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Analysis of FWM Penalties in DWDM Systems Based on G.652, G.653, and G.655 Optical Fibers

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***Abstract*—**This paper presents an investigation of the power penalties imposed by four-wave mixing (FWM) on G.652 (Single-Mode Fiber - SMF), G.653 (Dispersion-Shifted Fiber - DSF), and G.655 (Non-Zero Dispersion-Shifted Fiber - NZDSF) compliant fibers, considering the DWDM grids suggested by the ITU-T Recommendations G.692, and G.694.1, with uniform channel spacing of 100, 50, 25, and 12.5 GHz. The mathematical/numerical model assumes undepleted pumping, and shows very clearly the deleterious effect of FWM on the performance of DWDM systems, measured by the signal-to-noise ratio (SNR). The results make it evident that non-uniform channel spacing is practically mandatory for WDM systems based on DSF fibers.

***Keywords*—**DWDM systems, Four-Wave Mixing (FWM), G.652, G.653, G.655 compliant fibers, Signal-to-noise ratio.

I. Introduction

DENSE wavelength-division-multiplexing (DWDM) is the key technology to enable the very high-capacity photonic networks required by our communication thirsty society. In modern WDM systems, the primary nonlinear effects are cross phase modulation (XPM), and the four-wave mixing (FWM). The XPM mechanism was studied by the authors previously [1], [2], and two important effects associated with XPM were investigated: frequency shifting, and the generation of dark pulse trains from CW light. The latter is used in the context of high speed optical networks for wavelength conversion. On the other hand, FWM generates new optical frequencies (or FWM products) that may cause channel crosstalk, and is the object of the study reported in this paper. The occurrence of FWM depends on several factors, such as the frequency spacing between channels, the input power per channel, the dispersion characteristics of the optical fiber, and the distance along which the channels interact. In long haul links, the deployment of optical amplifiers aggravates the problem, as not only the transmitted signal are amplified, but also the generated FWM products, which mix again with the signals, giving rise to new products. In addition, if dispersion-shifted fibers (DSF) are used, the FWM mechanism is enhanced, due to a reduction of the phase mismatch associated to the fiber's chromatic dispersion.

The ITU-T Recommendation G.692 (02/98) specifies optical interfaces for the operation of amplified WDM systems on fibers that conform to recommendations G.652 (Single-Mode Fiber - SMF), G.653 (Dispersion-Shifted Fiber - DSF), and G.655 (Non-Zero Dispersion-Shifted Fiber - NZDSF). Initially, two equally spaced channel grids were defined, with the channels spaced by 100 and 50 GHz. Later on, the recommendation G.692 received as an addendum a reference to recommendation G.694.1 (06/02), and two new channel grids were incorporated, with 25 and 12.5 GHz channel spacing. Such narrower channel spacing will be indispensable in the near future to provide for the increased capacity required by further progress of information technology.

The crosstalk caused by FWM becomes more intense as the spacing between channels diminishes. Also, the deployment of the equally spaced channel grids recommended by ITU-T heightens the FWM phenomenon, as most of the new frequencies coincide with the existing channel frequencies, resulting in coherent interference that is bit-pattern dependent. In consequence, the detected signal power will fluctuate considerably. Therefore, the nonlinear process of FWM mechanism is the one of the major limitations to modern DWDM communication systems based on optical fibers.

Different techniques have been proposed to reduce the deleterious effects of FWM, such as [3]: spectral allocation of the channels so that the spacing between neighboring channels is as large as possible, spectral allocation of the channels as far as possible from the zero-dispersion wavelength (λ_{ZD}), deployment of non-zero dispersion-shifted fiber (NZDSF), and spectral allocation of unequally spaced channels, which requires a complex system design.

Although much work has already been dedicated to the analysis of the FWM phenomenon, a review of the literature shows that the majority of the papers tackle the problem from

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the point of view of a generic dispersive, nonlinear optical fiber. However, the commercial fibers, as well as the photonic systems/networks, comply with pertinent ITU-T recommendations, and the authors feel that more information regarding the occurrence and effects of FWM in such a context is needed.

This paper then investigates the FWM penalties imposed on DWDM systems based on G.652, G.653, and G.655 fibers, considering equally spaced channel grids of 100, 50, 25, and 12.5 GHz. Also, the rapid evolution of the DWDM technology – with increasing channel density, and bit rate per channel, as well as the occupancy of new wavelength bands – has fostered the development of a variety of fibers. Each type of fiber requires a specific approach to the balancing of dispersion, nonlinear effects, channel spacing, input signal power and chirp. The designer is then faced with new challenges to match the right fiber technology to the DWDM network specifications. Therefore, by comparing the effects of the different fiber types on the system performance, the study carried out in this paper aims at providing information that is useful for the reduction of the FWM crosstalk. A numerical model developed earlier [4], which considered only two channels, was extended and improved to accommodate a general DWDM system, with arbitrary number of channels, and channel spacing.

II. Mathematical Model

The evolution of the amplitude of a FWM signal along the length of a monomode fiber is described by [4]-[7]:

$$\frac{d}{dz}A_F(z)+\frac{\alpha}{2}A_F(z)=i\frac{n_2\omega_F}{cA_{eff}}A_p(z)A_q(z)A_r^*(z)\exp\left[i\left(\beta_p+\beta_q-\beta_r-\beta_F\right)z\right] \tag{1}$$

where $A_F(z)$ is the amplitude of the FWM signal generated at the frequency $f_F = f_p + f_q - f_r = \omega_F/2\pi$, (p, q, r = 1, ..., N; p, q $\neq$ r), $A_s(z)$ (s = p, q, r) is the amplitude of one of the N channels, of frequency f_s, originally injected in the fiber, β_s (s = p, q, r) is the phase constant, z is the position along the fiber, α is the fiber loss coefficient, n_2 is the nonlinear refractive index coefficient, c is the velocity of light in vacuum, A_{eff} is the effective area of the fiber core, $i = \sqrt{-1}$, and * indicates the complex conjugate. The fiber dispersion characteristics are included indirectly through the variation of the phase constant with frequency.

Equation (1) assumes CW operation (which represents the worst-case scenario for FWM generation), and no pump depletion, i.e. the pump (channel) waves are considered much more intense than the generated FWM waves. After a length L of fiber, the solution of (1) is written as [4]-[7]:

$$A_F(L)=\frac{in_2\omega_F}{cA_{eff}}A_p(0)A_q(0)A_r^*(0)\ e^{-\alpha L/2}\ .\frac{e^{(-\alpha+i\Delta\beta)L}-1}{i\Delta\beta-\alpha} \tag{2}$$

with $\Delta\beta = \beta_p + \beta_q - \beta_r - \beta_F$

The average FWM power generated at the frequency $\omega_F = 2\pi c/\lambda$ is then calculated as:

$$P_F(L)=\sum_{f_r=f_p+f_q-f_F}\ \sum_{f_q}\sum_{f_p}\left|A_F(L)\right|^2= \tag{3}$$

$$\frac{4\pi^2n_2^2}{A_{eff}^2\lambda^2}d\,P_p(0)P_q(0)P_r(0)\exp\left(-\alpha L\right)\left|\frac{e^{(-\alpha+i\Delta\beta)L}-1}{i\Delta\beta-\alpha}\right|^2$$

In (3), λ is the wavelength of the generated FWM signal, and d is the so called degeneracy factor: d = 1 if p = q $\neq$ r, and d = 2 if p $\neq$ q $\neq$ r; the term $\Delta\beta$ represents the phase mismatch, i.e., the difference between the phase constants of the various waves. The smaller this phase mismatch, the more efficient is the FWM generation. An analytical expression for the parameter $\Delta\beta$ is obtained expanding the phase constant β in a Taylor series in the neighborhood of a certain frequency $f_0 = c/\lambda_0$, which can be the frequency of one channel, the frequency of the dispersion zero of the fiber, or any suitable frequency. After some calculation, $\Delta\beta$ is finally given by [4]-[7]:

$$\Delta\beta=\beta(f_p)+\beta(f_q)-\beta(f_r)-\beta(f_F)$$

$$=\left[(f_r-f_0)^2+(f_p-f_0)(f_q-f_r)-(f_q-f_0)(f_r-f_0)\right]\frac{2\lambda_0^2\pi D}{c}$$

$$-(f_p-f_r)(f_q-f_r)[(f_p-f_0)+(f_q-f_0)]\frac{\lambda_0^4\pi}{c^2}\left[\frac{2D}{\lambda}+\frac{dD}{d\lambda}\right] \tag{4}$$

In (4), D is the dispersion parameter of the fiber, and $dD/d\lambda$ is the corresponding dispersion slope. The equation is valid in a frequency range around f_0, where the dispersion slope is linear, i.e., a frequency range where the second order dispersion is constant. According to (4), the phase mismatch depends on the type of fiber, through D, and $dD/d\lambda$, and the spacing between neighboring channels. The phase matching condition, $\Delta\beta = 0$, is therefore approximately satisfied at wavelengths close to the zero-dispersion wavelength of the fiber.

In practice it is important to guarantee that the WDM system has a good SNR, so that the transmitted information can be recovered with no ambiguity. Not knowing the details of transmitter and receiver deployed in the system, it is assumed that a minimum SNR of 20 dB is required [8], considering that the noise is totally due to the generated FWM, and the signal power loss is due solely to the fiber attenuation. The signal-to-noise ration is then defined as:

$$\mathrm{SNR(dB)}=10\log_{10}\left(\frac{P_{signal}}{P_{FWM}}\right) \tag{5}$$

For the calculation of the SNR, it is then necessary to identify all the FWM products that fall within the pass band of the optical filter responsible for the channel separation; the corresponding FWM powers are then added together. Generally, the crosstalk varies with the position of the channel in the grid: the crosstalk of the center channels differs from the crosstalk of the edge channels. Therefore, the SNR analysis will be based on the worst case among the channels, as explained later on.

Equations (1)-(5) represent all the mathematical formalism needed to investigate the effect of the FWM mechanism in WDM systems. Theses equations were implemented in the numerical model used in the simulations presented next. Before discussing the results, it is worth mentioning that this work focuses the specific context of the ITU-T Recommendations G.692, and G.694.1 that suggest equally spaced channel grids. However, both the mathematical formulation, and the resulting numerical model are completely general, and can be applied to unequally spaced channel grids as well [9], [10].

III. Case Analysis and Results

In a previous work [4], the authors verified that, for equally spaced channels, several of the generated FWM products coincide in frequency with the channels injected into the fiber, giving rise to severe crosstalk. Additionally, the results then obtained showed that, in a single-mode fiber (SMF), the FWM power decreases very rapidly as the channel spacing increases. However, for DSF fibers, the FWM power can be very high, independent of the spacing between channels, if the channels are allocated in the 1550 nm window. As this is exactly the scenario for the majority of the long haul optical communication systems, it will be the focus of the present analysis.

Three case analyses are presented. The first one investigates how the positioning of the channels in the 1550 nm window affects the signal-to-noise ratio of systems based on DSF, and NZDSF fibers. The second case investigates how the channel spacing affects the FWM power growth, considering SMF, DSF, and NZDSF fibers. The third and final case investigates how the input power per channel varies with the length of the fiber, also for the three fibers.To help the understanding of the physical processes involved, systems with 3, 5, 7, 9, and 11 channels are considered, as well as the four WDM grids: 100, 50, 25, and 12.5 GHz.

Before discussing the effects of FWM on the system performance, it is necessary to determine which channel is the most affected. In systems with equally spaced channels that employ DSF fiber, the worst case is always that of the channel that coincides with the fiber's zero-dispersion wavelength, independent of the number of channels. With SMF, and NZDSF fibers, the worst case is that of the centre channels, as more FWM products coincide with these channels. For example, with just 3 channels, nine FWM products will be generated, and one coincides with the middle channel (channel no. 2). It is not difficult to verify that, with 11 channels, 37 FWM products will coincide with the centre channel.

A. SNR and Positioning of the Channels in the 1550 nm Window

To investigate how the system SNR is influenced by the positioning of the channels in the 1550 nm window, for a certain WDM grid with a given number of channels, the middle channel is shifted in wavelength from 1515 nm to 1585 nm, and the whole grid follows suit.

Fig. 1 shows the variation of the system SNR as a function of the wavelength of the middle channel for systems with 3, 5, 7, 9, and 11 channels; in Fig. 1(a) the channels are spaced by 100 GHz, and in Fig. 1(b) by 50 GHz. The corresponding curves for the FWM powers have exactly the same shape, but up side down, therefore they are not shown. In both cases, the input power per channel is 1 mW (0 dBm). Fig. 1 refers to a DSF fiber, whose parameters at 1550 nm are: D = 0, $dD/d\lambda$ = 0.07 ps/km-nm^2, A_{eff} = 50 μm^2, α = 0.2 dB/km. A length of fiber L = 22 km is considered.

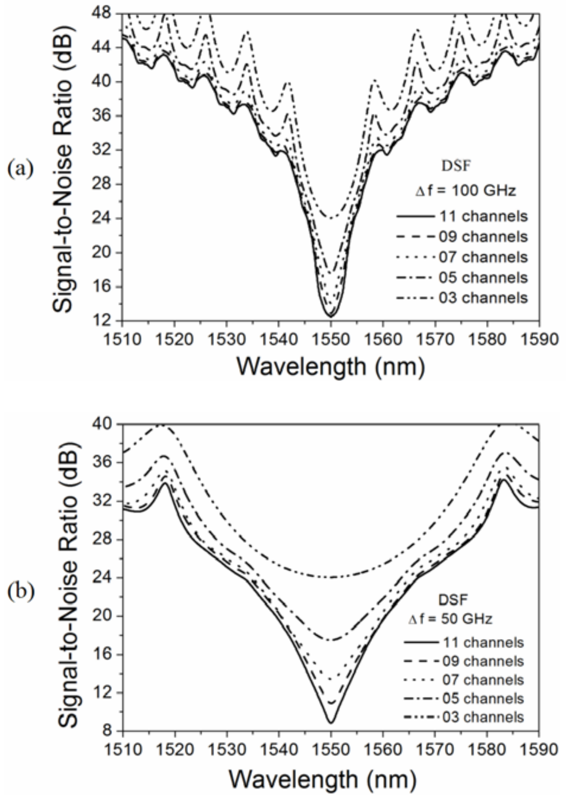

Fig. 1 Variation of the system SNR as a function of the wavelength with channel spacing of (a) 100 GHz, and (b) 50 GHz.

In Fig. 1(a), it is apparent that, independent of the number of channels, the signal-to-noise ratio is minimal at 1550 nm (the zero-dispersion wavelength of the DSF fiber), and increases as the middle channel is shifted from this wavelength, indicating that the FWM power decreases as the middle channel is shifted from λ_{ZD}. However, the SNR decreases very rapidly as the number of channels increases, as more FWM products are generated at the position of the middle channel. The oscillations seen in the SNR curves are associated with the behavior of the phase mismatch $\Delta\beta$, according to (4).

If the range of observation encompasses all of the C band (1530-1565 nm), the increase in the SNR – and corresponding decay of the FWM power – is apparently fast. Nevertheless, for operation close to 1550 nm, and considering the narrowly-spaced channel grids suggested by the ITU-T recommendations, the penalties imposed on the system by the FWM mechanism are still too severe. For example, considering 11 channels spaced by 100 GHz (0.8 nm), the resulting SNR is as low as 12 dB, as shown in Fig. 1(a). The situation is aggravated when the channel spacing is reduced to 50 GHz (0.4 nm), with the resulting SNR as low as 8 dB, as illustrated in Fig. 1(b). The results summarized in Fig. 1 indicate that the use of DSF fiber is not recommended, as far as the generation of FWM products is concerned, even for a small number of channels.

The influence of the channel spacing on the system performance is investigated next. Fig. 2 shows the variation of the system SNR as a function of the wavelength of the middle channel, for an 11-channel DSF fiber system, with the channel spacing as a parameter. It is evident from this figure that, when the channels are spaced by 100, 50, and 25 GHz, the middle channel must be at least 5 nm away from the zero-dispersion wavelength, so that an SNR of about 23 dB can be obtained. When the channels are spaced by 12.5 GHz or less, the situation is even more critical, and the resulting SNR values are unacceptably low.

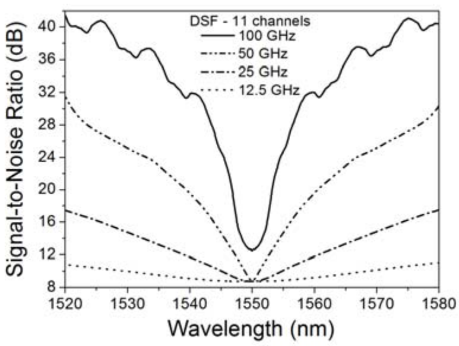

Fig. 2 Variation of the system SNR as a function of the wavelength for an 11-channel DSF fiber system.

A DSF seems an ideal means to maximize the reach of optical communication systems in the 1550 nm window, and it is indeed suitable for TDM or single-channel applications. However, as the previous results show, having zero-dispersion at 1550 nm is a negative condition for DWDM applications: the "absence" of chromatic dispersion enhances not only the FWM phenomenon, but also other critical nonlinear impairments, like cross-phase modulation (XPM). Together, these effects basically limit the ultimate system performance. To counteract the role of nonlinear effects in DWDM systems, and still benefit from reduced dispersion in the 1550 nm region, a new generation of fibers has been developed: the so called non-zero dispersion-shifted fibers (NZDSF). In order to mitigate cross-channel nonlinear effects (FWM and XPM), a certain level of chromatic dispersion is actually desirable.

Next, an NZDSF fiber is addressed, with the following dispersion parameters at 1550 nm: D = 3.7 ps/km-nm, and $dD/d\lambda$ = 0.07 ps/km-nm^2; the other parameters and length are the same as those of the DSF used previously. Fig. 3 shows the results for the system SNR, considering an 11-channel system. The general behavior of the curves is similar to that observed in Fig. 2. The fact that the dispersion parameter D is small but non zero causes a shifting of the curves towards the shorter wavelengths, with a valley near 1500 nm. In the region of interest, around 1550 nm, it is seen that the curves exhibit a slower variation than in the case of DSF fibers, and that SNR values above 23 dB are easily obtained with channel spacing as small as 25 GHz. This indicates that the use of NZDSF does indeed reduce the deleterious effects of the FWM mechanism, while keeping total dispersion low. However, for 12.5 GHz, and smaller channel spacing, the SNR remains prohibitively low.

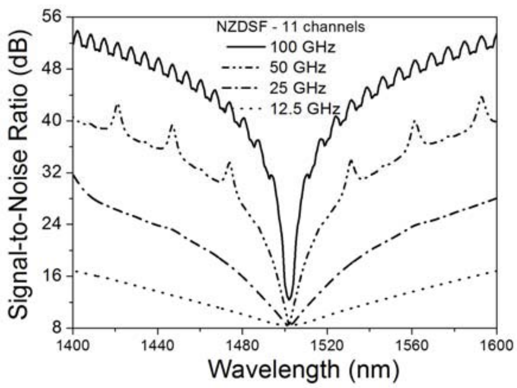

Fig. 3 Variation of the system SNR as a function of the wavelength for an 11-channel NZDSF fiber system.

B. FWM Power and Channel Spacing

To investigate how the fiber dispersion characteristics affect the FWM power growth, G.652 (SMF), G.653 (DSF), and G.655 (NZDSF) compliant fibers are considered. The dispersion characteristics of the DSF, and NZDSF fibers were already listed; for the SMF fiber, the following values are used at 1550 nm: D = 17 ps/km-nm, $dD/d\lambda$ = 0.055 ps/km-nm^2; the other data are the same as in Fig. 1.

Fig. 4 shows, for a 9-channel system, the variation of the FWM power as a function of the channel spacing. It is seen that the FWM power is maximum with the DSF fiber, and, with respect to the other fibers, practically constant and independent of the channel spacing. One can also conclude that SNR values in excess of 20 dB are obtainable only if the channels are separated by 200 GHz or more. With the NZDSF, and SMF fibers, the FWM power shows an oscillatory behavior, which decays as the channel spacing increases.

For example, with the SMF fiber, the FWM power is lower than -45 dBm, for channel spacing greater than 25 GHz; with the NZDSF fiber, a similar behavior is observed for channel spacing above 50 GHz, which, according to (3)-(5), guarantees an excellent signal-to-noise ratio.

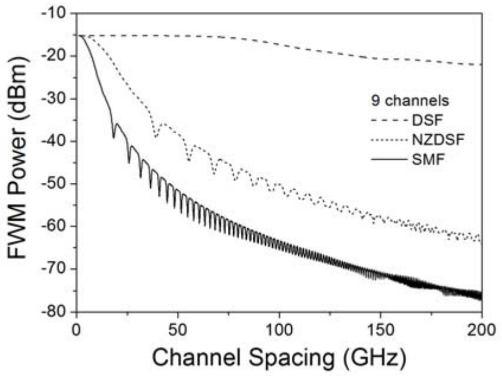

Fig. 4 Variation of the FWM power as a function of the channel spacing for a 9-channel system.

The results reported in Fig. 4 can also be explained from (4), which, for the DSF fiber, indicates that the corresponding phase mismatch depends only on the dispersion slope, and also that (i) it is nil, and independent of the channel spacing (Δf), in the case of three channels, and (ii) it varies with Δf^3 for more than three channels. For the NZDSF, and SMF fibers, the phase mismatch $\Delta\beta$ varies with Δf^3, but it now depends on both the dispersion slope, and on the dispersion parameter D. It is worth mentioning that the oscillation observed in the curves for the NZDSF, and SMF fibers are totally associated with the behavior of the phase mismatch, and do not depend on the number of channels.

This fact is illustrated in Fig. 5 for the NZDSF fiber, considering 3-, 5-, 7-, 9-, and 11-channel systems. It is clear in this figure that the influence of the number of channels decreases as the channel spacing increases.

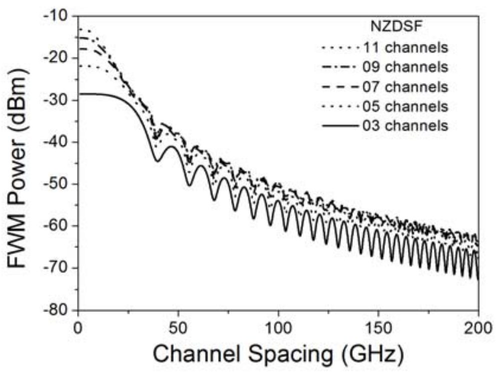

Fig. 5 Variation of the FWM power as a function of the channel spacing for a NZDSF fiber system.

Therefore, the previous results indicate that when the channels are spaced by 100, and 50 GHz (many WDM systems still deploy such separations between channels), the FWM is not a real concern with NZDSF, and SMF fibers, for a reduced number of channels (up to 20 channels). However, FWM can become a severe problem with NZDSF fibers when smaller spacing - 25 GHz or 12.5 GHz - is adopted.

C. *Input Power per Channel and Fiber Length*

To complete the analysis and better understand all the factors that affect the system signal-to-noise ratio, new simulations were performed, varying both the input power per channel, and the fiber length.

Fig. 6 shows, for a 7-channel system, the input power per channel needed to guarantee a minimum SNR of 23 dB as the length of the fiber increases, and considering (a) NZDSF, and (b) DSF fibers. For the latter, a wider channel spacing of 200 GHz is included.

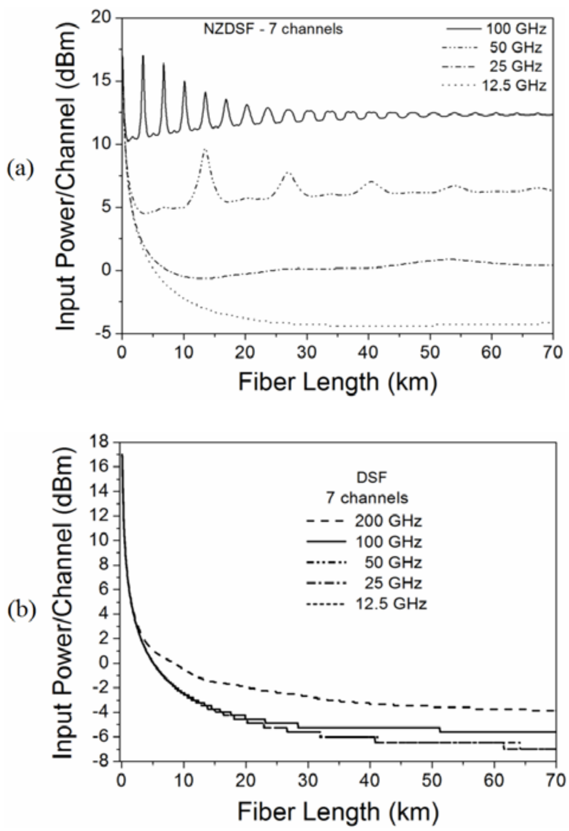

Fig. 6 Variation of the input power per channel as a function of the fiber length for a 7-channel system: (a) NZDSF, and (b) DSF fibers.

It is seen in Fig. 6(a) that, for a given length of fiber, the acceptable input power levels decay as the channel spacing decreases, as the FWM mechanism becomes more intense. It is also seen that the oscillatory behavior of the curve strengthens as the channel spacing increases; according to (4), this is due to the larger phase mismatch. The figure indicates that, for the 25 GHz channel spacing, up to 0 dBm can be injected in each channel for fiber lengths smaller than 70 km; if the channel spacing is reduced to 12.5 GHz, values of the input power of about -4 dBm already excite the FWM mechanism in NZDSF fibers. Other simulations showed similar results for large numbers of channels, but the acceptable power levels decrease as the number of channels increases, as more FWM power is generated.

For the DSF fiber, the phase matching condition is practically satisfied, and the occurrence of FWM is significant, and depends only slightly on the channel spacing. This is apparent in Fig. 6(b), where the acceptable levels of input power per channel (to guarantee a minimum SNR of 23 dB) decay exponentially - as dictated by (3) - for small lengths of fiber. For fiber length above 30 km, the input power varies very little. Only for channel spacing of 200 GHz can the input power levels be alleviated to more reasonable values. This fact becomes more noticeable as the number of channels increases, due to the higher number of FWM products coinciding with the regarded channel. Results of other simulations, e.g. for an 11-channel system with $\Delta f \leq 100$ GHz, and $L \sim 30$ km, indicate that the input power must be reduced by at least 3 dB in comparison with the $\Delta f = 200$ GHz case.

Fig. 7 shows results for an 11-channel system, with $\Delta f = 100$ GHz, considering the three types of fiber. The SMF fiber, with a high dispersion parameter at 1550 nm, favors the phase mismatch, thus reducing the FWM efficiency. The curve for the SMF fiber indicates that an SNR of 23 dB is easily obtained for input power of up to 50 mW. The same observation applies to the NZDSF fiber, with $\Delta f = 200$ GHz. The oscillatory behavior observed in the other curves is also seen in the curve for the SMF fiber, provided the scales are adjusted accordingly.

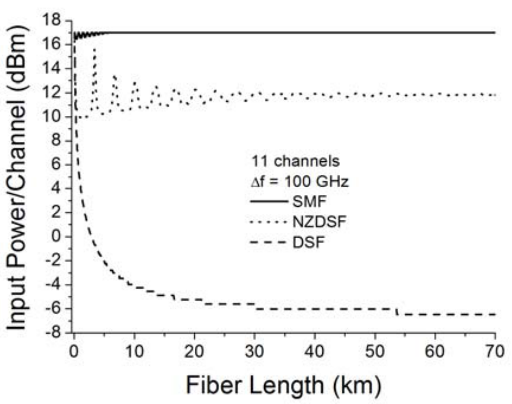

Fig. 7 Variation of the input power per channel as a function of the fiber length for an 11-channel system.

Other simulations that were performed - considering systems of up to 20 channels, as well as all the previous comments, assure that the DSF fiber offers the most favorable conditions to excite the FWM mechanism, and thus imposes the most severe penalties on WDM systems, resulting in acceptably low values of signal-to-noise ratio, even for channel spacing as wide as 200 GHz. For this reason, DSF fibers are no longer commercialized, and gradually the newer DWDM installations benefit from the enormous variety of NZDSF fibers available in the market.

IV. Conclusion

This paper presented an analysis of the penalties imposed by the FWM phenomenon on WDM systems using G.652, G.653, G.655 compliant fibers, in the specific context of the ITU-T Recommendations G.692, and G.694.1, which specify uniform spacing – 100, 50, 25, and 12.5 GHz – between channels. Conditions for worst-case scenario were identified and explored. The numerical model developed - based on the undepleted pump hypothesis - allows for the evaluation of the phase mismatch, generated FWM power, and the system signal-to-noise ratio.

The various results indicate that a reduction of the deleterious effects of the FWM phenomenon is possible, in part, by allocating the WDM channels away from the zero-dispersion wavelength of a DSF fiber. The results show that the NZDSF fiber, with a local low but non-zero dispersion at 1550 nm – and also a large effective area, may alleviate the nonlinear crosstalk between channels. The results also show that for the SMF fiber (largely deployed all over the world) the FWM problem is irrelevant, due to the high phase mismatch. However, the SMF-based systems require complex and expensive schemes for compensating the dispersion accumulated along the fiber link. The results further indicate that the system SNR depends mostly on the dispersion characteristics of the optical fiber, on the channel spacing, and on the input power per channel. Therefore, in those systems that require the channels to be very closely spaced, the power levels cannot be too high.

The numerous simulations performed corroborate the propositions put forward in the ITU-T Recommendations G.692, and G.694.1, and also make it clear that non-uniform channel spacing is practically mandatory in WDM systems based on DSF fibers. Such channel allocating schemes were already incorporated in the numerical model, and the results are reported elsewhere [6], [9], [10].

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