Impact of four-wave mixing on the downlink channel performance of dense wavelength division multiplexed gigabit-capable passive optical networks

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In this paper, FWM impact on the downlink channel performance of dense wavelength division multiplexed gigabit-capable passive optical networks (DWDM-GPONs) has been analyzed. Simulations have been performed on center downlink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems having 12.5 GHz, 25 GHz, 50 GHz and 100 GHz channel spacings. The downlink channel performance has been evaluated focusing on signal-to-crosstalk ratio (SXR) variations due to FWM impacts. Simulation results obtained for severe FWM impacts give hints about system parameters satisfying a minimum 23 dB SXR, i.e. an appropriate value for system reliability under FWM impacts in current GPON applications.

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Keywords: Four-wave mixing, Dense wavelength division multiplexing, Gigabit-capable passive optical network, Downlink, Optical fiber

1. Introduction

Gigabit-capable passive optical network (GPON) architecture is widely used in current access networks [1-5]. Considering the ever-increasing numbers and demands of end-users as well as system flexibility, dense wavelength division multiplexing (DWDM) technique is an important choice for GPON applications [6]. Nonlinear phenomena arising from optical Kerr and inelastic scattering effects have crucial impacts on the performance of DWDM-based networks [7-10]. Among all those phenomena, four-wave mixing (FWM) is the major performance-limiting factor [11, 12]. Therefore, the impact of FWM on DWDM-based optical networks should be evaluated for a reliable optical transmission. There are various papers in the literature focusing on the long-haul DWDM system performance under FWM impacts [13-20] while some papers reporting performance analysis results for downlink channels of passive optical networks (PONs) [21-23] and optical receivers of GPONs [24] exist. However, to the best of our knowledge, there is no paper dealing with downlink channel performance of DWDM-GPONs under FWM impacts focusing on the signal-to-crosstalk ratio (SXR) variations due to FWM. In this paper, we have concentrated on that topic. In the second section, theoretical background of FWM is described and in the third section, architecture of a DWDM-GPON system is introduced. The simulation model and important system characteristics used in simulations are given in the fourth section. Simulation results are presented and interpreted in the fifth section.

2. Theoretical background of FWM

The FWM phenomenon can be described as interaction of three distinct optical wave propagating in the fiber with frequencies of f_i, f_j and f_k because of the third order nonlinearity of the fiber material and generation of a novel wave having a frequency of f_{ijk} as a result of this interaction. FWM effect in optical fibers can mathematically be defined as

$$f_{ijk} = f_i + f_j - f_k \qquad (1)$$

In (1), $k \neq i, j$ must be satisfied for generation of the novel wave with the frequency f_{ijk}. In a wavelength division multiplexing (WDM) system, i, j and k indices denote three distinct channels.

In WDM systems having equally-spaced channels, novel signals generated by the FWM effect, i.e. FWM products, can form phase-matching interferences with signals in existing channels. Those interferences are called as FWM crosstalks. In the case of unequally-spaced channels, most of FWM products fall in those spacings and are added to the total system noise. The system performance is negatively affected in both cases. However, due to the phase-matching character of the FWM crosstalk, the signal-to-noise ratio (SNR) in the receiver degrades dramatically in the case of equal channel spacing [22].

The total number of FWM products generated in WDM systems depends on the number of channels. The total number of FWM products in an N-channel WDM system can be computed with

$$M = \frac{N^2(N-1)}{2} \quad (2)$$

However the most important FWM products in this total are the ones causing FWM crosstalk in WDM channels as mentioned above.

The power of a FWM signal can be determined with

$$P_{FWM}(f_{ijk}) = \left(\frac{d_{ijk}\gamma L_{eff}}{3}\right)^2 P_i P_j P_k \; e^{-\alpha L} \, \eta_{ijk} \quad (3)$$

where d_{ijk} is the degeneracy factor, i.e. $d_{ijk} = 3$ for $i = j \neq k$ and $d_{ijk} = 6$ for $i \neq j \neq k$, γ is the nonlinearity coefficient, L_{eff} is the effective length of the fiber, P_i, P_j and P_k are the input powers of channels i, j and k, respectively, α is the attenuation coefficient of the fiber, L is the fiber length and η_{ijk} is the FWM efficiency.

FWM efficiency η_{ijk} can be expressed as

$$\eta_{ijk} = \frac{\alpha^2}{\alpha^2 + \Delta B_{ijk}^2}\left[1 + \frac{4e^{-\alpha L}}{(1-e^{-\alpha L})^2} sin^2\left(\frac{\Delta B_{ijk}\, L}{2}\right)\right] \quad (4)$$

where ΔB_{ijk} denotes the phase mismatching factor and can be described as

$$\Delta B_{ijk} = \frac{2\pi\lambda_k^2}{c}\Delta f_{ik}\Delta f_{jk}\left[D_c + \frac{\lambda_k^2}{2c}\frac{dD_c}{d\lambda}(\Delta f_{ik} + \Delta f_{jk})\right] \quad (5)$$

where λ_k denotes the channel wavelength of k^{th} channel, D_c denotes the chromatic dispersion, $dDc/d\lambda$ denotes the chromatic dispersion slope S, $\Delta f_{ik}=|f_i-f_k|$ and $\Delta f_{jk}=|f_j-f_k|$, c denotes the speed of light in vacuum.

To analyze the impact of total FWM crosstalk on a distinct channel of a WDM system, a parameter called signal to crosstalk ratio (SXR) can be defined as

$$SXR = 10log_{10}\left(\frac{P_{out}}{P_{FWM}}\right) \quad (6)$$

where P_{out} is the channel output power, i.e. $P_{out} = P_{in}.e^{-\alpha L}$ for the channel input power P_{in}, and P_{FWM} is the total FWM crosstalk in that channel.

In a WDM system having equal channel spacings, the total FWM crosstalk in a distinct channel with a frequency f_c is given in [25] as

$$P_{FWM}(f_c) = \sum_{f_k=f_i+f_j-f_c}\sum_{f_j}\sum_{f_i} P_{FWM}(f_i + f_j - f_k) \quad (7)$$

3. DWDM-GPON architecture

DWDM system applications began to emerge in mid-1990s due to ever-increasing number of end-users in data communications [26].Telecommunication Standardization Sector of International Telecommunication Union (ITU-T) has defined the term "DWDM device" for a class of WDM devices having channel spacing values of less than or equal to 1000 GHz in [27] and has determined nominal central frequencies supporting DWDM applications for channel spacings of 12.5 GHz, 25 GHz, 50 GHz, 100 GHz and above in [28].

Currently, PONs providing access to end-users and built with passive devices are one of the important types of DWDM system applications. As shown in Fig. 1, a PON consists of an optical line termination (OLT), a number of optical network units (ONUs), an optical splitter and optical fibers connecting those devices.

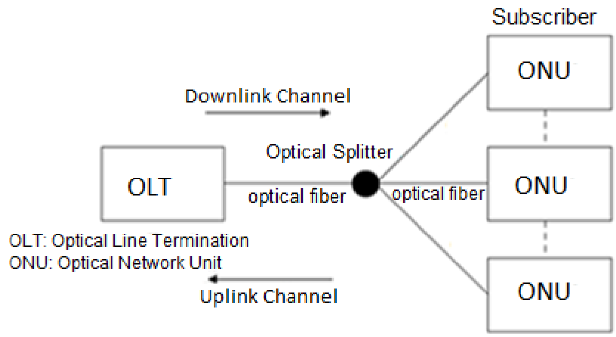

Fig. 1. Components of a PON

The OLT located to the central office provides the bi-directional transmission of the data through the optical network. In other words, the OLT device is responsible for transmitting the data coming from the metropolitan network to ONU devices via the downlink channel and the data coming from ONUs via the uplink channel to the metropolitan network. The OLT device uses distinct wavelengths for downlink and uplink traffics, i.e. 1490 nm wavelength for downlink and 1310 nm wavelength for uplink transmission. The ONU device is an interface between the end-user and the PON located directly in the house or the office of the end-user and forms a connection point to the PON providing required electrical/optical conversions. Optical splitter acts as a demultiplexer for the downlink traffic and a multiplexer for the uplink traffic.

In DWDM-PON applications, the downlink and uplink traffic can be transmitted via distinct channels operating at distinct wavelengths on the same optical fiber. Furthermore, considering the dynamic variation in the number of end-users, both channels can be divided into sub-channels. Therefore, the splitting ratio (1/N) of the optical splitter is important. Currently, splitting ratios up to 1/128 are available in applications.

There are various PON standards, i.e. ATM PON (APON), Broadband PON (BPON), Ethernet PON (EPON), Gigabit Ethernet PON (GEPON) and Gigabit-capable PON (GPON). GPON standardized by ITU-T with Recommendations G.984.x [29-33] provides connections of an OLT with 64 ONUs over a distance of 15 km, 32 ONUs over a distance of 20 km and 16 ONUs over a distance of 30 km. Downlink and uplink transmission rates are 2.5 Gbps and 1.25 Gbps, respectively.

4. Simulation model and important system characteristics used in simulations

Simulations have been focused on the FWM impact on the most heavily affected downlink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems having equal channel spacings of 12.5 GHz, 25 GHz, 50 GHz and 100 GHz to obtain worst-case values that are vital for a reliable system design. Simulations have been performed with MATLAB R2011b on G.652 standard single-mode fiber (SSMF) connecting the OLT to the optical splitter shown in Fig. 1. Parameters of SSMF for the downlink channel operating at 1490 nm wavelength are given in Table 1.

Table 1. SSMF parameters for the downlink channel

D_c (ps/nm.km)	S (ps/nm^2.km)	γ (1/W.km)	α (dB/km)
12.720	0.086	1.350	0.220

Since the most severely impacted channels in DWDM-based systems implemented with SSMFs are center channels [34], center channels of 7-, 15-, 29- and 35-channel DWDM systems, i.e. 4th, 8th, 15th and 18th channels, respectively, have been considered. The numbers of FWM products falling into the center channels of 7-, 15-, 29- and 35-channel systems are 13, 73, 294 and 433, respectively. FWM products falling into the center channels of 7- and 15-channel DWDM systems are given in Tables 2 and 3.

Table 2. FWM products falling into the center channel of a 7-channel DWDM system

i/j	1	2	3	4	5	6	7
1					k=2	k=3	k=4
2			k=1		k=3	k=4	k=5
3			k=2		k=4	k=5	k=6
4							
5					k=6	k=7	
6							
7							

Table 3. FWM products falling into the center channel of a 15-channel DWDM system

i/j	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1									k=2	k=3	k=4	k=5	k=6	k=7	k=8
2							k=1		k=3	k=4	k=5	k=6	k=7	k=8	k=9
3						k=1	k=2		k=4	k=5	k=6	k=7	k=8	k=9	k=10
4					k=1	k=2	k=3		k=5	k=6	k=7	k=8	k=9	k=10	k=11
5					k=2	k=3	k=4		k=6	k=7	k=8	k=9	k=10	k=11	k=12
6						k=4	k=5		k=7	k=8	k=9	k=10	k=11	k=12	k=13
7							k=6		k=8	k=9	k=10	k=11	k=12	k=13	k=14
8															
9									k=10	k=11	k=12	k=13	k=14	k=15	
10										k=12	k=13	k=14	k=15		
11											k=14	k=15			
12															
13															
14															
15															

In Tables 2 and 3, i, j and k denote numbers of channels interacting to form FWM products having the same optical frequency with the center channels of 7-, 15-, 29- and 35-channel DWDM systems. For example, the 5th (i=5), the 9th (j=9) and the 6th (k=6) channels interact to form an FWM product in the center channel, i.e. the 8th channel, of a 15-channel DWDM system. As mentioned in Section 2, k ≠ i, j and since i and j are interchangeable, only half-spaces are considered in Tables 2 and 3. Considering the page constraints, similar -but of course more massive- tables for 29- and 35-channel DWDM systems are not given in the paper.

5. Simulations

Simulation results analyzing variations of SXR with varying channel input powers, channel spacings and channel lengths are presented and interpreted in this section.

5.1. Variation of SXR with channel input power variations

In this subsection, simulation results analyzing variations of SXR with varying channel input powers in the range of 1-100 mW for the center downlink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems are given. The operating wavelength of the center downlink channel has been fixed to 1490 nm. All channel input powers have been considered as equal. The link length between the OLT and the splitter has been taken as 15 km for all DWDM-GPON systems to provide limits in GPON standards. Simulation results for equally-spaced DWDM-GPON systems for channel spacing values of 12.5 GHz, 25 GHz, 50 GHz and 100 GHz are shown in Figs. 2-5.

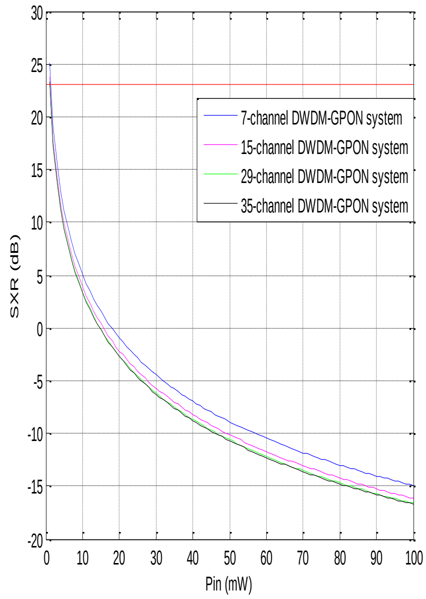

Fig. 2. Variation of SXR with channel input power variations for center channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems for 12.5 GHz channel spacings

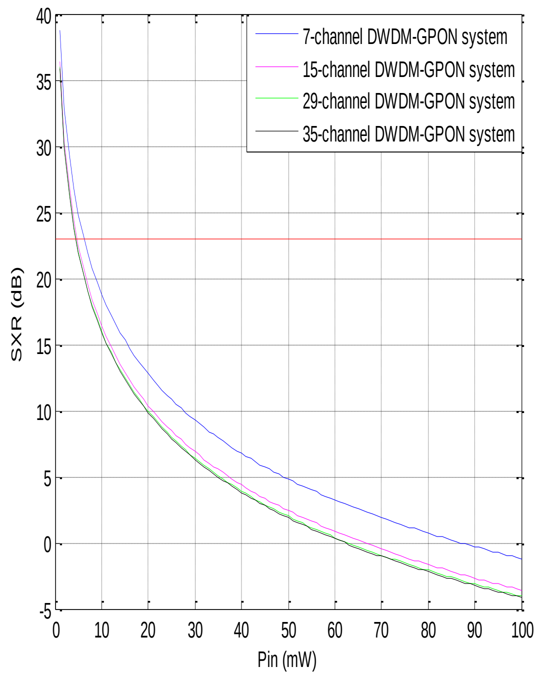

Fig. 3. Variation of SXR with channel input power variations for center channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems for 25 GHz channel spacings

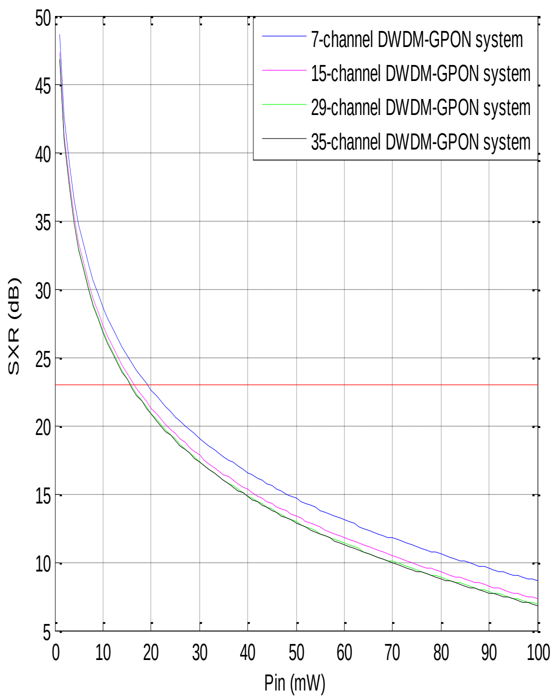

Fig. 4. Variation of SXR with channel input power variations for center channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems for 50 GHz channel spacings

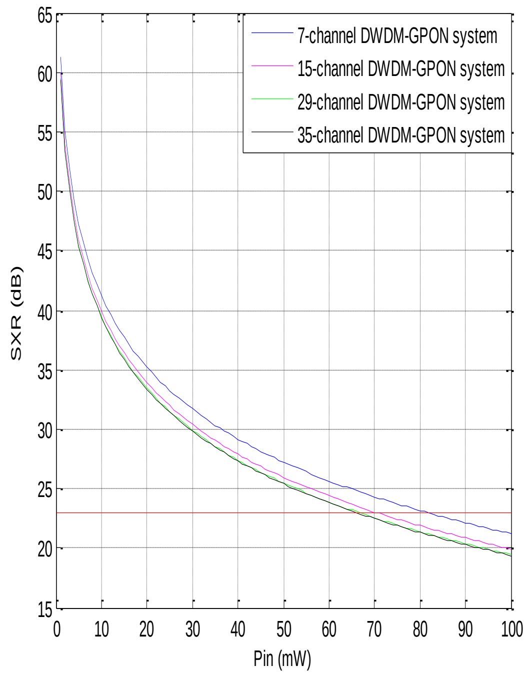

Fig. 5. Variation of SXR with channel input power variations for center channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems for 100 GHz channel spacings

Choosing a convenient SXR level is important for analyzing the impact of FWM. In the literature, a minimum 20 dB, 23 dB or 25 dB SXR values have been taken into account for DWDM-based systems [34-36]. In this research a 23 dB minimum SXR value has been considered. 23 dB SXR level is shown with red color in Figs. 2-5. Evaluating simulation results given in Figs. 2-5, comparative results obtained for maximum channel input powers satisfying 23 dB SXR condition at center channels are shown in Table 4.

Table 4. Comparative results for maximum channel input powers satisfying 23 dB SXR condition at center channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems for 12.5 GHz, 25 GHz, 50 GHz and 100 GHz channel spacings

DWDM-GPON Systems	**Δf (GHz)**	**12.5**	**25**	**50**	**100**
7-channel	**Maximum P_{in} satisfying 23 dB SXR (mW)**	1.34	6.17	19.09	81.45
15-channel		1.14	4.71	16.44	70.29
29-channel		1.06	4.47	15.68	66.48
35-channel		1.05	4.42	15.56	65.93

Figs. 2-5 and Table 4 show that SXR decreases with the decrease in values of channel spacings and the increase in values of channel input powers and channel numbers. Narrowing the channel spacings degrades the phase mismatching factor ΔB_{ijk}. Degradation of ΔB_{ijk} increases the FWM efficiency η_{ijk} and subsequently FWM signal generated in the center channel increases with the increase in η_{ijk} and causes a decrease in SXR. In the case of equal channel input powers, the FWM signal power generated in the channel is directly proportional to P_{in}^3 and therefore SXR shows an exponential decay with the increase in channel input powers. The number of FWM products generated in the center channel increases with the increasing numbers of channels. Thus an increment in FWM crosstalk occurs and subsequently SXR degrades. In optical fiber transmission systems, maximizing the channel input powers is the general method used in avoiding effects of attenuation and reducing numbers of optical amplifiers in the system. Therefore, results shown in Table 4 give important clues for input power maximization considering the impact of FWM on the system.

5.2. Variation of SXR with channel spacing value variations

In this subsection, simulation results analyzing variations of SXR with varying channel spacing values, i.e. *Δf*, up to 100 GHz for the center downlink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems are given. The operating wavelength of the center downlink channel has been fixed to 1490 nm. All channel input powers have been considered as equal and 1 mW to provide a minimum 23 dB SXR criterion for all channel numbers and channel spacing values. The link length between the OLT and the splitter has been taken as 15 km for all DWDM-GPON systems to provide limits in GPON standards. Simulation results for equally-spaced DWDM-GPON systems are shown in Fig. 6 and comparative SXR values for 7-, 15-, 29- and 35-channel DWDM-GPON systems having 12.5 GHz, 25 GHz, 50 GHz and 100 GHz channel spacings are given in Table 5.

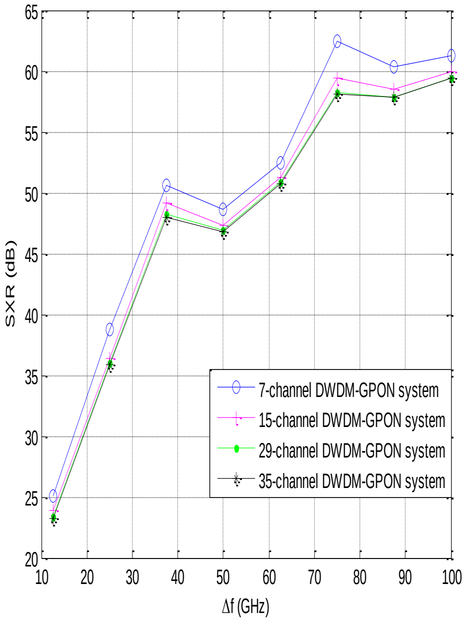

Fig. 6. Variation of SXR with variations in channel spacing values for center channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems for 1 mW channel input powers

Table 5. Comparative SXR values for 7-, 15-, 29- and 35-channel DWDM-GPON systems having 12.5GHz, 25 GHz, 50 GHz and 100 GHz channel spacings and 1mW channel input powers

DWDM-GPON Systems	Δf (GHz)	12.5	25	50	100
7-channel	SXR at center channel (dB)	25.08	38.79	48.62	61.22
15-channel		23.85	36.41	47.32	59.94
29-channel		23.37	35.96	46.91	59.45
35-channel		23.28	35.85	46.84	59.38

Results show that channel spacing values have a more significant effect on SXR values than channel numbers at fixed channel input powers. SXR values at 100 GHz are 36.08-36.14 dB higher than the values at 12.5 GHz for the same channel numbers while SXR values for 7-channel DWDM-GPON systems are 1.78-2.94 dB higher than the values for 35-channel DWDM-GPON systems at the same channel spacing values. This is an important result for DWDM-GPON system implementations. It must be considered that narrowing channel spacings for more efficient usage of fiber bandwidth may result in a dramatic SXR degradation and minimum SXR level for reliable data transmission may not be provided under the FWM impact unless appropriate input powers are selected.

5.3. Variation of SXR with channel length variations

In this subsection, simulation results analyzing variations of SXR with varying channel lengths for the center downlink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems are given. The operating wavelength of the center downlink channel has been fixed to 1490 nm. All channel input powers have been considered as equal and 1 mW to provide a minimum 23 dB SXR criterion for all channel numbers and channel spacing values. The upper limit of the range for the link length between the OLT and the splitter has been taken as 30 km for 7- and 15-channel DWDM-GPON systems, 20 km for 29-channel DWDM-GPON systems and 15 km for 35-channel DWDM-GPON systems to provide the maximum range limitations of ITU-T Recommendations G.984.x. Simulation results for equally-spaced DWDM-GPON systems are shown in Figs. 7-10.

It is clear in Figs. 7-10 that SXR shows an oscillatory variation with varying channel lengths in particular at 50 GHz and 100 GHz. This is due to the phase mismatch becoming stronger with high channel spacings. This is also another important result for DWDM-GPON implementations that must be taken into account since the channel length can cause significant SXR degradations especially at 50 GHz and 100 GHz channel spacings, i.e. for a 0.5 km increment in channel lengths the maximum SXR degradation can reach to 8.86 dB at 50 GHz channel spacing and 8.66 dB at 100 GHz channel spacing for 7-channel DWDM-GPON systems, 7.75 dB at 50 GHz channel spacing and 5.43 dB at 100 GHz channel spacing

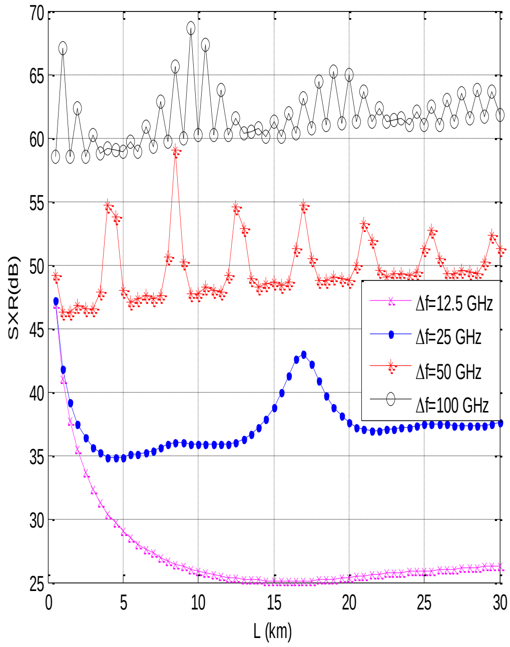

Fig. 7. Variation of SXR with varying channel lengths for center channels of 7-channel DWDM-GPON systems having 12.5 GHz, 25 GHz, 50 GHz and 100 GHz channel spacing values and 1 mW channel input powers

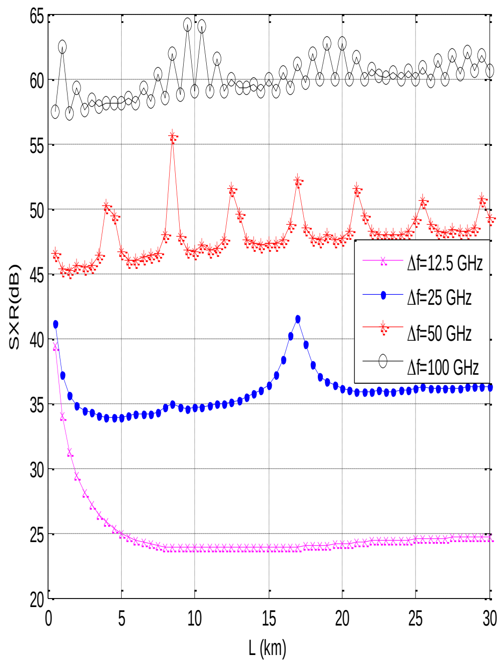

Fig. 8. Variation of SXR with varying channel lengths for center channels of 15-channel DWDM-GPON systems having 12.5 GHz, 25 GHz, 50 GHz and 100 GHz channel spacing values and 1 mW channel input powers

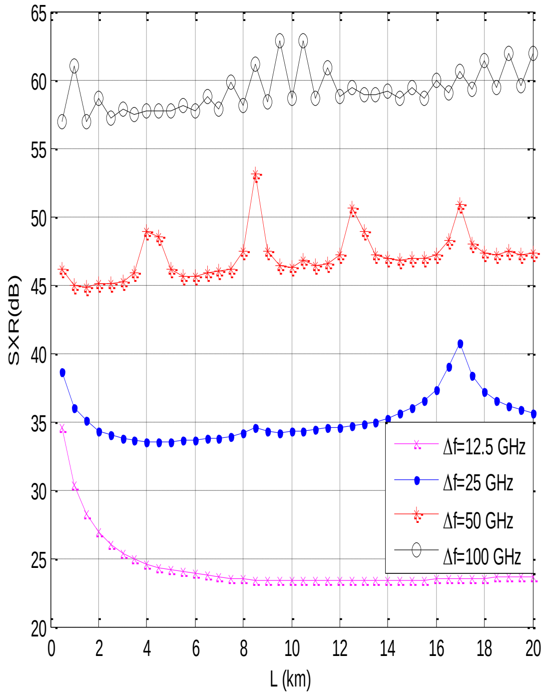

Fig. 9. Variation of SXR with varying channel lengths for center channels of 29-channel DWDM-GPON systems having 12.5 GHz, 25 GHz, 50 GHz and 100 GHz channel spacing values and 1 mW channel input powers

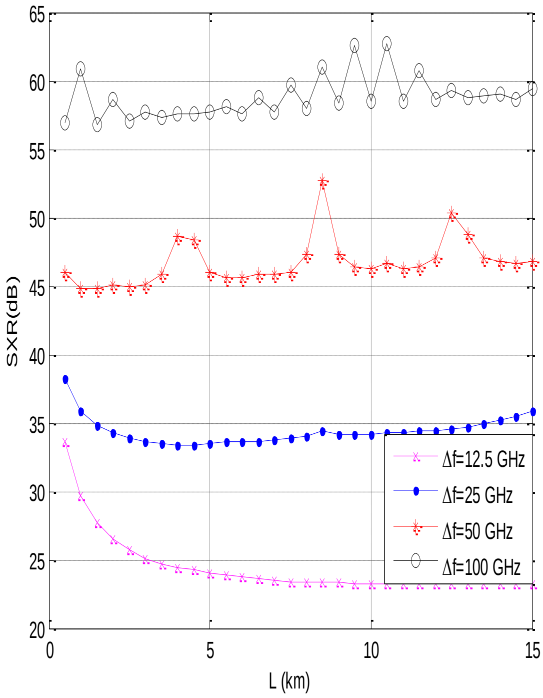

Fig. 10. Variation of SXR with varying channel lengths for center channels of 35-channel DWDM-GPON systems having 12.5 GHz, 25 GHz, 50 GHz and 100 GHz channel spacing values and 1 mW channel input powers

for 15-channel DWDM-GPON systems, 5.65 dB at 50 GHz channel spacing and 4.47 dB at 100 GHz channel spacing for 29-channel DWDM-GPON systems and 5.40 dB at 50 GHz channel spacing and 4.33 dB at 100 GHz channel spacing for 35-channel DWDM-GPON systems.

6. Conclusions

The FWM impact on the performance of center downlink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems using SSMFs has been analyzed focusing on SXR simulations. Simulations about SXR vs. channel input powers have remarkable results about limits of input power maximization done to avoid effects of attenuation in optical fiber communication systems considering the impact of FWM on the system. Simulations about SXR vs. channel spacings show that narrowing channel spacings for a more efficient usage of fiber bandwidth may result in a dramatic SXR degradation and minimum SXR level required for a reliable data transmission may not be provided. Simulations about SXR vs. channel lengths emphasize that channel length variations as small as 0.5 km at high channel spacing values of 50 GHz and 100 GHz can cause significant SXR degradations due to SXR oscillations resulting from strong phase mismatch occurring at those channel spacing values. All simulation results show worst-case values for the system performance under the impact of FWM and therefore give important clues for a reliable DWDM-GPON system design.

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