Paper

Power penalty caused by Stimulated Raman Scattering in WDM Systems

Sławomir Pietrzyk, Waldemar Szczęsny, and Marian Marciniak

Abstract — In this paper we present results of an investigation into the power penalty introduced by Stimulated Raman Scattering (SRS) in WDM systems with concentration on application of dispersion-shifted single-mode optical fibres (G.653) and unequal channel allocation schemes. System parameters based on ITU-T Recommendation G.692 and analytic formulas were used in calculations. It is shown that SRS does present a practical limitation to the multichannel systems. We also indicate limitations of the G.692 Recommendation and we point at directions of study in the area of nonlinear phenomena and multichannel systems.

Keywords* — *optical communications, WDM systems, Stimulated Raman Scattering.

Introduction to WDM systems

Recent years have shown a rapid growth of demand for capacity of telecommunication networks. It has inspired many laboratories to explore new techniques of more efficient utilization of the huge bandwidth offered by optical fibre links. One of the most promising and cost effective ways to increase optical link throughput is a technique known as Wavelength Division Multiplexing (WDM).

In a WDM system we transmit many information channels through one fibre using different optical wavelengths modulated by independent data streams. This method is analogous to Frequency Division Multiplexing (FDM) which is widely exploited in other communication systems, especially in radio broadcasting. Using WDM we can easily increase the capacity of already existing fibre links that is particularly significant in the areas where placing new cables is impossible or too expensive. WDM is a technique compatible with the idea of all-optical networks, where we can create the transparent optical paths connecting successive network nodes by switching optical channels organised at the different light wavelengths. One can also envision the application of WDM in broadcast networks and/or in subscriber loop [2].

These and other advantages of WDM have prompted the beginning of standardization work [8]. Nevertheless the job is not yet completed and further research and estimations are required [10].

Nonlinear limitations

In spite of its merits the WDM technique is not free from limitations. The most characteristic and essential problem for multichannel optical systems, beside attenuation and dispersion, is interchannel crosstalk [1]. One can distinguish crosstalk caused by nonlinear interactions between the light and the fibre material, such as: Stimulated Raman Scattering (SRS), Stimulated Brillouin Scattering (SBS), Cross-Phase Modulation (XPM) and Four-Wave Mixing (FWM). This paper is devoted to the influence of SRS on WDM transmission.

Stimulated Raman Scattering is an interaction between the light and molecular vibrations of SiO_2. It results itself as a frequency conversion of the light wave that is put into the fibre. Two new spectral lines appear around the main one. The lower frequency wave is called the Stokes wave and is usually much stronger than the higher frequency wave called the anti-Stokes wave. This causes power depletion of the light injected into the fibre. Generally, this is not a problem for single channel systems, because of relatively high power threshold at which the degradation introduced by SRS is noticeable. But if we inject two optical waves separated by the Stokes frequency into the fibre where Raman interactions take place, the power of the lower frequency wave (called the probe) will increase at the expense of the higher frequency wave (called the pump). Such an energy transfer from one channel to another is called interchannel crosstalk. It is important to underline that SRS appears when the light is present in both channels, i.e. "1" bits are transmitted simultaneously. The Stokes frequency is also called a bandwidth of the Raman gain. In more complex case of higher number of channels, the lower frequency channels are amplified at the expense of the higher frequency channels if only the frequency difference between them lies in the bandwidth of the Raman gain. This phenomenon requires much lower optical power levels than in the case of single channel systems.

Power penalty calculus

In multichannel systems, the channel that is most severely affected by SRS is the highest frequency channel (called the 0-th channel). The power loss that is present at the 0-th channel may be calculated as the sum of power fractions transmitted from this channel to each of the other channels located at lower frequencies. The total fractional power lost by the 0-th channel is given by [1, 3]

$$D = \sum_{i=1}^{N-1} \frac{f_0 P_i g_i L_{eff}}{f_i A_{eff}} , \qquad (1)$$

where: i – channel index, f_0 – frequency of the 0-th channel, f_i – frequency of the i-th channel, N – number of channels, P_i – power injected in the i-th channel, L_{eff} – effective fibre length, A_{eff} – effective core area, g_i – Raman gain coefficient coupling the i-th channel with the 0-th channel.

Effective fibre length L_{eff} can be expressed by

$$L_{eff} = \frac{1 - e^{-\alpha L}}{\alpha} , \tag{2}$$

where α denotes the fibre loss coefficient and L is the actual fibre length.

Raman gain coefficient g_i depends on the frequency difference between the channels that exchange power. Assuming a triangular approximation of the Raman gain profile in silica fibres [3] and full polarization scrambling occurring inside the fibre, we obtain

$$g_i = \frac{G \Delta f_i}{2 \Delta F} , \tag{3}$$

where G is the peak Raman gain coefficient, ΔF is the Raman gain bandwidth, $\Delta f_i = f_0 - f_i$.

The fraction of the power that remains at the 0-th channel (expressed in dB) is:

$$P\_rem1 = -10 \lg(1 - D) . \tag{4}$$

Applying the analysis proposed by [10] we obtain the following equation determining the fraction of the power that remains at the 0-th channel (expressed in dB):

$$P\_rem2 = -10 \lg \left[1 - \sum_{i=1}^{N-1} \left(1 - \exp \left(\frac{P_i f_0 L_{eff} g_i}{f_i A_{eff}} \right) \right) \right] . \tag{5}$$

Results of theoretical approach

Using the above relations we calculated power penalties introduced by SRS in point to point unidirectional WDM system without in-line amplifiers, employing unequal channel spacing [8] and the dispersion-shifted single-mode optical fibre [6].

The transmission on G.653 fibres is strongly limited by Four-Wave Mixing (FWM) if channels are equispaced. One way to avoid crosstalk introduced by FWM is to apply unequal channel allocation scheme. According to [8] all the channels should be placed on a frequency grid anchored at the reference frequency of 193.1 THz ($\lambda = 1552.52$ nm) with interchannel spacings equal to integer multiples of 100 GHz. The set of the integers is determined by choosing channel allocation scheme. In our work we considered 8-channel system with the following unequal channel allocation plans: A - {1, 3, 5, 6, 7, 10, 2} times 100 GHz, counting from the highest frequency channel (the 0-th channel is assumed to be at 196.1 THz); B - {2, 4, 10, 3, 8, 7, 5} times 100 GHz; C - 3, 7, 12, 2, 6, 5, 4 times 100 GHz; D - {6, 7, 8, 9, 10, 12, 11} times 100 GHz. These values are suggested by [8]. We also calculated power depletion for the similar system but with equal channel separation (100 GHz), referring to it as the scheme E. Table 1 shows channel frequencies for each of the above allocation schemes.

In our calculations we also assumed the following system parameters:

- fibre loss coefficient for the G.653 fibre: $\alpha = 0.2$ dB/km,
- mode field diameter for the G.653 fibre: MFD = 7 μm; this gives the effective core area [5]: $A_{eff} = 36.33\ \mu\text{m}^2$,
- fibre span length: L = 120 km,
- frequency of the 0-th channel: f_0 = 196.1 THz,
- Raman gain bandwidth $\Delta F = 15$ THz,
- peak Raman gain coefficient G = $7 \cdot 10^{-14}$ m/W,
- range of power injected in each of the channels: $1 \div 17$ mW.

The analysis concerns the 'worst case', i.e. the case of the 0-th channel and the simultaneous presence of "1" bits in all the channels. Power in the other channels (different than the 0-th one) is assumed not to be affected by the nonlinearities. Beside SRS, influence from other nonlinear phenomena as well as from the dispersion is neglected. The results of calculations are presented in Fig. 1.

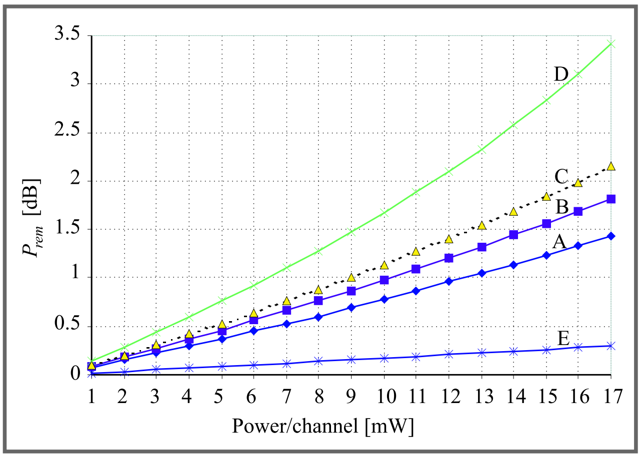


Fig. 1. Worst case power penalty introduced by SRS
The fraction of the power P_rem1 as a function of the power levels injected in each of the channels for various channel allocation schemes (A, B, C, D, E) calculated using formula (4).

Using formula (5) we got the curves very similar to the above ones. The biggest difference between the results obtained by (4) and (5) was 0.3 dB.

In [8] the Class 3A laser limit (17 dBm @ 1550 nm) is suggested as the maximum total optical power. Let us assume

Table 1
Channel frequency choices (in THz) for 8-channel system working on G.653 fibre and different channel allocation schemes (A, B, C, D, E)

Scheme	Channel index							
	0	1	2	3	4	5	6	7
A	196.1	196.0	195.7	195.2	194.6	193.9	192.9	192.7
B	196.1	195.9	195.5	194.5	194.2	193.4	192.7	192.2
C	196.1	195.8	195.1	193.9	193.7	193.1	192.6	192.2
D	196.1	195.5	194.8	194.0	193.1	192.1	190.9	189.8
E	196.1	196.0	195.9	195.8	195.7	195.6	195.5	195,4

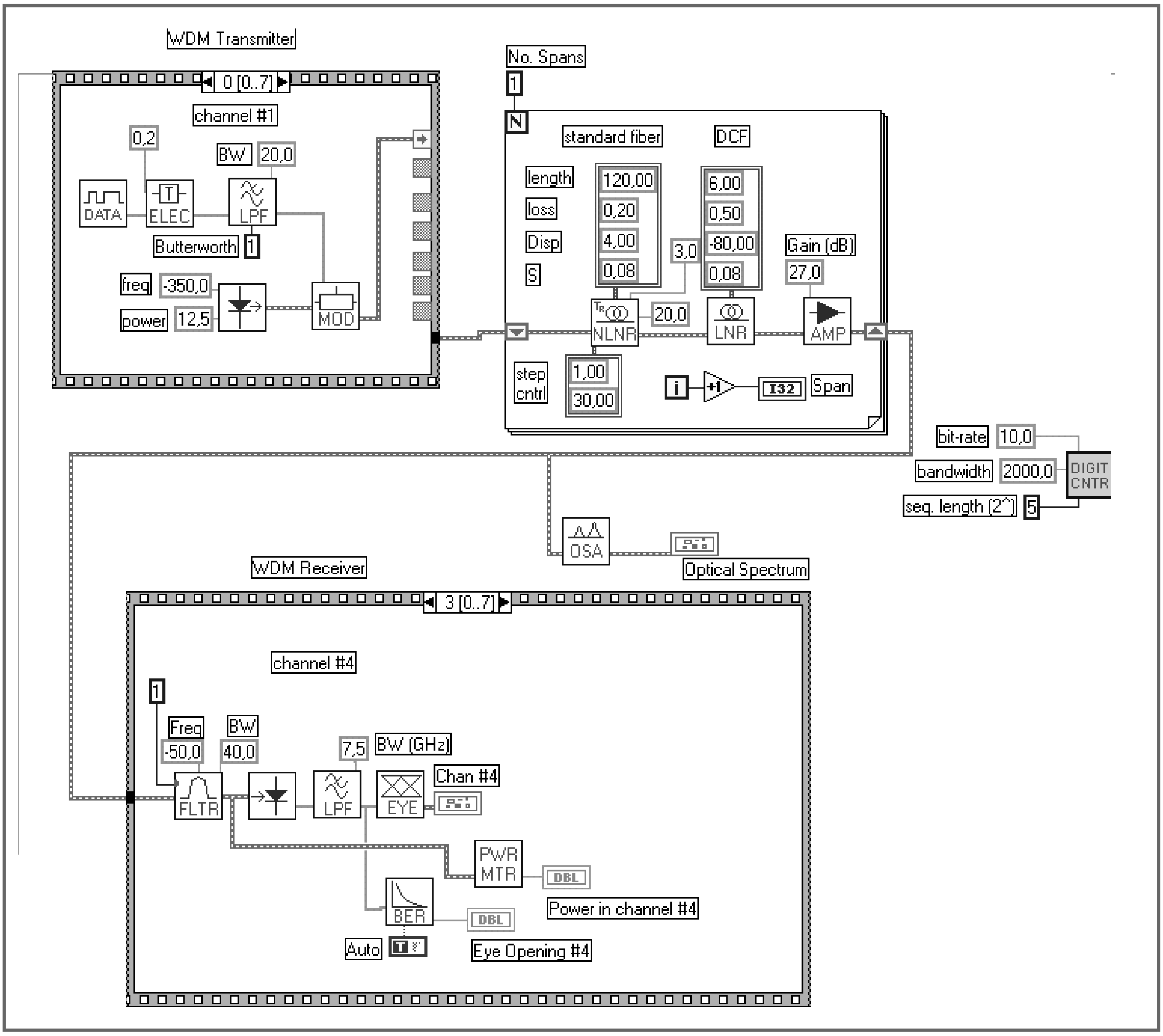
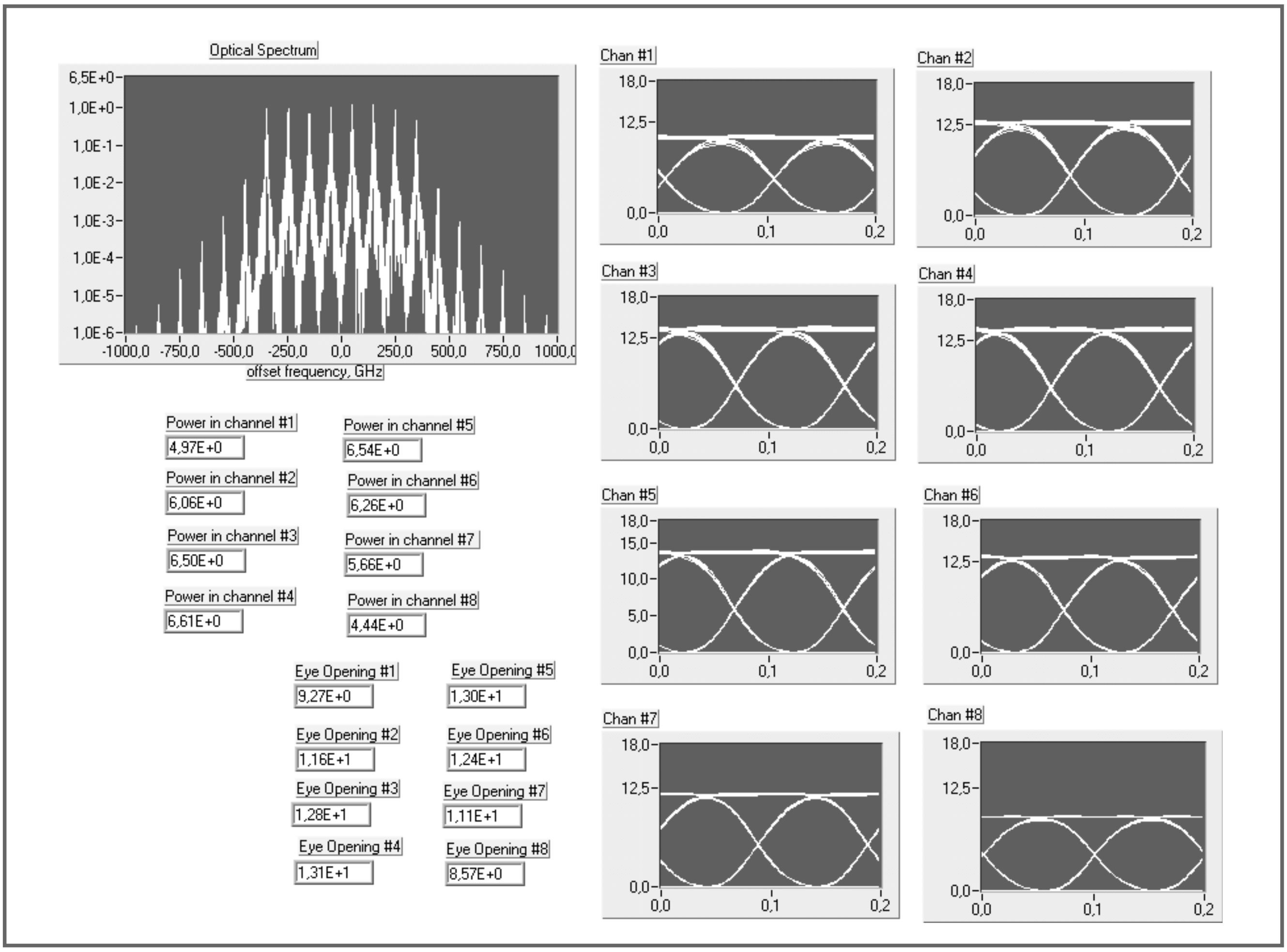


Fig. 2. Simulation model of the 8-channel WDM system



Power in channel #1: 4,97E+0
Power in channel #2: 6,06E+0
Power in channel #3: 6,50E+0
Power in channel #4: 6,61E+0
Power in channel #5: 6,54E+0
Power in channel #6: 6,26E+0
Power in channel #7: 5,66E+0
Power in channel #8: 4,44E+0

Eye Opening #1: 9,27E+0
Eye Opening #2: 1,16E+1
Eye Opening #3: 1,28E+1
Eye Opening #4: 1,31E+1
Eye Opening #5: 1,30E+1
Eye Opening #6: 1,24E+1
Eye Opening #7: 1,11E+1
Eye Opening #8: 8,57E+0

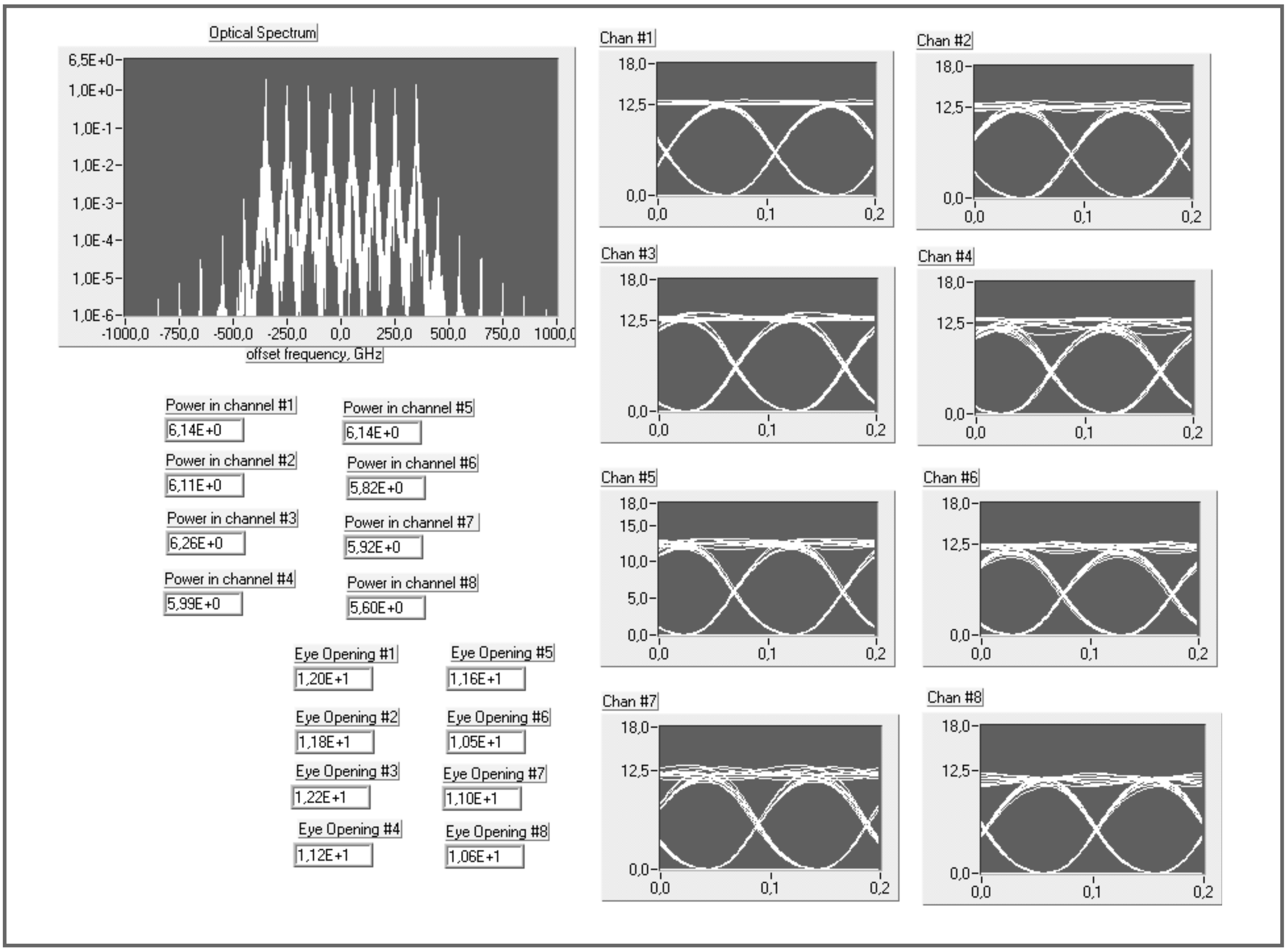
Fig. 3. Simulation of Raman scattering in a nonlinear fibre transmission of identical binary data streams in all WDM channels - referred as *Case 1*

the scheme A of frequency plan for simplification. An important issue is whether we should use peak or average per channel power [4]. If we consider the average power of the channels in our calculations then for 17 dBm limit the per channel power will be equal to 6.25 mW (for 8-channel system, scheme A) and we will obtain power penalty at 0.47 dB. This corresponds to 90% of the power that remains at the 0-th channel. But if instead of the average per channel power we use the peak per channel power, what is recommended in [10] for G.653 fibres, then for 17 dBm limit we will obtain power penalty at 1 dB. This gives 79% of the power that remains at the highest frequency channel. It is for this reason that the line coding is binary non-return to zero (NRZ) [7], scrambled according to [9] and the probabilities of 1 and 0 bits are equal. Hence the peak per channel power is double the average per channel power (12.5 mW). As seen in Fig. 1, much worse situation occurs for other channel allocation schemes. For example, for scheme D the power penalty is 2.22 dB at 12.5 mW of input peak per channel power and it corresponds to only 60% of the power remaining at the 0-th channel.

Simulation of the WDM system

In order to evaluate the exactness of the theoretical approach we have done extensive computer simulations of the 8 STM-64 channel WDM transmission system reported in the previous section. The highest value of total-mean optical power level of 17 dBm has been investigated. A GOLD$^{\mathrm{TM}}$ simulation software has been applied. The architecture of the analysed WDM system is shown in Fig. 2. A 100 GHz frequency grid has been chosen for eight DFB laser sources. The lasers are externally modulated with 10 GHz pseudo-random data sequences. Since the theoretical approach does not include fibre dispersion effects, a 6-km long dispersion compensating fibre is added at the end of the link in order to eliminate totally the pulse dispersion in the link. Propagation of the field in the X-polarization state in a nonlinear fibre is modelled using the following nonlinear partial differential equation [11]:

$$\frac{\partial A_x}{\partial z} - \frac{i}{2}\beta_2 \frac{\partial^2 A_x}{\partial T^2} - \frac{1}{6}\beta_3 \frac{\partial^2 A_x}{\partial T^2} + \frac{\alpha}{2} A_x = \\ -i\gamma \left[|A_x|^2 A_x - T_R A_x \frac{\partial^2 |A_x|^2}{\partial T^2} \right], \tag{6}$$



Power in channel #1: 6,14E+0
Power in channel #2: 6,11E+0
Power in channel #3: 6,26E+0
Power in channel #4: 5,99E+0
Power in channel #5: 6,14E+0
Power in channel #6: 5,82E+0
Power in channel #7: 5,92E+0
Power in channel #8: 5,60E+0

Eye Opening #1: 1,20E+1
Eye Opening #2: 1,18E+1
Eye Opening #3: 1,22E+1
Eye Opening #4: 1,12E+1
Eye Opening #5: 1,16E+1
Eye Opening #6: 1,05E+1
Eye Opening #7: 1,10E+1
Eye Opening #8: 1,06E+1

Fig. 4. Simulation of Raman scattering in a nonlinear fibre transmission of non-correlated data streams in different WDM channels referred as *Case 2*

where $A_x(z,T)$ is the slowly varying field envelope and β_2, β_3, α and γ are related to the dispersion, dispersion slope, loss and nonlinearity of the fibre. Equation (6) is solved using the split step Fourier method [11]. The algorithm uses an adaptive step-size [14].

The nonlinear coefficient γ for the fibre is defined as [11]: $\gamma = \frac{n_2 \omega}{c A_{eff}}$.

Here, n_2 is the Kerr nonlinear index coefficient, ω is the angular optical frequency, A_{eff} is the effective core area, and c is vacuum speed of the light. The coefficient γ accounts for the effects of SPM [12], XPM [13] and FWM [14].

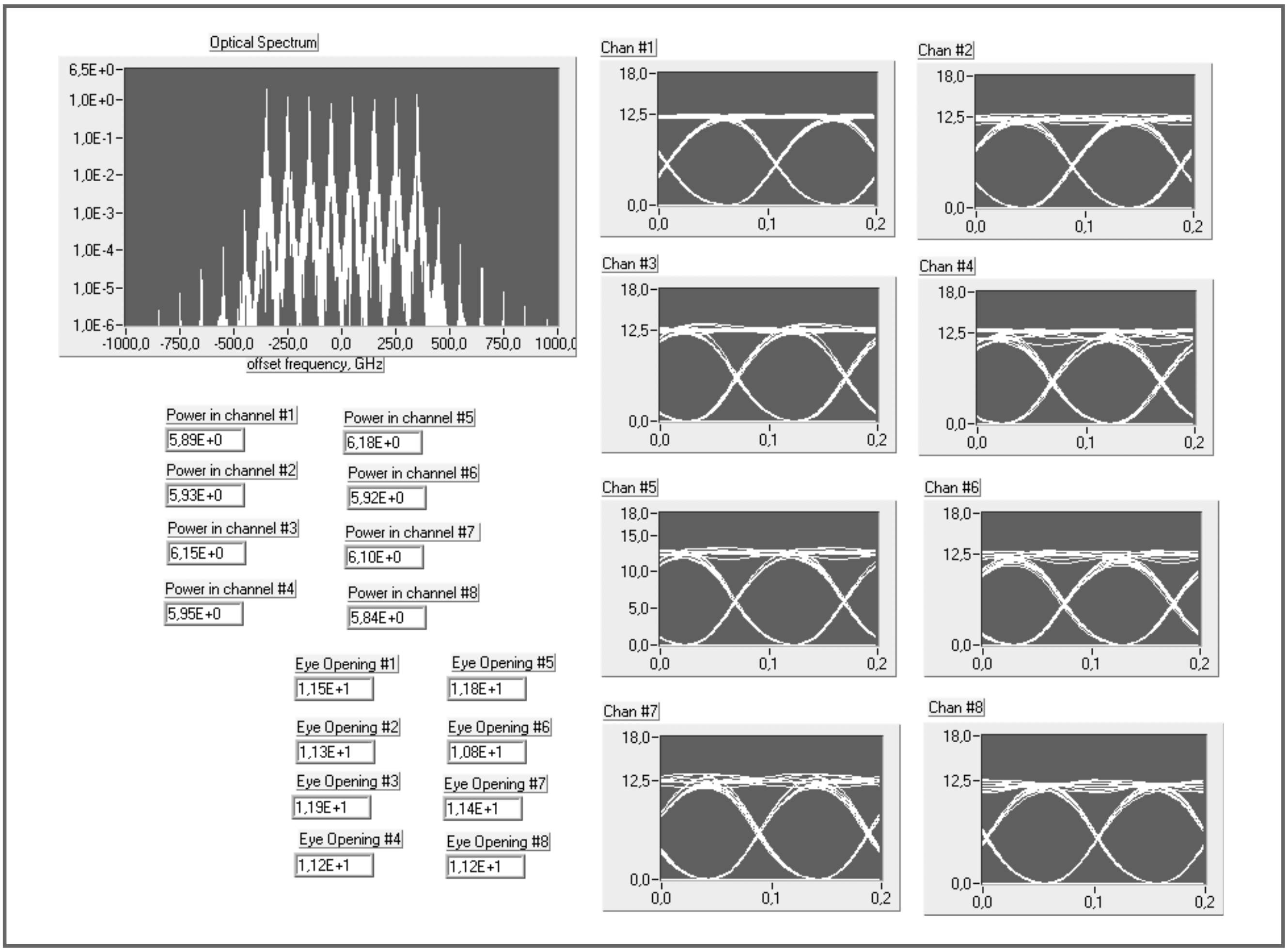
The parameter T_R is related to the slope of the Raman gain and is assumed to vary linearly with frequency in the vicinity of the carrier frequency [11]. The parameter T_R is estimated to be ~ 5 fs [11]. Raman gain is polarization dependent, and consequently the value of T_R has to be halved from its value for identical states of polarization if one wants to account for the effective SRS effect between WDM channels that will have their states of polarization randomly scrambled at long distances.

In order to verify the accuracy of theoretical calculations, simulations for three different cases have been carried out: *Case 1*: Raman scattering in a nonlinear fibre transmission of identical binary data streams in all WDM channels (worst case), *Case 2*: Raman scattering in a nonlinear fibre transmission of non-correlated data streams in different WDM channels, *Case 3*: the same as in *Case 2* but with absence of SRS.

A comparison of plots in Fig. 3 for *Case 1* (correlated data with Raman scattering) and in Fig. 5 for *Case 3* (non-correlated data without Raman scattering) reveals that additional loss increase resulting from SRS is c.a. 1.2 dB (from 5.84 mW in Fig. 5 to 4.44 mW in Fig. 3) for the highest frequency channel (here marked as the 8-th channel).

A comparison of plots for non-correlated data in Fig. 4 for *Case 2* (with Raman scattering) and in Fig. 5 for *Case 3* (without Raman scattering) gives a small influence of Raman scattering in the absence of data correlation in the channels. The SRS in *Case 2* gives only a small increase of eye closure and decrease of power in the highest frequency channel (from 5.84 mW in Fig. 5 to 5.60 mW in Fig. 4).

Therefore, we conclude that the theoretical approach is valuable for real multichannel optical systems.



Power in channel #1 5,89E+0
Power in channel #2 5,93E+0
Power in channel #3 6,15E+0
Power in channel #4 5,95E+0
Power in channel #5 6,18E+0
Power in channel #6 5,92E+0
Power in channel #7 6,10E+0
Power in channel #8 5,84E+0

Eye Opening #1 1,15E+1
Eye Opening #2 1,13E+1
Eye Opening #3 1,19E+1
Eye Opening #4 1,12E+1
Eye Opening #5 1,18E+1
Eye Opening #6 1,08E+1
Eye Opening #7 1,14E+1
Eye Opening #8 1,12E+1

Fig. 5. Simulation of Raman scattering in a nonlinear fibre transmission of non-correlated data streams in different WDM channels without Raman scattering – referred as *Case 3*

Conclusions

Our results indicate that the proper choice of channel allocation plan is significant for WDM transmission with application of G.653 fibres. Contrary to what is stated in [8], SRS does present a practical limitation to the multichannel systems.

Moreover, some of the schemes proposed in [8] are contradictory with what can be found in other parts of [8], for example: (1) once 100 GHz is recommended as a minimal frequency spacing (as it is in scheme A) then it is stated that 200 GHz is more suitable because of the EDFA gain dip, (2) in the case of some schemes (like scheme D), the total occupied bandwidth falls out of the EDFA bandwidth, (3) there is no indication in [8] where the channel allocation plan must begin (i.e. the 0-th channel frequency is not determined).

The problems with SRS can be overcome either by employing other channel allocation plans or by reducing the power level injected into the fibre and at the same time lowering the receiver threshold. There are also other important issues that require further study: (1) the impact from SRS on repeated systems with in-line amplifiers [10] which is expected to be more severe than for unrepeated systems, (2) the influence from dispersion that should decrease nonlinear effects, (3) the case of bi-directional WDM transmission, etc.

A standardization procedure of the G.692 Recommendation is not yet closed and we should believe that the future version of this recommendation will be more complete.

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Sławomir Pietrzyk
Technical University of Kielce, Al. 1000-lecia P. P. 7, 25-314 Kielce, Poland, e-mail: slav@srv1.tu.kielce.pl

Waldemar Szczęsny
National Institute of Telecommunications, 1 Szachowa Str., 04-894 Warsaw, Poland, e-mail: W.Szczesny@itl.waw.pl

Marian Marciniak
Technical University of Kielce, Al. 1000-lecia P. P. 7, 25-314 Kielce, Poland; National Institute of Telecommunications, 1 Szachowa Str., 04-894 Warsaw, Poland, e-mail: M.Marciniak@itl.waw.pl