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FOUR-WAVE MIXING IMPACTS ON THE UPLINK PERFORMANCE OF DENSE WAVELENGTH DIVISION MULTIPLEXING GIGABIT PASSIVE OPTICAL NETWORKS

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Abstract: Four-wave mixing (FWM) is an important nonlinear effect severely limiting the performance of optical fiber networks. In this paper, FWM impact on the uplink performance of dense wavelength division multiplexing gigabit passive optical networks (DWDM-GPONs) using standard single mode fibers (SSMFs) has been analyzed. Simulations have been carried out on the center uplink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems that have 12.5 GHz, 25 GHz, 50 GHz and 100 GHz channel spacing values. Signal-to-crosstalk ratio (SXR) variations occurring due to FWM impacts have been considered in evaluating the uplink performance. Simulation results exhibit worst-case values under FWM impacts and therefore are important in giving clues about choosing system parameters satisfying a minimum 23 dB SXR, which is an appropriate value for current GPON applications showing system reliability under FWM impacts.

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

Yoğun Dalgaboyu Bölmeli Çoğullamalı Gigabit Pasif Optik Ağlarda Dört Dalga Karışımının Yukarı Yönlü Hat Performansına Etkisi

Öz: Dört dalga karışımı (FWM), optik fiberli ağların performansını şiddetli biçimde sınırlayan önemli bir doğrusal olmayan etkidir. Bu makalede, FWM'nin standart tek-modlu fiberler (SSMFs) kullanan yoğun dalgaboyu bölmeli çoğullamalı gigabit pasif optik ağların (DWDM-GPONs) yukarı yönlü hat performansı üzerindeki etkisi incelenmiştir. Kanallar arası boşluk değerleri 12.5 GHz, 25 GHz, 50 GHz ve 100 GHz olan 7-, 15-, 29- ve 35-kanallı DWDM-GPON sistemlerinin yukarı yönlü hat merkez kanalları için benzetimler yapılmıştır. Yukarı yönlü hat performansını değerlendirmede, FWM etkisi nedeniyle oluşan işaret çapraz karışım oranı (SXR) değişimleri dikkate alınmıştır. Benzetim sonuçları, FWM etkisi altındaki sistem performansının en kötü hal değerlerini sergilemekte ve bu nedenle, mevcut GPON uygulamalarında FWM etkisi altındaki sistem güvenilirliğini gösteren uygun bir değer olan minimum 23 dB SXR kriterini sağlayan sistem parametrelerinin seçimi için önemli ipuçları sergilemektedir.

Anahtar Kelimeler: Dört dalga karışımı, Yoğun dalgaboyu bölmeli çoğullama, Gigabit pasif optik ağ, Optik fiber, Yukarı yönlü hat

1. INTRODUCTION

In current access networks, gigabit passive optical network (GPON) is a widely-used architecture. Dense wavelength division multiplexing (DWDM) method is an important choice

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for GPON applications with its advantage in system flexibility and giving service to ever-increasing numbers and demands of end-users (Sorin and Kim, 2006). Nonlinear phenomena which arise from optical Kerr and inelastic scattering effects have significant impacts on the performance of DWDM-based networks. Four-wave mixing (FWM) is the major performance-limiting factor among all those phenomena (Agrawal, 2013). Therefore, FWM impact on DWDM 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 (Souza and Harboe, 2011; Hiçdurmaz et. al., 2013; Song and Brandt-Pearce, 2013; Sharma and Kaur 2013; Karlık, 2016a; Karlık, 2016b) and some papers reporting results of performance analysis for downlink channels of passive optical networks (PONs) (Reis et. al., 2012; Bi et. al., 2014). However to the best of our knowledge there is no paper dealing with uplink channel performance of PON systems under FWM impacts. In this paper, FWM impact on the uplink performance of DWDM-GPONs is evaluated with MATLAB simulations. In the second section, theoretical background of FWM and DWDM-GPON system architecture are introduced. The simulation model and important system characteristics are given in the third section. Simulation results are presented and interpreted in the fourth section.

2. THEORETICAL BACKGROUND OF FWM AND DWDM-GPON ARCHITECTURE

The interaction among three distinct optical wave that propagate in the fiber with f_i, f_j and f_k frequencies occurring due to the third order nonlinearity of the fiber material and a novel wave generation having a frequency of f_{ijk} as a result of this interaction is called as FWM. FWM effect can mathematically be described as

$$f_{ijk} = f_i + f_j - f_k \tag{1}$$

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

In WDM systems having equally-spaced channel architecture, FWM products, i.e. novel signals generated by the FWM effect, can form phase-matching interferences with signals in existing channels. Those interferences are called FWM crosstalks. In the case of unequally-spaced channels, most of FWM products are generated in those spacings and therefore they are added to total system noise. In both cases, the system performance is negatively affected. However, signal-to-noise ratio (SNR) in the receiver degrades dramatically in the case of equal channel spacing because of the phase-matching character of the FWM crosstalk (Bi et. al., 2014).

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 determined with

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

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

The power of an FWM signal can be computed with

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

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 fiber effective length, P_i, P_j and P_k are channel input powers, α is the fiber attenuation coefficient, L is the fiber length and η_{ijk} is the FWM efficiency.

FWM efficiency η_{ijk} can be expressed as

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

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

$$\Delta B_{ijk} = \frac{2\pi \lambda_k^2}{c}\left(|f_i - f_k||f_j - f_k|\right)\left[D_c + \frac{\lambda_k^2}{2c}\frac{dD_c}{d\lambda}\left(|f_i - f_k| + |f_j - f_k|\right)\right] \tag{5}$$

where λ_k is the channel wavelength of k^{th} channel, D_c is the chromatic dispersion; $dD_c/d\lambda$ is the chromatic dispersion slope S and c is the speed of light in vacuum.

Signal-to-crosstalk ratio (SXR) parameter, which can be used in analysis of FWM crosstalk impact on a distinct channel of a WDM system, can be defined as

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

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

In a WDM system that has equal channel spacings, the total FWM crosstalk in a distinct channel with a frequency f_c is given in Maeda et. al. (1990) as

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

Due to ever-increasing number of end-users in data communications, DWDM system applications began to emerge in mid-1990s (Judy, 1997). ITU-T has addressed the nominal central frequencies that support DWDM applications for 12.5 GHz, 25 GHz, 50 GHz, 100 GHz and above channel spacing values in ITU-T Recommendation G.694.1 (2002).

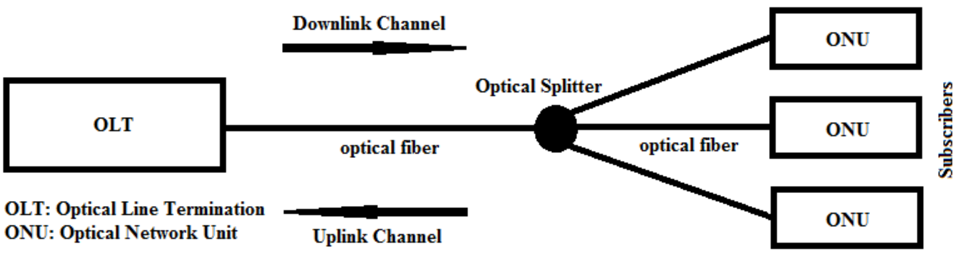

Figure 1:
Components of a PON

Passive optical networks (PONs), which provide access to end-users and are built with passive devices, are important types of current DWDM system applications. A PON contains an optical line termination (OLT), a number of optical network units (ONUs), an optical splitter and optical fibers connecting those devices as shown in Fig. 1.

The OLT is located in the central office and it 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 1490 nm wavelength for the downlink traffic and 1310 nm wavelength for uplink transmission. The ONU device, which is located directly in the house or the office of the end-user, is an interface between the end-user and the PON and it 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.

GPON standardized by ITU-T with Recommendations G.984.x (ITU-T Recommendation G.984.1, 2008; ITU-T Recommendation G.984.2, 2003; ITU-T Recommendation G.984.3, 2014; ITU-T Recommendation G.984.4, 2008; ITU-T Recommendation G.984.5, 2014) provides connections of an OLT with 64 ONUs over a 15 km distance, 32 ONUs over a 20 km distance and 16 ONUs over a 30 km distance. Downlink and uplink transmission rates are 2.5 Gbps and 1.25 Gbps, respectively.

3. SIMULATION MODEL AND IMPORTANT CHARACTERISTICS

Simulations have been done with MATLAB R2011b on uplink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems that have 12.5 GHz, 25 GHz, 50 GHz and 100 GHz equal channel spacing values. G.652 standard single-mode fiber (SSMF) connecting the OLT to the optical splitter as shown in Fig. 1 has been focused on in simulations. SSMF parameters used for the uplink channel operating at 1310 nm wavelength are given in Table 1.

Table 1. SSMF parameters of the uplink channel operating at 1310 nm wavelength

Dc (ps/nm.km)	S (ps/nm^2.km)	γ (1/W.km)	α (dB/km)
-0.26	0.086	1.54	0.35

In Tables 2-5, i, j and k show channels that interact to generate FWM products having the same optical frequency with the center channel in the DWDM system. For example, the 3rd (i=3)**,** the 6th (j=6) and the 5th (k=5) channels interact and form an FWM product in the center channel, i.e. the 4th channel, in a 7-channel DWDM system. As mentioned in Section 2, $k \neq i, j$ and only semi-spaces in Tables 2-5 are taken into account since i and j are exchangeable.

Table 2. FWM products that fall into the center channel in 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							

Since center channels of SSMFs are the worst impacted channels with FWM in DWDM-based systems (Harboe et. al., 2008), center channels of 7-, 15-, 29- and 35-channel DWDM systems, i.e. 4^{4h}, 8th, 15th and 18th channels, respectively, are considered. The numbers of FWM products that fall into center channels in 7-, 15-, 29- and 35-channel systems are given in Tables 2-5, respectively.

Table 3. FWM products that fall into the center channel in 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=5	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=11	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															

Table 4. FWM products that fall into the center channel in a 29-channel DWDM system

i/j	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
1																k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9	k=10	k=11	k=12	k=13	k=14	k=15
2														k=1		k=3	k=4	k=5	k=6	k=7	k=8	k=9	k=10	k=11	k=12	k=13	k=14	k=15	k=16
3													k=1	k=2		k=4	k=5	k=6	k=7	k=8	k=9	k=10	k=11	k=12	k=13	k=14	k=15	k=16	k=17
4												k=1	k=2	k=3		k=5	k=6	k=7	k=8	k=9	k=10	k=11	k=12	k=13	k=14	k=15	k=16	k=17	k=18
5											k=1	k=2	k=3	k=4		k=6	k=7	k=8	k=9	k=10	k=11	k=12	k=13	k=14	k=15	k=16	k=17	k=18	k=19
6										k=1	k=2	k=3	k=4	k=5		k=7	k=8	k=9	k=10	k=11	k=12	k=13	k=14	k=15	k=16	k=17	k=18	k=19	k=20
7									k=1	k=2	k=3	k=4	k=5	k=6		k=8	k=9	k=10	k=11	k=12	k=13	k=14	k=15	k=16	k=17	k=18	k=19	k=20	k=21
8								k=1	k=2	k=3	k=4	k=5	k=6	k=7		k=9	k=10	k=11	k=12	k=13	k=14	k=15	k=16	k=17	k=18	k=19	k=20	k=21	k=22
9									k=3	k=4	k=5	k=6	k=7	k=8		k=10	k=11	k=12	k=13	k=14	k=15	k=16	k=17	k=18	k=19	k=20	k=21	k=22	k=23
10										k=5	k=6	k=7	k=8	k=9		k=11	k=12	k=13	k=14	k=15	k=16	k=17	k=18	k=19	k=20	k=21	k=22	k=23	k=24
11											k=7	k=8	k=9	k=10		k=12	k=13	k=14	k=15	k=16	k=17	k=18	k=19	k=20	k=21	k=22	k=23	k=24	k=25
12												k=9	k=10	k=11		k=13	k=14	k=15	k=16	k=17	k=18	k=19	k=20	k=21	k=22	k=23	k=24	k=25	k=26
13													k=11	k=12		k=14	k=15	k=16	k=17	k=18	k=19	k=20	k=21	k=22	k=23	k=24	k=25	k=26	k=27
14														k=13		k=15	k=16	k=17	k=18	k=19	k=20	k=21	k=22	k=23	k=24	k=25	k=26	k=27	k=28
15																													
16																k=17	k=18	k=19	k=20	k=21	k=22	k=23	k=24	k=25	k=26	k=27	k=28	k=29	
17																	k=19	k=20	k=21	k=22	k=23	k=24	k=25	k=26	k=27	k=28	k=29		
18																		k=21	k=22	k=23	k=24	k=25	k=26	k=27	k=28	k=29			
19																			k=23	k=24	k=25	k=26	k=27	k=28	k=29				
20																				k=25	k=26	k=27	k=28	k=29					
21																					k=27	k=28	k=29						
22																						k=29							
23																													
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26																													
27																													
28																													
29																													

Table 5. FWM products that fall into the center channel in a 35-channel DWDM system

i/j	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
1																			k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9	k=10	k=11	k=12	k=13	k=14	k=15	k=16	k=17	k=18
2																	k=1		k=3	k=4	k=5	k=6	k=7	k=8	k=9	k=10	k=11	k=12	k=13	k=14	k=15	k=16	k=17	k=18	k=19
3																k=1	k=2		k=4	k=5	k=6	k=7	k=8	k=9	k=10	k=11	k=12	k=13	k=14	k=15	k=16	k=17	k=18	k=19	k=20
4															k=1	k=2	k=3		k=5	k=6	k=7	k=8	k=9	k=10	k=11	k=12	k=13	k=14	k=15	k=16	k=17	k=18	k=19	k=20	k=21
5														k=1	k=2	k=3	k=4		k=6	k=7	k=8	k=9	k=10	k=11	k=12	k=13	k=14	k=15	k=16	k=17	k=18	k=19	k=20	k=21	k=22
6													k=1	k=2	k=3	k=4	k=5		k=7	k=8	k=9	k=10	k=11	k=12	k=13	k=14	k=15	k=16	k=17	k=18	k=19	k=20	k=21	k=22	k=23
7												k=1	k=2	k=3	k=4	k=5	k=6		k=8	k=9	k=10	k=11	k=12	k=13	k=14	k=15	k=16	k=17	k=18	k=19	k=20	k=21	k=22	k=23	k=24
8											k=1	k=2	k=3	k=4	k=5	k=6	k=7		k=9	k=10	k=11	k=12	k=13	k=14	k=15	k=16	k=17	k=18	k=19	k=20	k=21	k=22	k=23	k=24	k=25
9										k=1	k=2	k=3	k=4	k=5	k=6	k=7	k=8		k=10	k=11	k=12	k=13	k=14	k=15	k=16	k=17	k=18	k=19	k=20	k=21	k=22	k=23	k=24	k=25	k=26
10										k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9		k=11	k=12	k=13	k=14	k=15	k=16	k=17	k=18	k=19	k=20	k=21	k=22	k=23	k=24	k=25	k=26	k=27
11											k=4	k=5	k=6	k=7	k=8	k=9	k=10		k=12	k=13	k=14	k=15	k=16	k=17	k=18	k=19	k=20	k=21	k=22	k=23	k=24	k=25	k=26	k=27	k=28
12												k=6	k=7	k=8	k=9	k=10	k=11		k=13	k=14	k=15	k=16	k=17	k=18	k=19	k=20	k=21	k=22	k=23	k=24	k=25	k=26	k=27	k=28	k=29
13													k=8	k=9	k=10	k=11	k=12		k=14	k=15	k=16	k=17	k=18	k=19	k=20	k=21	k=22	k=23	k=24	k=25	k=26	k=27	k=28	k=29	k=30
14														k=10	k=11	k=12	k=13		k=15	k=16	k=17	k=18	k=19	k=20	k=21	k=22	k=23	k=24	k=25	k=26	k=27	k=28	k=29	k=30	k=31
15															k=12	k=13	k=14		k=16	k=17	k=18	k=19	k=20	k=21	k=22	k=23	k=24	k=25	k=26	k=27	k=28	k=29	k=30	k=31	k=32
16																k=14	k=15		k=17	k=18	k=19	k=20	k=21	k=22	k=23	k=24	k=25	k=26	k=27	k=28	k=29	k=30	k=31	k=32	k=33
17																	k=16		k=18	k=19	k=20	k=21	k=22	k=23	k=24	k=25	k=26	k=27	k=28	k=29	k=30	k=31	k=32	k=33	k=34
18																																			
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20																				k=22	k=23	k=24	k=25	k=26	k=27	k=28	k=29	k=30	k=31	k=32	k=33	k=34	k=35		
21																					k=24	k=25	k=26	k=27	k=28	k=29	k=30	k=31	k=32	k=33	k=34	k=35			
22																						k=26	k=27	k=28	k=29	k=30	k=31	k=32	k=33	k=34	k=35				
23																							k=28	k=29	k=30	k=31	k=32	k=33	k=34	k=35					
24																								k=30	k=31	k=32	k=33	k=34	k=35						
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4. SIMULATIONS

Simulation results analyzing SXR variations vs. channel input powers, channel spacings and channel lengths are given and interpreted in this section.

4.1. SXR vs. Channel Input Powers

In this subsection, simulation results analyzing SXR variations vs. channel input powers in the range of 1-5 mW for center uplink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems are presented. The center uplink channel operating wavelength has been taken as 1310 nm. Equal channel input powers have been taken into account. 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 Figs. 2-5.

In the literature, there are various minimum SXR values such as 20 dB, 23 dB or 25 dB that have been taken into account for DWDM-based systems as convenient SXR levels in analyzing FWM impacts (Nakajima et. al., 1997; Bogoni and Poti, 2004; Harboe et. al., 2008). In this paper, a minimum 23 dB SXR value has been considered. 23 dB SXR level is shown with green color in Figs. 2-5. Evaluating simulation results given in Figs. 2-5, comparative results displaying maximum channel input powers that satisfy 23 dB SXR condition in center channels are given in Table 6.

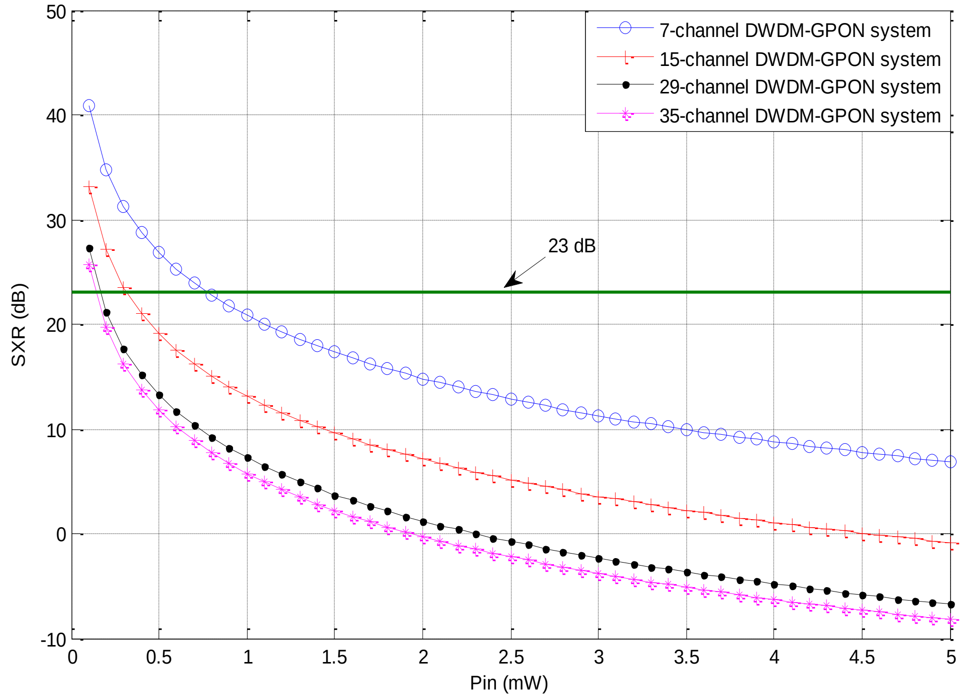

Figure 2:
SXR variation vs. channel input powers in center uplink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems for 12.5 GHz channel spacings

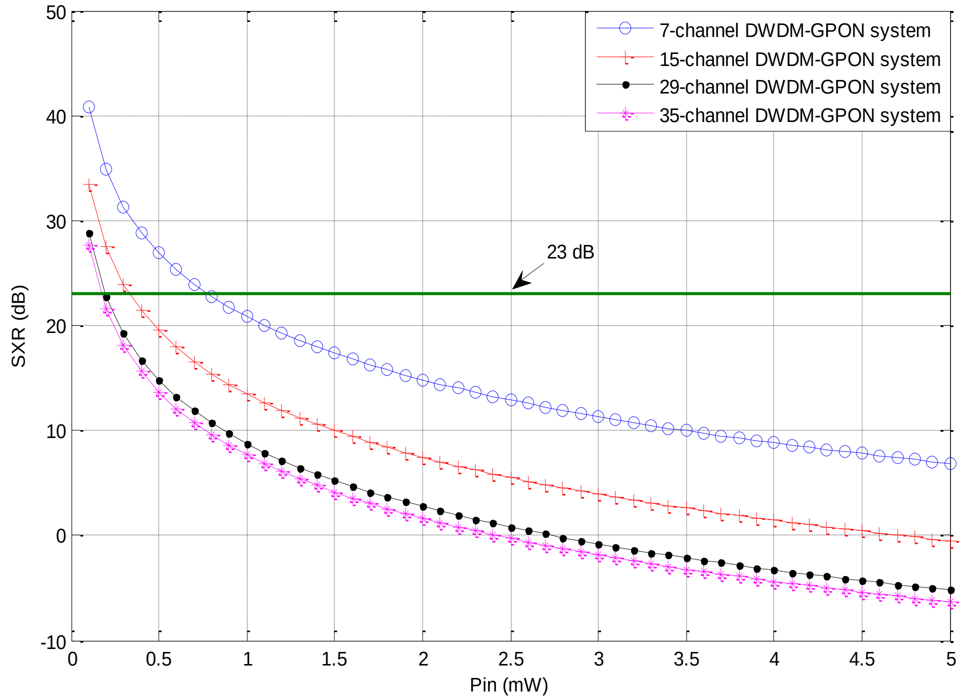

Figure 3:
SXR variation vs. channel input powers in center uplink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems for 25 GHz channel spacings

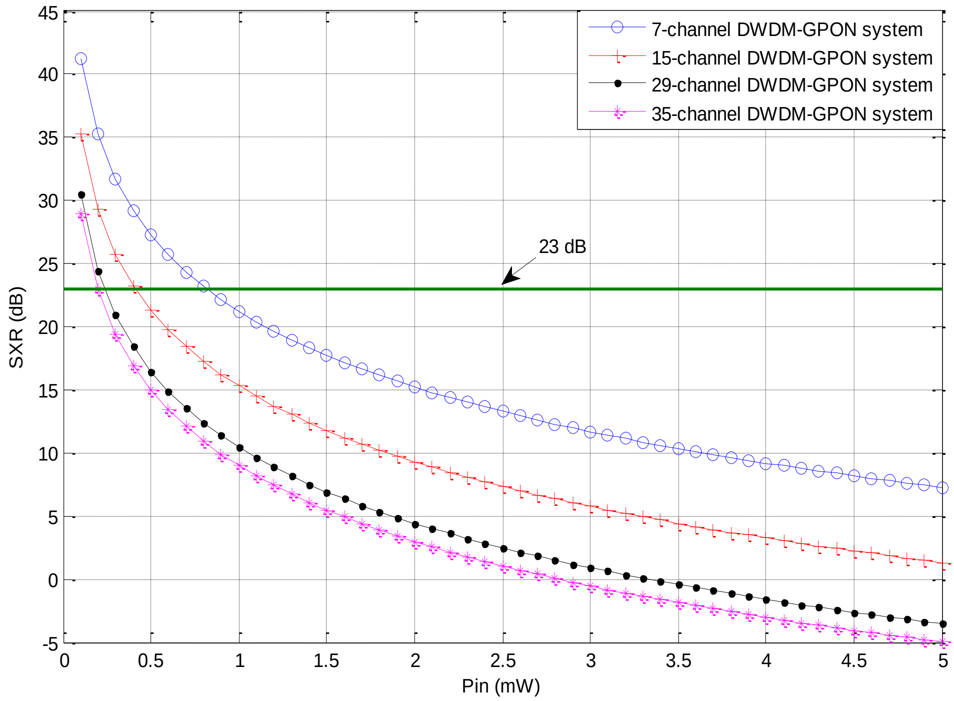

Figure 4:
SXR variation vs. channel input powers in center uplink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems for 50 GHz channel spacings

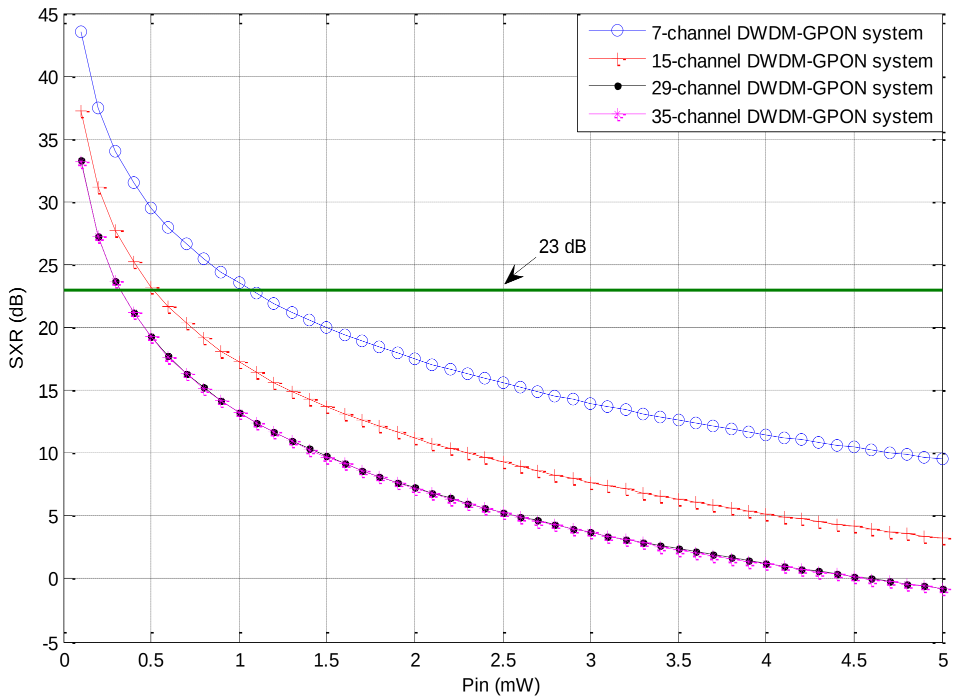

Figure 5:
SXR variation vs. channel input powers in center uplink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems for 100 GHz channel spacings

Table 6. Comparative results displaying maximum channel input powers that satisfy 23 dB SXR condition in center uplink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems

DWDM-GPON Systems	Δf (GHz)	12.5	25	50	100
7-channel	Maximum P_{in} satisfying 23 dB SXR (mW)	0.78	0.78	0.81	1.06
15-channel		0.32	0.33	0.41	0.51
29-channel		0.17	0.19	0.24	0.32
35-channel		0.14	0.17	0.19	0.32

Figs. 2-5 and Table 6 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 that is 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 that is generated in the center 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 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 6 give important clues for input power maximization considering the FWM impact in the uplink channels of DWDM-GPON systems.

4.2. SXR vs. Channel Spacings

In this subsection, simulation results analyzing SXR variations vs channel spacing values, i.e. Δf, up to 100 GHz for the center uplink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems are given. The center uplink channel operating wavelength has been taken as 1310 nm. Equal channel input powers have been taken into account and considered as 0.1 mW to provide 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 are given in Table 7.

Results emphasize that channel numbers have a more significant effect on SXR values than channel spacing values at fixed channel input powers. SXR values at 100 GHz are 2.69-7.47 dB higher than the values at 12.5 GHz for the same channel numbers while SXR values for 7-channel DWDM-GPON systems are 10.30-15.08 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 and it emphasizes that contrary to the case in long-haul DWDM transmission (Harboe et. al., 2008; Karlık, 2016a; Karlık, 2016b), narrowing channel spacings for more efficient usage of fiber bandwidth in the uplink transmission may not result in a dramatic SXR degradation and reliable data transmission may be achieved under the FWM impact when appropriate input powers are selected.

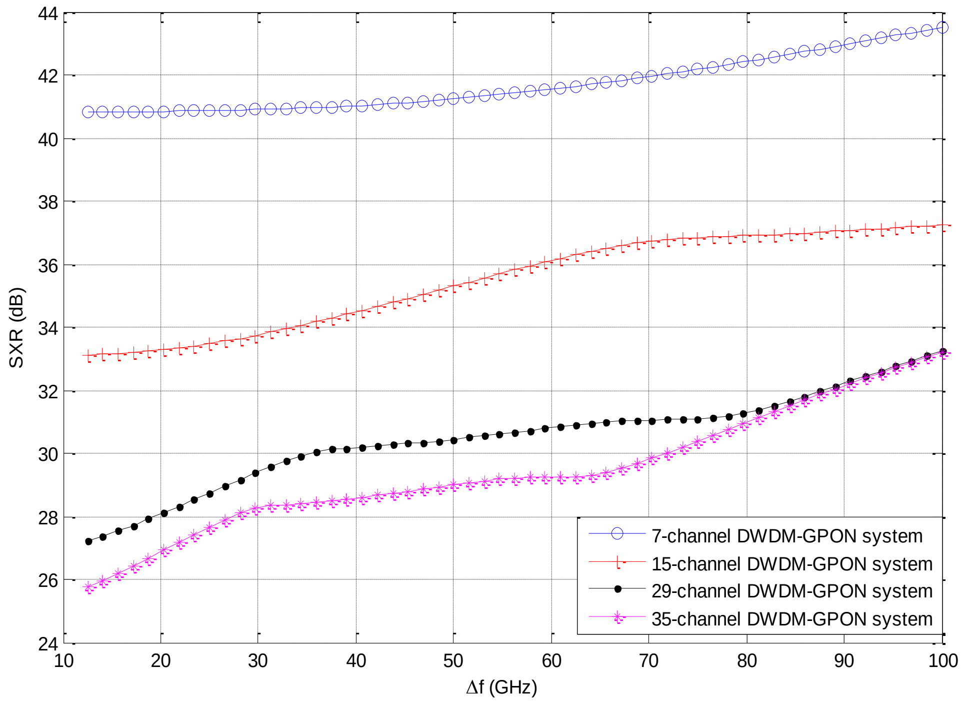

Figure 6:
SXR variation vs. channel spacing values in center uplink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems

Table 7. Comparative SXR values in center uplink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems

DWDM-GPON Systems	Δf (GHz)	12.5	25	50	100
7-channel	SXR at center uplink channel (dB)	40.83	40.86	41.24	43.52
15-channel		33.11	33.47	35.30	37.23
29-channel		27.23	28.75	30.44	33.25
35-channel		25.75	27.67	29.00	33.22

4.3. SXR vs. Channel Lengths

In this subsection, simulation results analyzing SXR variations vs. channel lengths in the center uplink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems are given. The center uplink channel operating wavelength has been taken as 1310 nm. Equal channel input powers have been taken into account and considered as 0.1 mW to provide 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 and comparative SXR values at variable channel lengths are given in Table 8.

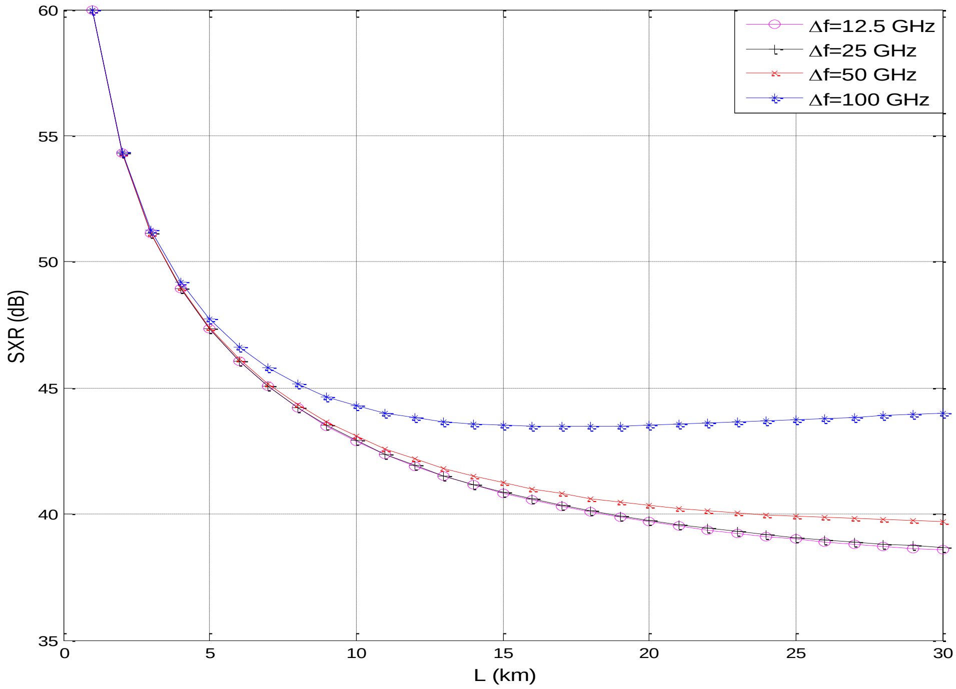

Figure 7:
SXR variation vs. channel lengths in center uplink channels of 7-channel DWDM-GPON systems

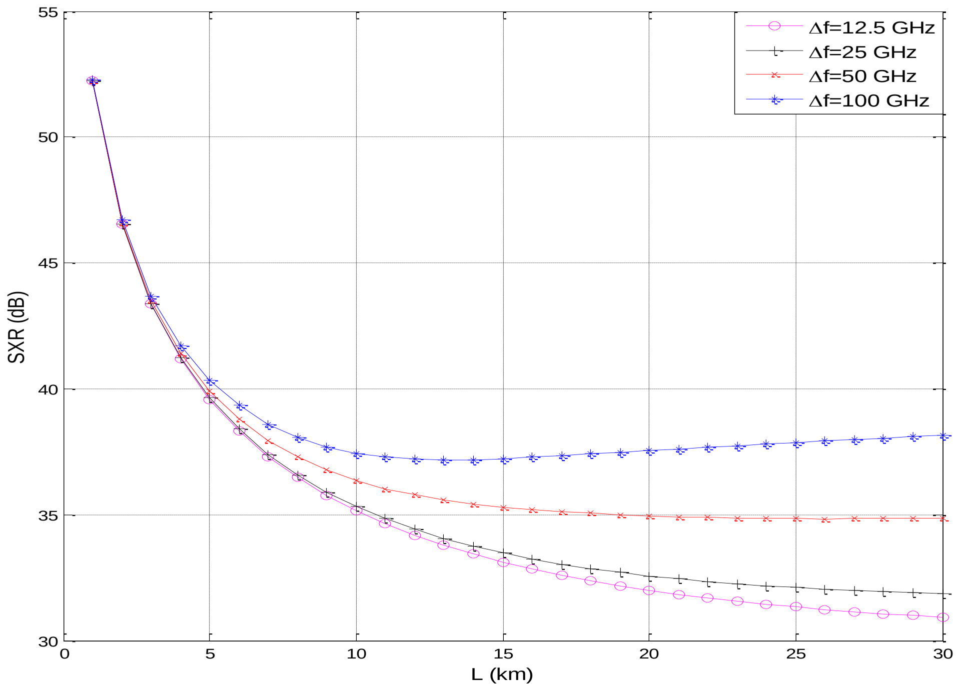

Figure 8:
SXR variation vs. channel lengths in center uplink channels of 15-channel DWDM-GPON systems

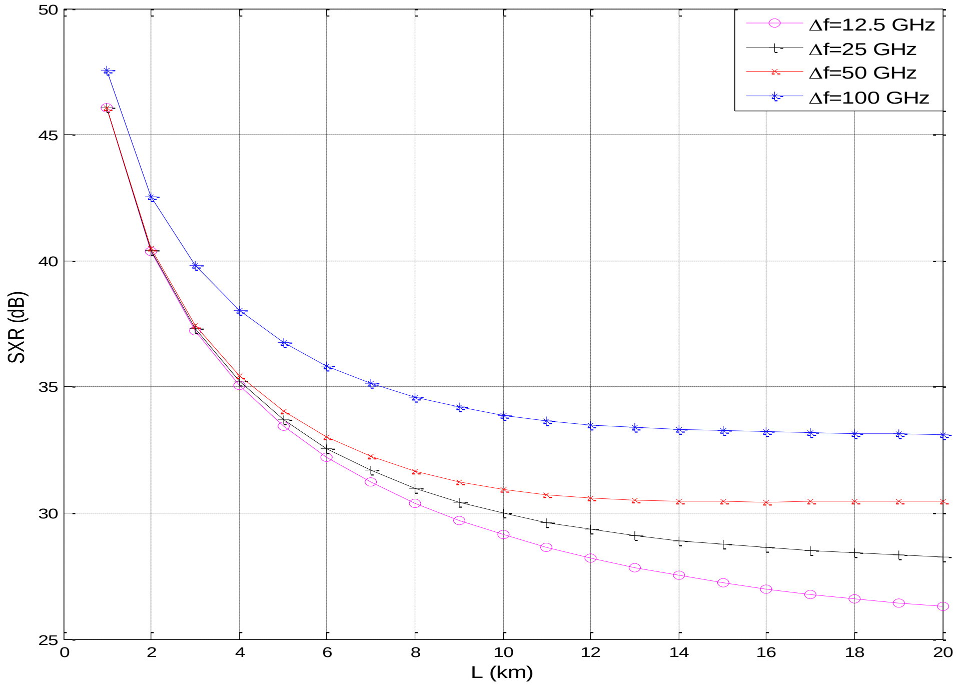

Figure 9:
SXR variation vs. channel lengths in center uplink channels of 29-channel DWDM-GPON systems

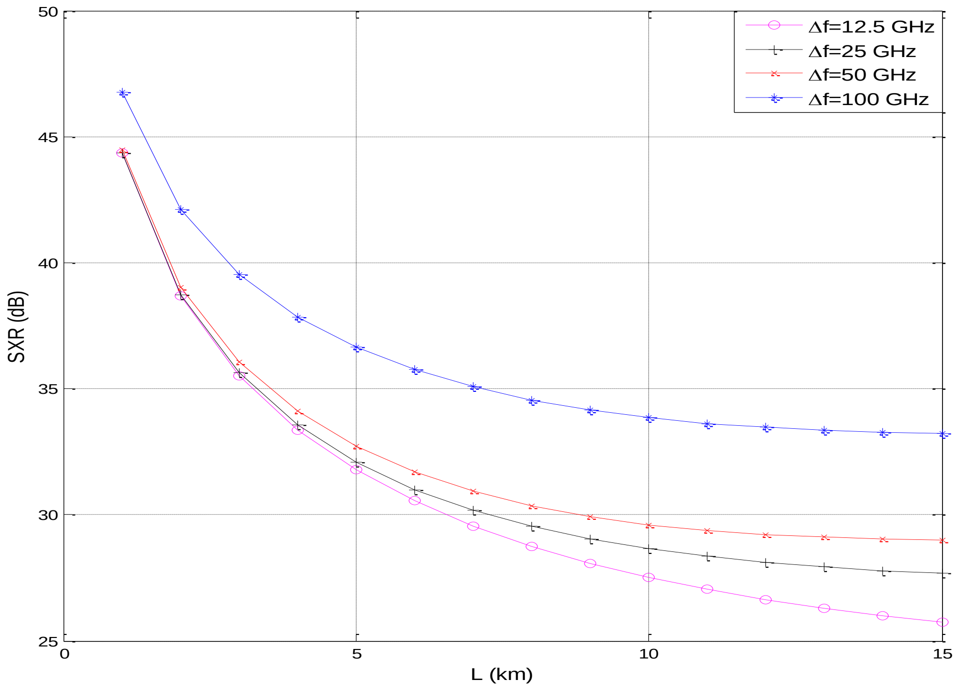

Figure 10:
SXR variation vs. channel lengths in center uplink channels of 35-channel DWDM-GPON systems

Table 8. Comparative SXR values at variable channel lengths for center uplink channels of 7-, 15-, 29- and 35-channel DWDM-GPON systems

Length (km)	DWDM-GPON Systems	Δf (GHz)	12.5	25	50	100
1	7-channel	SXR at center uplink channel (dB)	59.97	59.97	59.97	59.99
	15-channel		52.22	52.22	52.23	52.26
	29-channel		46.05	46.06	46.08	47.57
	35-channel		44.34	44.35	44.48	46.77
5	7-channel		47.33	47.34	47.38	47.72
	15-channel		39.59	39.63	39.93	40.34
	29-channel		33.46	33.70	34.04	36.77
	35-channel		31.77	32.10	32.72	36.65
10	7-channel		42.89	42.91	43.08	44.29
	15-channel		35.16	35.33	36.36	37.43
	29-channel		29.12	29.99	30.95	33.88
	35-channel		27.53	28.65	29.60	33.84
15	7-channel		40.83	40.86	41.24	43.52
	15-channel		33.11	33.47	35.30	37.23
	29-channel		27.23	28.75	30.44	33.25
	35-channel		25.75	27.67	29.00	33.22
20	7-channel		39.69	39.74	40.34	43.53
	15-channel		31.99	32.56	34.95	37.55
	29-channel		26.28	28.25	30.47	33.12
	35-channel		-	-	-	-
25	7-channel		39.00	39.08	39.91	43.73
	15-channel		31.33	32.10	34.84	37.86
	29-channel		-	-	-	-
	35-channel		-	-	-	-
30	7-channel		38.57	38.67	39.72	44.02
	15-channel		30.93	31.87	34.86	38.15
	29-channel		-	-	-	-
	35-channel		-	-	-	-

It is clear in Figs.7-10 that SXR exhibits an exponential decay with the increase in channel length. It can be computed from Table 8 that SXR degradations in center uplink channels of 7- and 15-channel DWDM-GPON systems are in the range of 15.97 dB-21.4 dB and 14.11 dB-21.29 dB, respectively, for the channel length range of 1 km-30 km and channel spacing range of 12.5 GHz-100 GHz while that for 29-channel DWDM-GPON systems are in the 14.45 dB-19.77 dB range for the channel length range of 1 km-20 km and that for 35-channel DWDM-GPON systems are in the 13.55 dB-18.59 dB range for the channel length range of 1 km-15 km. Another remarkable point observed in simulations is that contrary to the results obtained for long-haul DWDM systems operating at 1550 nm wavelength (Harboe et. al., 2008; Karlık, 2016a; Karlık, 2016b), SXR variation in uplink channels of DWDM-GPON systems operating at 1310 nm wavelength does not show an oscillatory behavior with varying channel lengths and channel spacing values. This is due to the weaker phase mismatch in 1310 nm with respect to that in 1550 nm operating wavelength. The lack of this oscillatory behavior is an important point in system design and implementation enhancing the system reliability and simplifying the performance analysis since the threat of rapid SXR degradation for short increments in fiber link lengths does not occur.

5. CONCLUSION

The FWM impact on the performance of center uplink 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 contrary to general expectations in long-haul DWDM-based communication, narrowing channel spacings in uplink transmission of DWDM-GPONs for a more efficient usage of fiber bandwidth may not result in a dramatic SXR degradation and minimum SXR level required for a reliable data transmission may be provided. Simulations about SXR vs. channel lengths emphasize that channel length variations cause exponential but easily predictable SXR degradations since contrary to the case in long-haul DWDM-based systems, there is no oscillatory behavior in SXR degradations in all channel spacing values for DWDM-GPON uplink channels and this results in enhancement of system reliability and simplifies the system performance analysis.

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