 ps nm^{-1}) and an erbium-doped fibre amplifier (EDFA) for tuning the signal power at the transponder input to the optimal value known from previous experiments (–10 to –15 dBm). A second demultiplexer (DEMUX2) at the end of the line served to 'cut off' the broadband ASE noise and reduce the total power at the receiver input to an acceptable level.

The 10 Gbit s^{-1} channel under study was generated by an Oclaro 10G module (UFEC algorithm) and was always in the middle of a group of transmission channels. The neighbouring channels were generated by tunable 10G SFP modules. We examined several configurations: one channel, three channels and five channels with channel frequency spacings of 100 and 200 GHz (Fig. 2). All the channels had identical input powers.

The dependence of the OSNR$_\mathrm{R}$ on input power P_in in the single-channel configuration was consistent with a theoretical model. Self-phase modulation extends the spectrum of the signal with increasing signal power and, accordingly, reduces the pulse duration and increases the pulse amplitude during bit 1 transmission. This leads to a decrease in OSNR$_\mathrm{R}$ before it begins to rise because of various nonlinear effects. Such an effect was also observed previously [17–19].

At the same time, optical signal quality improvement on the addition of neighbouring channels is abnormal. As seen in Fig. 2, the required OSNR in the working channel can be improved by up to 1.2 dB by adding four neighbouring channels with a spacing of 200 GHz (minimum OSNR$_\mathrm{R}$ = 8.4 dB for the single-channel configuration and 7.2 dB for five channels). A decrease in minimum OSNR$_\mathrm{R}$ was also observed in other configurations with additional channels (two neighbouring channels with spacings of 100 and 200 GHz or four neighbouring channels with a spacing of 100 GHz).

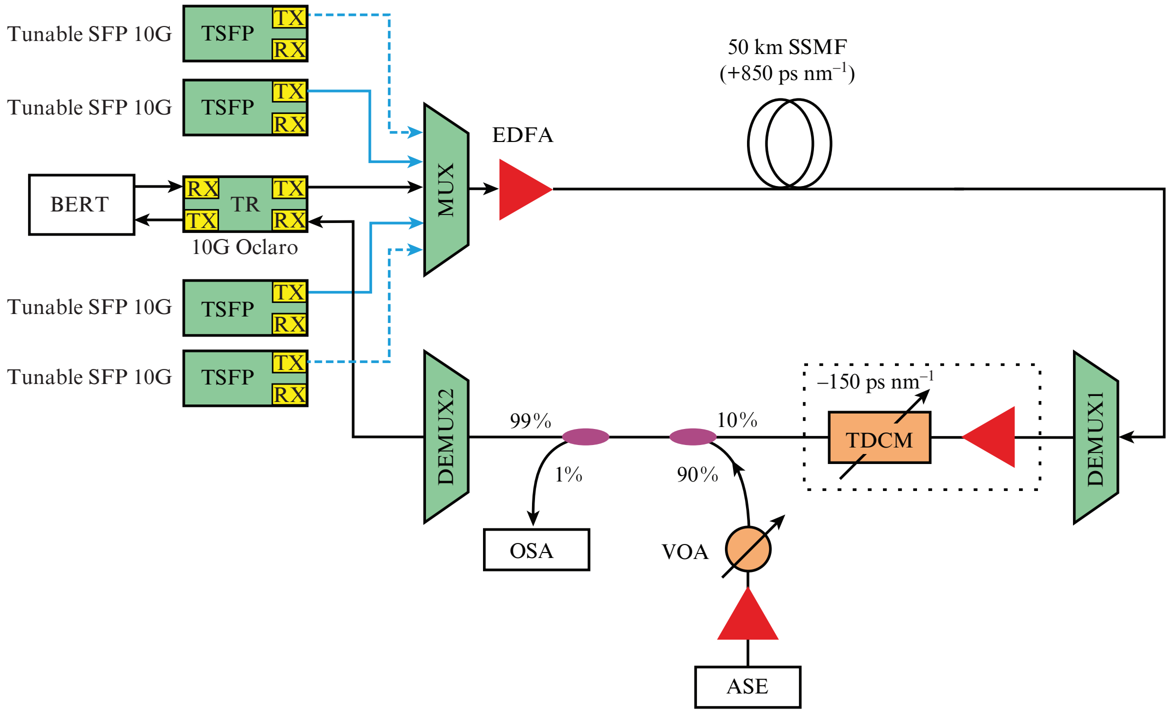

Figure 1. Schematic of an experimental single-span OFCS based on a 50-km length of SSMF.

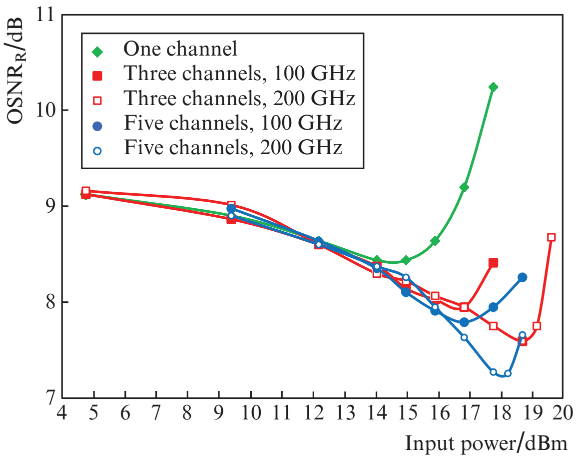

Figure 2. OSNR$_R$ as a function of channel input power P_{in}.

To explicitly demonstrate the anomalous behaviour of the OSNR$_R$ in the channel under investigation, we carried out one more experiment. The input power in the channel under investigation was set constant at a level of +18 dBm (i.e. in the nonlinear regime), whereas the power in the neighbouring channels was varied. We examined several configurations: one neighbouring channel with a spacing of 100 or 200 GHz and two neighbouring channels with a spacing of 200 GHz (Fig. 3).

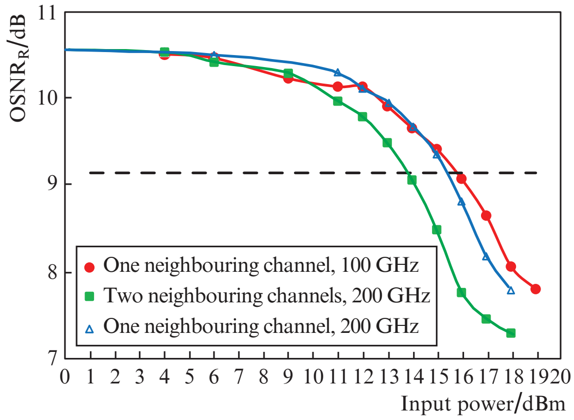

Figure 3. OSNR$_R$ in a given channel as a function of the input power in the neighbouring channels. The input power of the 10 Gbit s^{-1} channel under consideration is constant (+18 dBm). The dashed line represents the OSNR$_R$ level in the linear regime.

In the absence of neighbouring channels, the OSNR$_R$ in a channel with P_{in} = 18 dBm exceeds that in the linear regime by 1.3 dB. (The linear regime takes place at channel input powers under 5 dBm.) Thus, the single-channel configuration with an input power of +18 dBm has a marked nonlinear 'penalty' (+1.3 dB). On the addition of neighbouring channels and a gradual increase in their power, the OSNR$_R$ in the channel under consideration decreases. This is observed in both the two- and three-channel configurations, at spacings of 100 and 200 GHz. The maximum OSNR$_R$ gain in the nonlinear regime is 3.5 dB and is due to the cross interaction of the channel under consideration with its neighbours.

3. Discussion of the observed effect

We assume that the observed increase in OSNR$_R$ with increasing power P_{in} is mainly due not to the SPM effect but to SBS, which begins to influence the signal at lower powers than does SPM. In a multichannel system, however, the SBS threshold is influenced by the XPM effect. Figure 4 shows a schematic diagram illustrating the proposed interpretation of the observed effect.

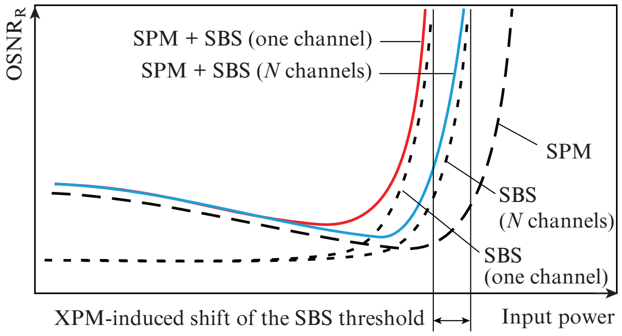

Figure 4. XPM-induced shift of the SBS threshold.

In the single-channel configuration, the main power-limiting factor is SBS. In multichannel systems, cross-phase modulation suppresses SBS. As a result, the SBS threshold shifts to higher P_{in} values. Because of the SBS suppression, the influence of self-phase modulation and cross-phase modulation becomes more pronounced. With increasing signal power P_{in}, the SPM effect first improves the optical quality of the signal and then degrades it. In the presence of SBS, this effect is disguised. In the case of the XPM-induced shift of the SBS threshold, signal quality improvement due to SPM becomes pronounced.

Cross-phase modulation per se degrades signal quality, and the signal degradation is stronger at a smaller channel spacing. This is well seen in Figs 2 and 3: optical signal quality in the multichannel system with a channel spacing of 200 GHz is higher than that in the system with a 100-GHz spacing. In both cases, XPM eliminates the negative effect of SBS, but the XPM-related 'penalty' at a 100-GHz spacing exceeds that at a 200-GHz spacing.

To verify the proposed interpretation of the observed behaviour, we carried out two experiments. First, the SBS threshold was directly measured in a single-span system. Next, we investigated a two-span configuration. In multispan configurations, nonlinear effects, such as SPM and XPM, accumulate, whereas the SBS threshold remains unchanged. Thus, investigation of a two-channel configuration allows our assumption to be verified.

4. Effect of SBS

To verify the above assumptions, we modified the experimental setup by adding a second span with a 50-km length of SSMF (Fig. 5). The spans had identical signal powers. To ensure complete dispersion compensation, a second Teraxion TDCM was placed after the first span. In addition, a 1/99 coupler was placed at the input of the first span in order to measure the backscattered power by an OSA2 optical spec-

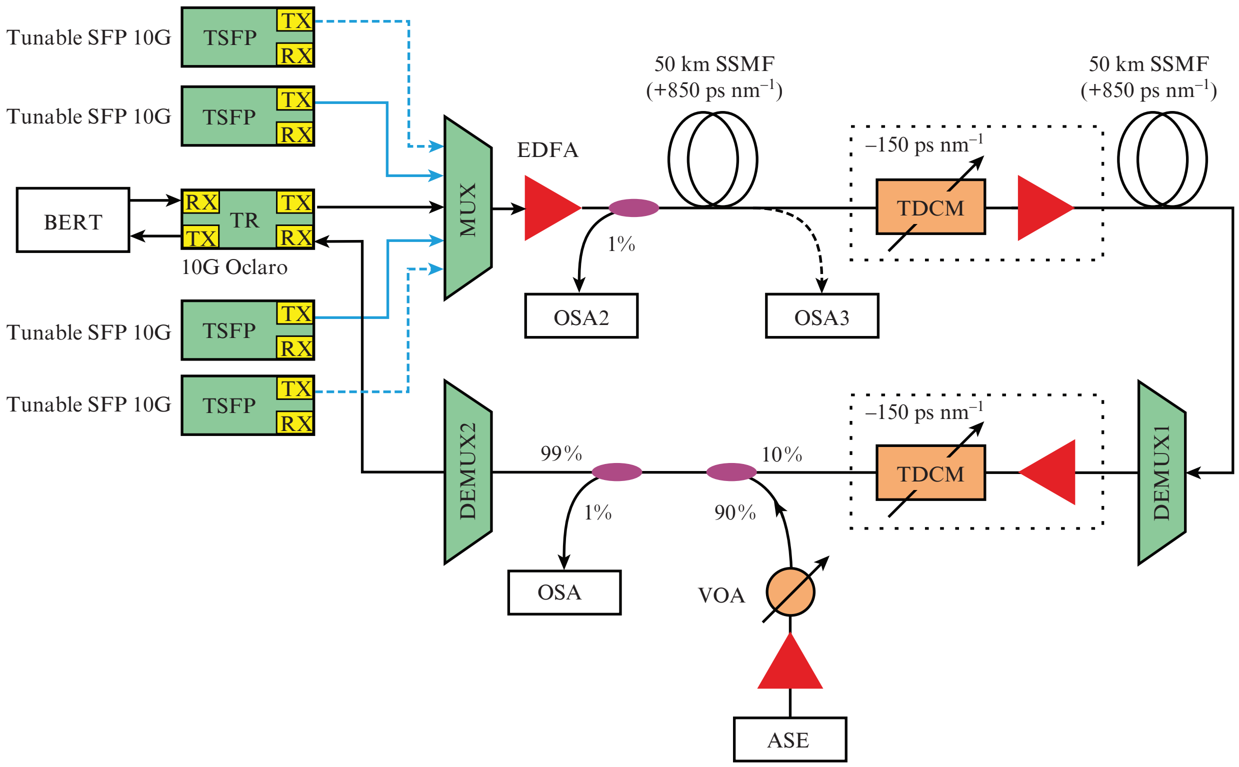

Figure 5. Schematic of an experimental setup based on two 50-km-long SSMF spans.

trum analyser. The output power after the first span was directly measured by switching the signal to an OSA3 optical spectrum analyser.

For direct SBS threshold measurement, we determined the output power (OSA3) (Fig. 6) and backscattered power (OSA2) (Fig. 7) as functions of the input power in the first span. All the experiments were carried out in the single-channel configuration.

Figure 8 shows the backscattered power as a function of input power (expressed in milliwatts).

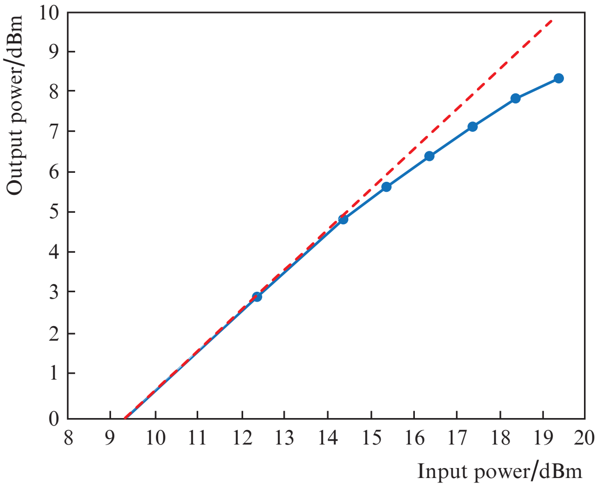

Figure 6. Output power in the first span (one channel) as a function of input power. The dashed line represents the calculation results with no allowance for SBS and the solid line represents experimental data.

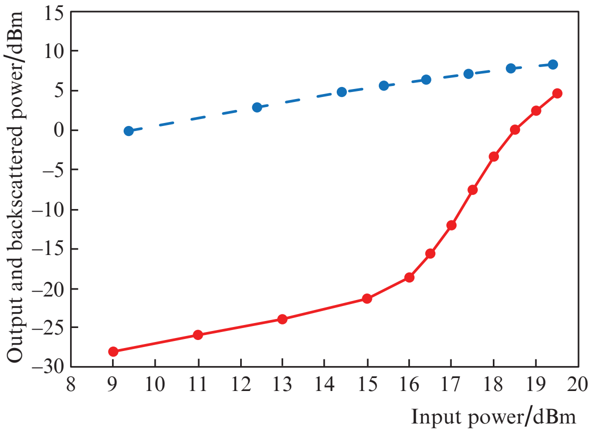

Figure 7. Output power (dashed line) and backscattered power (solid line) as functions of input power in the first span (one channel).

As seen in Figs 6–8, SBS may have a significant effect on the 10 Gbit s^{-1} signal if the input power exceeds 16–17 dBm (40–50 mW). Optical signal quality degradation (an increase in OSNR$_\mathrm{R}$) in a system with a 10 Gbit s^{-1} channel (Fig. 2) begins at roughly the same input power level. This supports the assumption that the increase in OSNR$_\mathrm{R}$ in the 10 Gbit s^{-1} channel under consideration is mainly caused by SBS.

5. Comparison of single- and two-span configurations

It is well known that, in multispan systems with dispersion compensation, the influence of nonlinear effects (SPM and

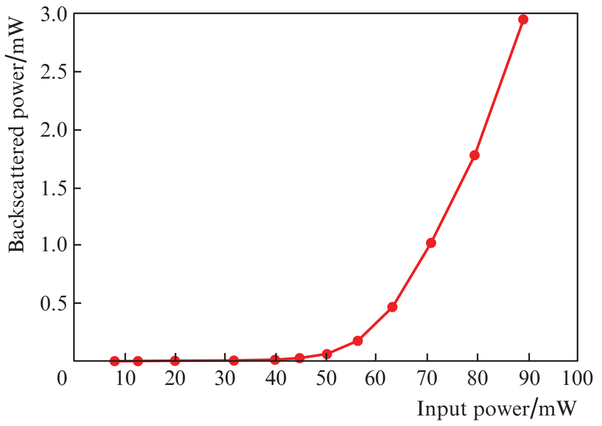

Figure 8. Backscattered power as a function of input power in the first span (one channel).

XPM) accumulates. Thus, it is reasonable to expect that the influence of these effects on the optical signal quality in a two-span system is the same as in a single-span system if the total signal power in the two spans is roughly equal to the signal power in the single-span system, in other words, if the signal power in each span of the two-span system is about 3 dB lower than that in the single-span system.

In contrast to the Kerr effect-induced nonlinear effects (SPM and XPM), the SBS thresholds in the single- and two-span systems are essentially identical. Thus, it would be expected that, due to the effect of SBS, the degradation of optical signal quality in the two-span system should begin at roughly the same signal power level in each span as in the single-span system.

Figure 9 shows the measured required OSNR as a function of input power for the single- and two-span systems. It is seen that the experimental data are well consistent with our assumptions: the effect of SBS becomes significant for one channel in the single-span configuration if the input power exceeds 15 dBm (30 mW) and for one channel in the two-span configuration if the input power in each span exceeds the same 15 dBm. This proves that the increase in required OSNR with increasing input power (the right part of the curves in Fig. 9) is mainly due to SBS.

At the same time, a given optical signal quality level (e.g. $\mathrm{OSNR_R}$ = 8.5 dB) is reached in the two-span system at an input power level in each channel about 3 dB lower than that in the single-span system. Thus, the decrease in required OSNR with increasing input power (the left part of the curves in Fig. 9) is mainly due to the nonlinear SPM effect, which accumulates in multispan systems.

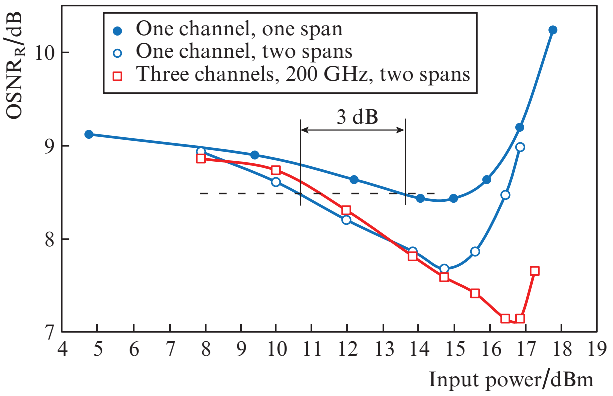

Figure 9. Required OSNR as a function of input power. For two-span configurations, the input power in each channel is indicated.

The addition of neighbouring channels leads to an even larger decrease in minimum $\mathrm{OSNR_R}$. The anomalous behaviour of the OSNR on the addition of neighbouring channels can be accounted for under the assumption that, in the presence of several channels, the effect of SBS (upturn of the curve) becomes discernible at a higher power than in the case of a single channel.

6. Conclusions

We have proposed a new technique for assessing the influence of nonlinear effects on a signal, which relies on optical signal quality ($1/\mathrm{OSNR_R}$) measurements. The use of this technique allowed us to experimentally demonstrate optical quality improvement in a 10 Gbit $\mathrm{s^{-1}}$ DWDM channel on the addition of neighbouring channels. Thus, it has been shown that SBS suppression due to nonlinear cross interaction between the channels, an effect known previously, leads to optical signal quality improvement and can be used in practice in communication link design.

The physical mechanism of the observed effect is that the influence of XPM on a given channel broadens the spectrum of the signal in this channel and, accordingly, leads to SBS mitigation in it. XPM per se degrades optical signal quality, but the concomitant SBS mitigation allows optical signal quality to be significantly improved owing to SPM, and this improvement prevails at least in some of the configurations examined. Thus, the observed 'anomalous' behaviour – signal quality improvement on the addition of neighbouring channels – is a consequence of the combined action of three nonlinear effects: SBS, SPM and XPM.

The feasibility of improving optical signal quality in long-haul communication systems under the action of nonlinear effects is a critical issue. On the one hand, nonlinear effects limit the maximum transmission capacity of OFCS's. On the other, it is nonlinear effects that offer the potential of surmounting the transmission capacity limit of linear systems, which is determined by Shannon's formula [22–24]. However, Shannon's capacity calculation for various nonlinear communication channels remains an unresolved issue.

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