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THE COMBINED IMPACT OF SRS AND FWM PHENOMENA ON THE DOWNLINK CHANNEL PERFORMANCE OF DWDM-GPON SYSTEMS

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Abstract: In this paper the combined impact of stimulated Raman scattering (SRS) and four-wave mixing (FWM) on the downlink channel performance of dense wavelength division multiplexed-gigabit passive optical networks (DWDM-GPONs) has been compared with the single impact of FWM via signal-to-crosstalk ratio (SXR) simulations performed on center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems. Simulation results show that SRS compensates negative impacts of FWM and compensation significance enhances with increasing channel numbers and channel spacing values. At high channel spacing values of 50 GHz and 100 GHz, variation of SXR can display a strong oscillatory behavior in very short channel length variations of 0.5 km. The combined impact of SRS and FWM enhances the maximum oscillation amplitude of SXR variation with respect to the single impact of FWM at those channel spacing values. It has been observed that Raman gain exhibits an approximately linear variation with channel input powers in 0.1-5 mW range and it increases with increasing fiber lengths, channel spacing values and channel numbers. Results of this research emphasize the significant difference between the combined impact of SRS and FWM and the single impact of FWM on DWDM-GPON systems and give important hints for current DWDM-GPON implementations.

Keywords: Dense wavelength division multiplexing, Gigabit passive optical network, Four wave mixing, Stimulated Raman scattering, Amplification factor, Optical fiber

SRS ve FWM Olaylarının DWDM-GPON Sistemlerin Aşağı Yönlü Kanal Performansları Üzerindeki Birleşik Etkisi

Öz: Bu makalede, 7-, 15- ve 31-kanallı yoğun dalgaboyu bölmeli çoğullamalı gigabit pasif optik ağ (DWDM-GPON) sistemlerinin merkez aşağı yönlü kanalları üzerinde gerçekleştirilen işaret-çapraz karışım oranı (SXR) benzetimleri yardımıyla, uyarılmış Raman saçılması (SRS) ve dört dalga karışımının (FWM), DWDM-GPON aşağı yönlü kanal performansları üzerindeki birleşik etkisi, FWM'nin tekli etkisi ile karşılaştırılmıştır. Benzetim sonuçları, SRS'nin FWM'nin negatif etkilerini kompanze ettiğini ve kompanzasyon belirginliğinin artan kanal sayıları ve kanallar arası boşluk değerleri ile arttığını göstermektedir. 50 GHz ve 100 GHz gibi yüksek kanallar arası boşluk değerlerinde, SXR değişimi, 0.5 km'lik çok kısa kanal uzunluğu değişimlerinde güçlü bir osilasyon davranışı sergilemektedir. Bu kanallar arası boşluk değerlerinde, SRS ve FWM birleşik etkisi, SXR değişimindeki maksimum osilasyon genliğini FWM'nin tekli etkisine göre daha da arttırmaktadır. 0.1-5 mW aralığında, Raman kazancının kanal giriş güçleri ile yaklaşık olarak doğrusal değişim sergilediği gözlenmiştir ve Raman kazancı artan fiber uzunlukları, kanallar arası boşluk değerleri ve kanal sayıları ile artmaktadır. Bu çalışmanın sonuçları, DWDM-GPON sistemler üzerindeki SRS ve FWM birleşik etkisi ile FWM tekli etkisi arasındaki belirgin farkı vurgulamakta ve mevcut DWDM-GPON uygulamaları için önemli ipuçları vermektedir.

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Anahtar Kelimeler: Yoğun dalgaboyu bölmeli çoğullama, Gigabit pasif optik ağ, Dört dalga karışımı, Uyarılmış Raman saçılması, Kuvvetlendirme faktörü, Optik fiber

1. INTRODUCTION

In modern optical communication systems, networks having longer lifetimes, higher speeds, higher bandwidths and lower costs with respect to their alternatives become more important due to ever-increasing demands of customers. Currently, passive optical network (PON) structures, in particular gigabit passive optical networks (GPONs), promise important features for access networks. Allowing information at different channels to be transmitted in various wavelengths through a single fiber at the same time in both upstream and downstream directions, dense wavelength division multiplexed-GPON (DWDM-GPON) systems have proved to be a better choice in increasing the capacity and the flexibility in network design. Telecommunication Standardization Sector of International Telecommunication Union (ITU-T) has standardized the channels spacings for DWDM as 12.5 GHz, 25 GHz, 50 GHz and 100 GHz with Recommendations G.671 (2002) and G.694.1 (2012). System specifications such as the number of DWDM channels, channel spacings, total transmission length and the input power per channel have important roles in overall system performance as well as the nonlinear effects occurring on the optical fiber during system operation. Among all fiber nonlinearities, four wave mixing (FWM) and stimulated Raman scattering (SRS) are expected to have major impacts on performance limitations in DWDM-GPON systems. There are various papers focusing on long-haul DWDM system performance under the impacts of FWM (Souza and Harboe, 2011; Song and Brandt-Pearce, 2013; Sharma and Kaur, 2013; Hiçdurmaz et. al., 2013; Karlık, 2016a; Karlık, 2016b) while analyses have been carried out for just SRS effects in some papers (Singh and Hudiara, 2004; Kaur et. al., 2015) or for the combined effect of SRS and FWM but in the presence of amplified spontaneous emission (ASE) noise generated by erbium-doped fiber amplifiers (EDFAs) in some others (Kaur and Singh, 2007a; Kaur and Singh, 2007b; Kaur et. al., 2010; Kaur et. al., 2011). However, to the best of our knowledge, there are no papers focusing on the combined impact of SRS and FWM on the downlink channel performance of DWDM-GPON systems. In this paper, using the signal-to-crosstalk ratio (SXR) variations, i.e. variations in the ratio of the power of the modified signal due to SRS to the power of FWM crosstalk, the combined impact of SRS and FWM on the downlink performance of DWDM-GPON systems has been analyzed with Matlab 2013a simulations considering channels spacings of 12.5 GHz, 25 GHz, 50 GHz and 100 GHz. The amplification factor of the Stokes wave in 7-, 15- and 31-channel DWDM-GPON systems has also been analyzed. In Section 2, the theoretical background required for FWM, SRS and PONs is given. Simulation models and necessary system characteristics are introduced in Section 3. Simulations results and their interpretation are presented in Section 4.

2. THEORETICAL BACKGROUND FOR FWM, SRS AND PONs

2.1. Four Wave Mixing (FWM)

During the FWM process, the interaction between three different optical waves propagating through the optical fiber with frequencies f_i, f_j and f_k generates a novel fourth wave with a novel frequency f_{ijk} due to the third order susceptibility of the fiber. The above mentioned process can be described with

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

where indices i, j and k present three different channels of DWDM system satisfying the condition $k \neq i, j$. The major impact of FWM on DWDM system occurs when novel optical signals generated by triple combinations of optical signals fall in original DWDM channels and interact with original signals in those channels. If channels are equally spaced in DWDM systems, a significant number of FWM products, i.e. generated optical signals, and original channels may propagate with the same frequencies and hence result in FWM crosstalk, which causes a significant degradation in the system performance

The total number of FWM products (M) generated in DWDM systems depends on the number of DWDM channels (N) and can be determined with

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

The FWM power generated at the frequency f_{ijk} can be computed with

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

where d_{ijk} indicates the degeneracy factor, where $d_{ijk} = 3$ for $i = j \neq k$ and $d_{ijk} = 6$ for $i \neq j \neq k$, γ indicates the nonlinearity coefficient, L_{eff} indicates the effective fiber length, $P_{i,}$ P_j and P_k indicate input powers of channels i, j, k, respectively, α indicates the attenuation coefficient of the fiber, L indicates the fiber length and η_{ijk} indicates the FWM efficiency, which can be given 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 the phase mismatching factor (ΔB_{ijk}) is

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

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

For the case of a DWDM system having equally spaced channels, the total FWM crosstalk in a channel with a frequency f_c can be expressed as (Maeda et. al., 1990)

$$P_{FWM}(f_c) = \sum_{f_k = f_i + f_j - f_c}\sum_{f_j}\sum_{f_i} P_{FWM}(f_i + f_j - f_k) \tag{6}$$

The signal-to-crosstalk ratio (SXR) parameter, which can be used for the analysis of FWM crosstalk impact on a specific channel of a DWDM system, can be defined as

$$SXR = 10log_{10}\left(\frac{P_{out}}{P_{FWM}}\right) \tag{7}$$

where P_{out} is the output power of the channel and is computed with $P_{out} = P_{in}.e^{-\alpha L}$ for the input power P_{in}.

2.2. Stimulated Raman Scattering (SRS)

In WDM fiber communication systems, SRS is one of the crucial nonlinear effects, which degrades the system performance due to the inter-channel crosstalk and that leads to a decrease in the SNR of the WDM system. In SRS, the incident light interacts with molecular vibrations of the fiber medium and because of this interaction, light can be scattered. Also in SRS, channels with higher frequencies (shorter wavelengths) transfer a part of their power to channels with lower frequencies (higher wavelengths) (Schneider, 2004).

Modified signal powers at various wavelengths due to SRS can be evaluated as (Singh and Hudiara, 2004)

$$P_M[k] = P_T[k] - P_T[k] \sum_{i=k+1}^{N} D[k,i] + P_T[k] \sum_{j=1}^{k-1} P_T[j]\, D[j,k] \tag{8}$$

In the right hand side of (8), the first term, i.e. $P_T[k]$, indicates the total power transmitted to the k^{th} channel, the second term, i.e. $P_T[k]\sum_{i=k+1}^{N} D[k,i]$, indicates the total power depleted from the k^{th} channel by the higher wavelength channels and the third term, i.e. $P_T[k]\sum_{j=1}^{k-1} P_T[j]\, D[j,k]$, gives the total power depleted by the k^{th} channel from lower wavelength channels. In (8), for k =1, 2, ..., N $D[k,i] = 0$ for i > N and for k=1 $D[j,k] = 0$.

The fraction of power depleted from the i^{th} channel by the j^{th} channel, i.e. $D[i,j]$, can be represented as

$$D[i,j] = \begin{cases} \left(\dfrac{\lambda_j}{\lambda_i}\right). P_T[j]. \left\{\dfrac{(f_i - f_j)}{1.5 * 10^{13}}\right\}. g_{Rmax}. \left\{\dfrac{(L_{eff}(\lambda_j) * 10^5)}{(b. A_{eff})}\right\} & ,(f_i - f_j) \leq\ 1.5 * 10^{13}\ Hz\ and\ j > i \\ 0 & ,(f_i - f_j) >\ 1.5 * 10^{13}\ Hz\ and\ j \leq i \end{cases} \tag{9}$$

where λ_i *and* λ_j are wavelengths of i^{th} and j^{th} channels, respectively, in terms of nm; $P_T[j]$ is the optical power launched in the j^{th} channel in terms of mW, g_{Rmax} is the peak Raman gain coefficient in terms of cm/W; f_i and f_j are center frequencies of i^{th} and j^{th} channels, respectively, in terms of Hz; $L_{eff}(\lambda_j)$ is the effective length of the j^{th} channel operating at the wavelength λ_j in terms of km; A_{eff} is the effective core area of the optical fiber in terms of cm^2 and the value b varies between 1 and 2 according to the polarization state of signals at different wavelength channels.

The actual optical power received at the receiver side of the k^{th} channel is defined as

$$P_R[k] = P_M[k]. e^{-\alpha L} \tag{10}$$

In SRS, the power transfer from channels with higher frequencies to the ones with lower frequencies is in fact the light amplification in the channel that has a higher wavelength by the help of the channel that has a lower wavelength. The amplification factor of the Stokes wave (channel that has a higher wavelength), i.e. G_R, can be defined as the ratio of the intensity of the Stokes wave with Raman scattering at the fiber output, i.e. $I_S(L)$, to the intensity it would have without the Raman scattering at the fiber output, i.e. $I_S(0)e^{-\alpha_S L}$ (Schneider, 2004).

$$G_R = \frac{I_S(L)}{I_S(0). e^{-\alpha_S L}} \tag{11}$$

Since the amplification of the Stokes wave causes a depletion in the pump wave (channel that has a lower wavelength), a depletion factor can be described for the pump wave in a similar way to the amplification factor.

Considering that $I_S(L) = P_{SRS}.e^{-\alpha_S L}$ and $I_S(0) = P_{in}$, (11) can be rewritten as

$$G_R = \frac{P_{SRS}}{P_{in}} \tag{12}$$

where P_{SRS} represents the modified power due to SRS.

The SXR given in (7) can be modified for DWDM systems under combined impacts of SRS and FWM as

$$SXR = 10log_{10}\left(\frac{P_{SRS}}{P_{FWM}}\right) \tag{13}$$

where P_{SRS} is the modified signal power due to SRS and P_{FWM} is the FWM crosstalk power.

2.3. Passive Optical Networks (PONs)

PON is an optical network technology which uses a point-to-multipoint topology that means a single fiber is used to support multiple users. It includes an Optical Line Termination (OLT), a group of an Optical Network Units (ONUs), a passive optical device or a splitter and optical fibers connecting those devices mentioned above. The OLT is located at the Central Office (CO) where it has an obligation to transmit the data coming from the metropolitan network to ONUs through the downlink stream and the data coming from ONUs to the metropolitan network via the uplink stream. Two wavelengths are used by OLT, one is 1490 nm for the downlink and the other is 1310 nm for the uplink. ONUs are located at customer premises. The optical splitter exists between the OLT and the ONU and it works as a demultiplexer for the downstream transmission and as a multiplexer for the upstream transmission. A PON architecture is shown in Fig. 1.

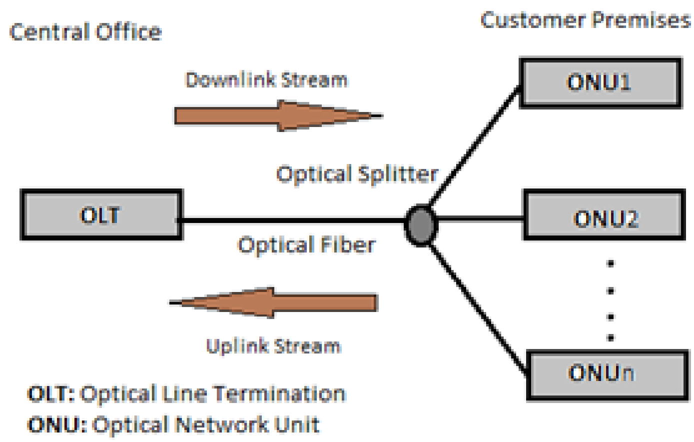

Figure 1:
PON architecture

PONs are important in current DWDM system applications, in particular GPONs. GPON technology has been standardized by ITU-T with Recommendations series of G.984.x (G.984.1, 2008; G.984.2, 2003; G.984.3, 2014; G.984.4, 2008; G.984.5, 2014).

GPONs have those specifications;

- A data packet or cell size of 53 to 1518 bytes.
- Maximum downstream data rate of 2.4 Gbps.
- Maximum upstream data rate of 1.2 Gbps.
- Downstream wavelength of 1490 nm and 1550 nm.
- Upstream wavelength of 1390 nm.
- Max splitting ratio of 1:64 and max transmission distance of 30 km.

Recommendations G.984.x supply 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.

In DWDM-GPON applications, considering the number of end-users in both channels, i.e. downlink and uplink channels, channels can be divided into sub-channels using the splitting ratio (1:N) feature of the optical splitter. 1:128 splitting ratios will be available in applications in the near future.

3. SIMULATION MODEL AND FIBER PARAMETERS

In this study, with the help of MATLAB 2013a simulation program and mathematical equations given in Section 2, simulations have been performed for center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems, which have equally spaced channels with channel spacing values of 12.5 GHz, 25 GHz, 50 GHz and 100 GHz.

In simulations, G.652 standard single-mode fiber (SSMF) has been used for the downlink channel operating at 1490 nm and important parameter values of this fiber are given in Table 1, where D_c indicates the chromatic dispersion, S indicates the chromatic dispersion slope, γ denotes the nonlinearity coefficient and α is the attenuation coefficient.

Table 1. Parameters of SSMF

Dc (ps/nm.km)	**S (ps/$nm^2.km$)**	**γ (1/W.km)**	**α (dB/km)**
12.72	0.086	1.35	0.22

Table 2. Channel combinations that generate FWM products in the center channel of a 7-channel DWDM-GPON 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							

In DWDM-GPON systems implemented with SSMFs, center channels are the most badly impacted channels (Harboe et. al., 2008). Therefore, center channels of 7-, 15- and 31-channel DWDM-GPON systems, i.e. 4^{th}, 8^{th} and 16^{th} channels, respectively, are taken into account in simulations. Tables 2-4 show the triple channel combinations that generate FWM products falling into center channels of 7-, 15- and 31-channel systems, respectively.

In Tables 2-4, i, j and k show channel numbers that construct FWM products in the center channel of the related DWDM-GPON system, e.g. in Table 2, channel 3 (i=3), channel 5 (j=5) and channel 4 (k=4) generate a FWM product in the center channel, i.e. the 4th channel, of the 7-channel DWDM-GPON system. As mentioned before in Section 2, k≠ i, j and only half spaces in Table 2-4 are considered since i and j are interchangeable.

Table 3. Channel combinations that generate FWM products in the center channel of a 15-channel DWDM-GPON 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. Channel combinations that generate FWM products in the center channel of a 31-channel DWDM-GPON 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
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
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
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
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
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
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
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
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
9									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
10										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
11											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
12												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
13													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
14														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
15															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
16																															
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	
18																		k=20	k=21	k=22	k=23	k=24	k=25	k=26	k=27	k=28	k=29	k=30	k=31		
19																			k=22	k=23	k=24	k=25	k=26	k=27	k=28	k=29	k=30	k=31			
20																				k=24	k=25	k=26	k=27	k=28	k=29	k=30	k=31				
21																					k=26	k=27	k=28	k=29	k=30	k=31					
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4. SIMULATIONS

In this section, simulation results analyzing SXR variations with variations in channel input powers, channel spacing values and channel lengths are explained and interpreted firstly under the single impact of FWM and then under the combined impact of SRS and FWM. Furthermore, simulation results focusing on variations of the amplification factor of the Stokes wave with variations in input powers have also been reported.

4.1. SXR-channel input power variations

In this subsection, simulation results exhibiting variation of SXR with channel input powers for center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems have been given in Figs. 2-5, where equal channel input powers are considered in the range of 0.1-5 mW. The operating wavelength for the center downlink channel has been taken as 1490 nm. To supply limits in GPON standards, the fiber length connecting the OLT and the splitter has been taken as 15 km for all DWDM-GPON systems. Simulation results shown in Figs. 2-5 have been determined for channel spacing values of 12.5 GHz, 25 GHz, 50 GHz and 100 GHz, respectively.

For analyzing the impact of FWM in DWDM-based systems, appropriate minimum SXR values like 20 dB, 23 dB or 25 dB have been considered in the literature (Nakajima et.al., 1997; Bogoni and Poti, 2004; Harboe et.al., 2008). In this study, a minimum 23 dB SXR value has been taken into account and shown by the green line in Figs. 2-5. Evaluating simulation results shown in Figs. 2-5, comparative results for maximum channel input powers satisfying 23 dB SXR condition are given in Tables 5 and 6 for the single impact of FWM and for the combined impact of SRS and FWM, respectively.

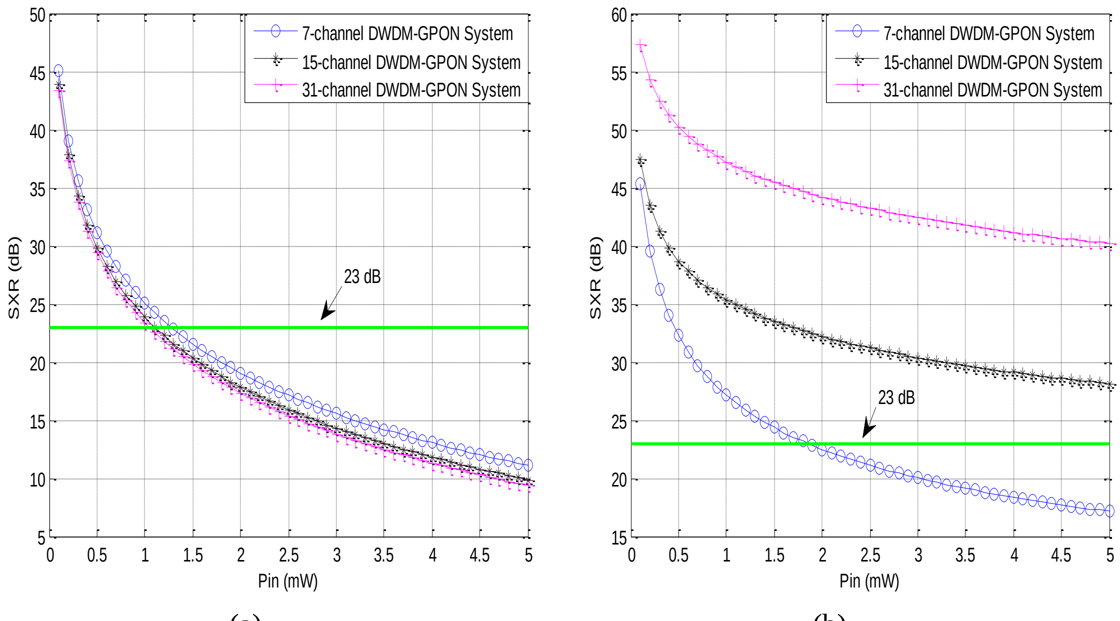
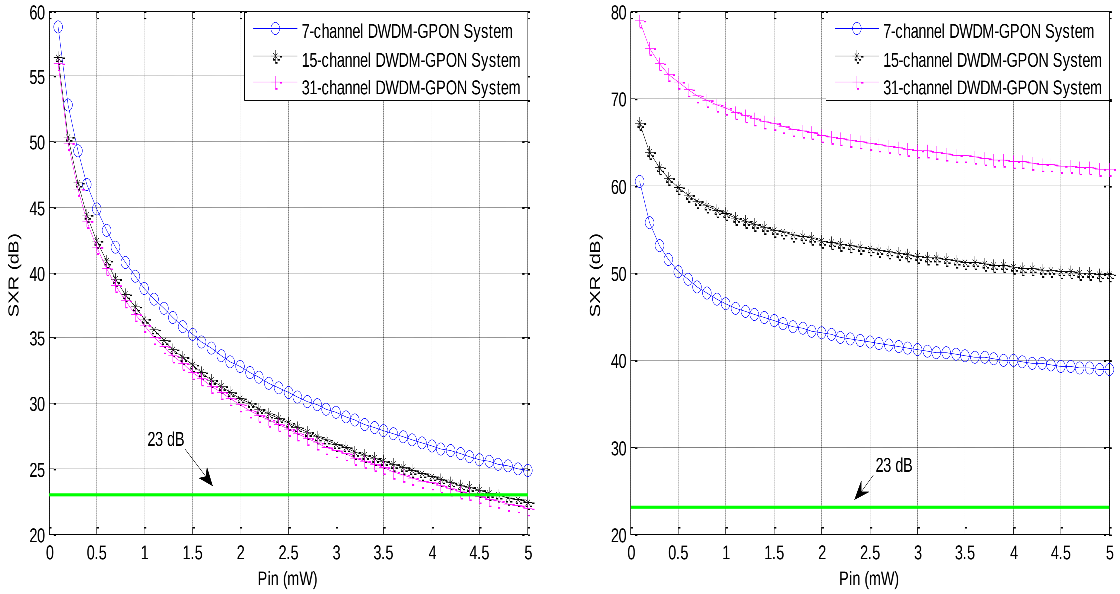
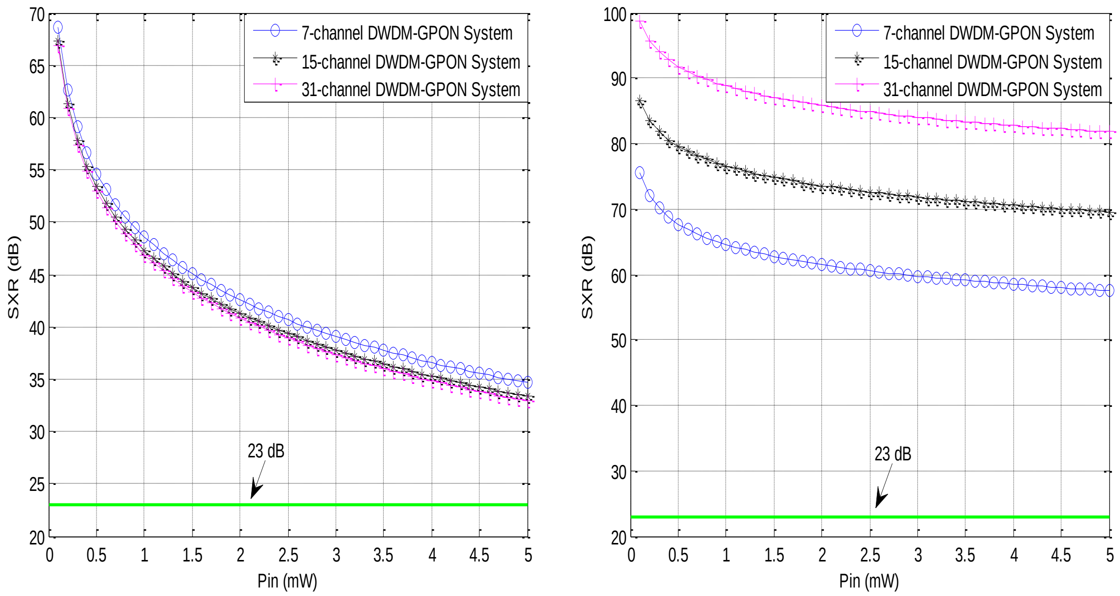


Figure 2:
SXR-channel input power variations in center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems that have 12.5 GHz channel spacing values due to the (a) single impact of FWM (b) combined impact of SRS and FWM



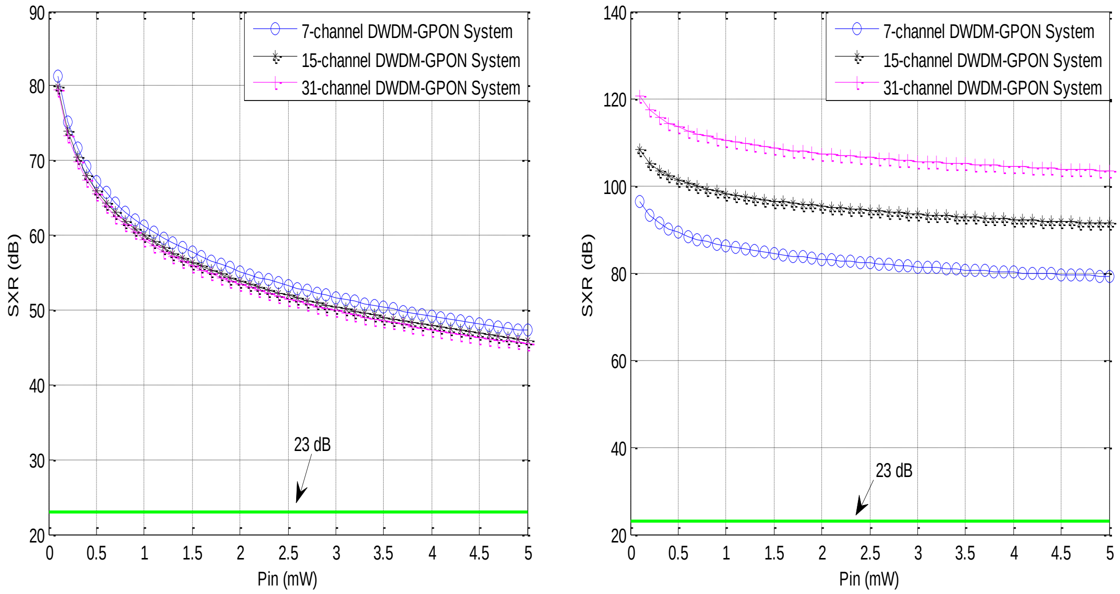
(a) (b)

Figure 3:
SXR-channel input power variations in center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems that have 25 GHz channel spacing values due to the (a) single impact of FWM (b) combined impact of SRS and FWM



(a) (b)

Figure 4:
SXR-channel input power variations in center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems that have 50 GHz channel spacing values due to the (a) single impact of FWM (b) combined impact of SRS and FWM



(a) (b)

Figure 5:
SXR-channel input power variations in center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems that have 100 GHz channel spacing values due to the (a) single impact of FWM (b) combined impact of SRS and FWM

Table 5. Comparative results for maximum channel input powers satisfying 23 dB SXR condition in center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems under the single impact of FWM

DWDM-GPON Systems	Δf (GHz)	12.5	25	50	100
7-channel	Maximum P_{in} satisfying 23 dB SXR (mW)	1.27	>5	>5	>5
15-channel		1.10	4.68	>5	>5
31-channel		1.04	4.42	>5	>5

Table 6. Comparative results for maximum channel input powers satisfying 23 dB SXR condition in center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems under the combined impact of SRS and FWM

DWDM-GPON Systems	Δf (GHz)	12.5	25	50	100
7-channel	Maximum P_{in} satisfying 23 dB SXR (mW)	1.85	>5	>5	>5
15-channel		>5	>5	>5	>5
31-channel		>5	>5	>5	>5

It has been observed in Figures 2a, 3a, 4a and 5a that SXR value shows an exponential decay with the increase in channel input powers due to the P_{in}^3 dependence of P_{FWM} for the case of equal channel input powers as given in (3). Furthermore SXR decreases with decreasing channel spacing values since narrower channel spacings cause degradation in the phase mismatching factor ΔB_{ijk} and this increases the FWM efficiency η_{ijk} and subsequently P_{FWM} increases as it can be easily seen from (3)-(5). SXR also decreases with increasing channel numbers from 7 to 31 and this is due to the increasing number of FWM products generated in center channels as given in Tables 2-4 which enhances the P_{FWM}. For 12.5 GHz channel spacing value, there is a risk to have an SXR value below 23 dB in all 7-, 15- and 31-channel DWDM-GPON systems for channel input powers exceeding 1 mW; for 25 GHz channel spacing value, there is a risk to have an SXR value below 23 dB in only 15- and 31-channel DWDM-GPON systems for channel input powers approaching 5 mW and there is no risk to have an SXR value below 23 dB for all 7-, 15- and 31-channel DWDM-GPON systems for 50 GHz and 100 GHz channel spacing values in the channel input power range of 0.1-5 mW. This is the case under the single impact of FWM.

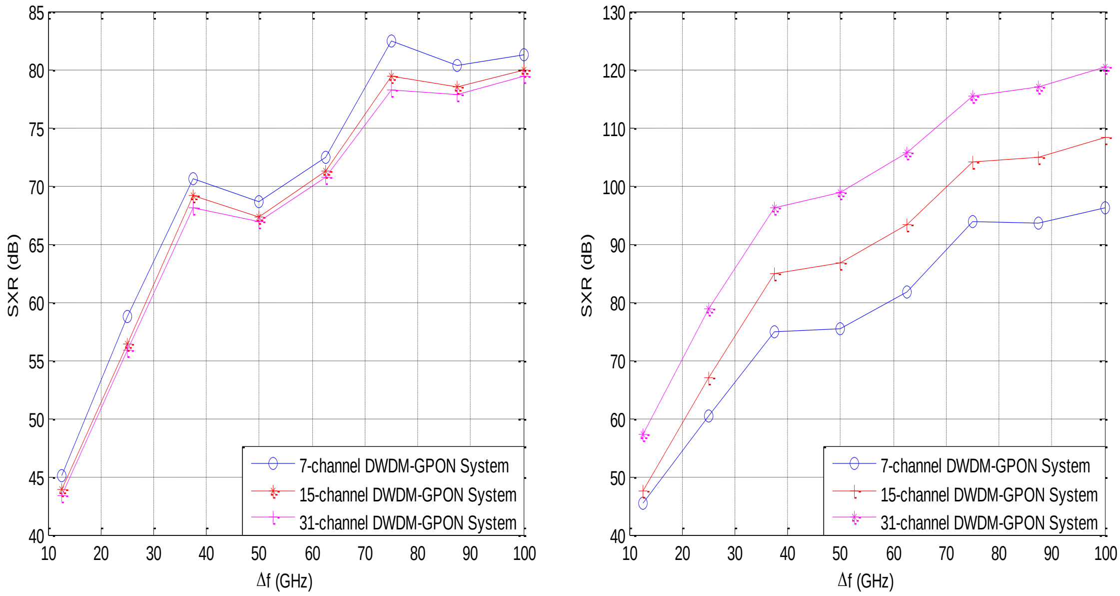
Comparing results given in Figs. 2b, 3b, 4b and 5b with Figs. 2a, 3a, 4a and 5a respectively, it can be easily concluded that SXR values under the combined impact of SRS and FWM are significantly greater than those under the single impact of FWM and furthermore contrary to the case under the single impact of FWM, SXR values increase with increasing channel numbers. This is in fact due to the amplification factor of the Stokes wave, i.e. the Raman gain G_R, increasing with the increasing channel numbers and resulting in an increase in the modified signal power P_{SRS} for center channels. Therefore SXR increases with the increase in P_{SRS} as it is obvious in (11)-(13). Under the combined impact of SRS and FWM, the risk to have an SXR value below 23 dB occurs for only 7-channel DWDM-GPON systems using 12.5 GHz channel spacing values and having channel input powers approaching 2 mW. There is no other risk for 7-, 15- and 31-channel DWDM-GPON systems unless channel input powers exceed the range of 0.1-5 mW. Comparative results show that SRS compensates negative impacts of FWM in center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems and significance of compensation enhances with increasing channel numbers and channel spacing values.

4.2. SXR-channel spacing value variations

In this subsection, simulation results displaying variations of SXR with channel spacing values for center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems have been shown in Fig. 6, where equal channel input powers of 0.1 mW have been considered. The operating wavelength for the center downlink channel has been taken as 1490 nm. To supply limits in GPON standards, the fiber length connecting the OLT and the splitter has been taken as 15 km for all DWDM-GPON systems. Simulation results shown in Fig. 6 have been determined for channel spacing value range of 12.5-100 GHz. Evaluating simulation results given in Figs. 10 and 11, comparative results for SXR values in center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems are displayed in Tables 7 and 8 under the single impact of FWM and the combined impact of SRS and FWM, respectively.

It is clear in Fig. 6 and Tables 7-8 that at fixed channel input powers channel spacing values have more considerable effects on SXR than channel numbers, e.g. at fixed channel numbers SXR values at 100 GHz are greater than those at 12.5 GHz in the range of 36.09-36.14 dB in Table 7 while in the range of 50.90-62.98 dB in Table 8 however at fixed channel spacing values the SXR variation between 7-channel and 31-channel systems is in the rage of 1.74-2.88 dB in Table 7 while it is in 11.99-24.07 dB range in Table 8.

Results given in this subsection is in good agreement with results given in the previous section about the compensating behavior of SRS on negative impacts of FWM in center downlink channels of DWDM-GPON systems, i.e. all SXR values in Table 8 are greater than related values in Table 7. Considering bold-written SXR values in Tables 7 and 8, the increasing significance of the compensating behavior of SRS with increasing channel numbers and channel spacing values can be easily seen.



(a) (b)

Figure 6:
SXR-channel spacing value variations in center downlink channels of 7-, 15- and 31- channel DWDM-GPON systems due to the (a) single impact of FWM (b) combined impact of SRS and FWM

Table 7. Comparative results for SXR values in center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems due to the single impact of FWM

DWDM-GPON Systems	**Δf (GHz)**	**12.5**	**25**	**50**	**100**
7-channel	**SXR values in the center downlink channel (dB)**	**45.08**	58.79	68.62	**81.22**
15-channel		43.85	56.41	67.32	79.94
31-channel		**43.34**	55.91	66.88	**79.43**

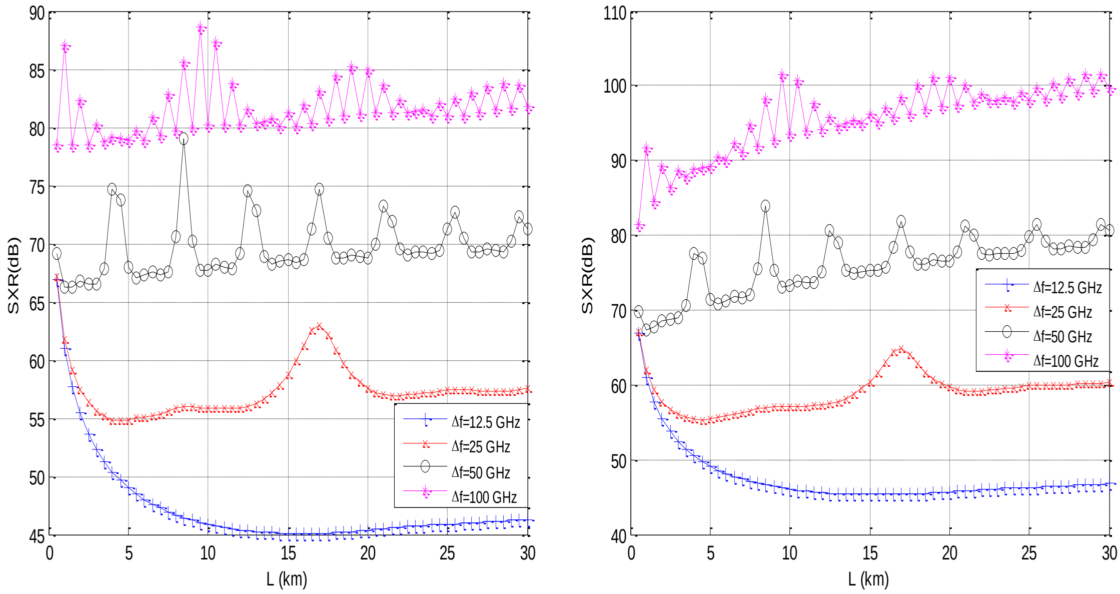
Table 8. Comparative results for SXR values in the center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems due to the combined impact of SRS and FWM

DWDM-GPON Systems	**Δf (GHz)**	**12.5**	**25**	**50**	**100**
7-channel	**SXR values in the center downlink channel (dB)**	**45.33**	60.49	75.46	**96.23**
15-channel		47.48	67.00	86.60	108.20
31-channel		**57.32**	78.77	98.76	**120.30**

4.3. SXR-channel length variations

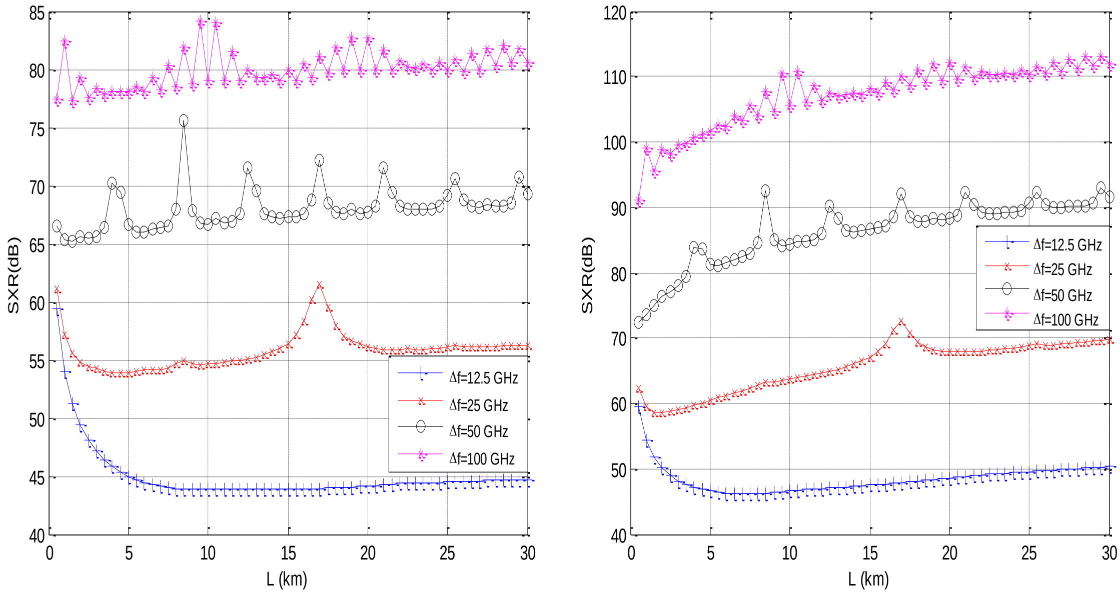
In this subsection, simulation results exhibiting variations of SXR with channel lengths for center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems have been shown in Figs. 7-9, where equal channel input powers of 0.1 mW have been considered. The operating wavelength for the center downlink channel has been taken as 1490 nm. To supply limits in GPON standards, the maximum length of the fiber connecting the OLT and the splitter has been taken as 30 km for 7- and 15-channel DWDM-GPON systems and as 20 km for 31-channel DWDM-GPON systems. Simulations have been performed for equally-spaced DWDM-GPON systems. Evaluating simulation results given in Figs. 7-9, comparative results for SXR values in center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems are displayed in Table 9 under the single impact of FWM and the combined impact of SRS and FWM for different channel lengths and channel spacing values.

The most remarkable point about simulation results given in Figs. 7-9 is the oscillatory behavior of the SXR variation with varying channel lengths which starts slightly in DWDM-GPON systems having 25 GHz channel spacing values and becomes stronger as channel spacing values reach 50 GHz and 100 GHz. Especially at 100 GHz a strong oscillation is obvious for all 7-, 15-, 31-channel DWDM-GPON systems under single impact of FWM and combined impact of SRS and FWM in very short channel length variations of 0.5 km. This is due to the phase mismatching phenomenon which becomes stronger at high channel spacing values like 50 GHz and 100 GHz, and it is very important in system implementation since SXR performance can be significantly degraded with very short channel length variations. For example, a 0.5 km increment in channel lengths can cause a maximum SXR degradation of 8.86 dB and 8.66 dB at 50 GHz and 100 GHz channel spacings, respectively, for 7-channel DWDM-GPON systems under single impact of FWM while 8.69 dB and 10.24 dB at 50 GHz and 100 GHz channel spacings, respectively, for 7-channel DWDM-GPON systems under combined impact of SRS and FWM; 7.75 dB and 5.43 dB at 50 GHz and 100 GHz channel spacings, respectively, for 15-channel DWDM-GPON systems under single impact of FWM while 7.98 dB at both 50 GHz and 100 GHz channel spacings, respectively, for 15-channel DWDM-GPON systems under combined impact of SRS and FWM; 5.54 dB and 4.41 dB at



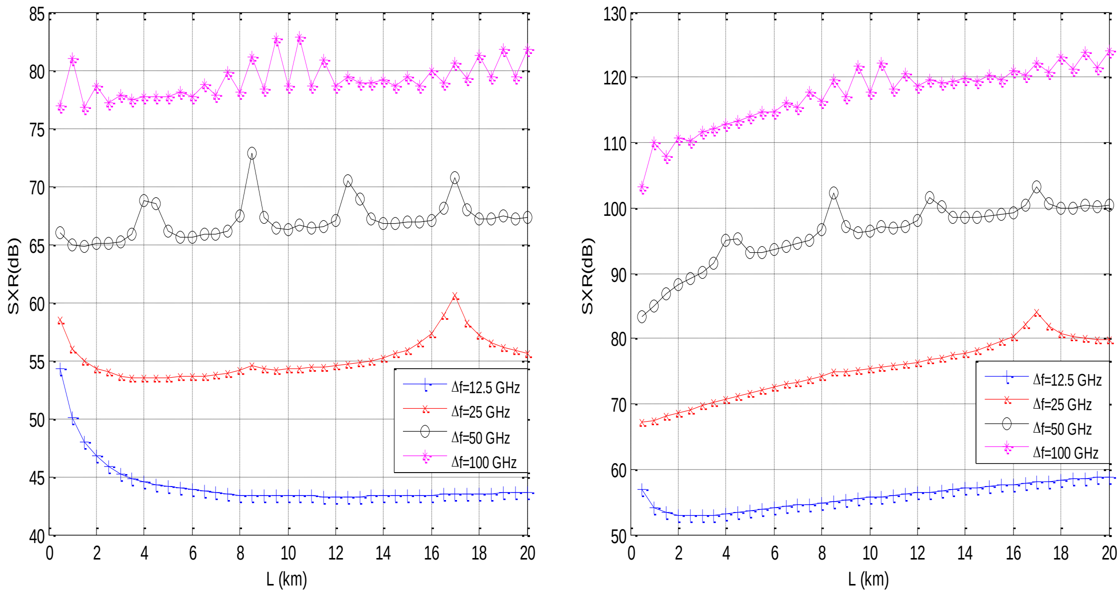
(a) (b)

Figure 7:
SXR-channel length variations in center downlink channels of 7-channel DWDM-GPON systems for the channel length range of 1-30 km and channel spacing values of 12.5 GHz, 25 GHz, 50 GHz and 100 GHz due to the
(a) single impact of FWM (b) combined impact of SRS and FWM



(a) (b)

Figure 8:
SXR-channel length variations in center downlink channels of 15-channel DWDM-GPON systems for the channel length range of 1-30 km and channel spacing values of 12.5 GHz, 25 GHz, 50 GHz and 100 GHz due to the
(a) single impact of FWM (b) combined impact of SRS and FWM



(a) (b)

Figure 9:
SXR-channel length variations in center downlink channels of 31-channel DWDM-GPON systems for the channel length range of 1-20 km and channel spacing values of 12.5 GHz, 25 GHz, 50 GHz and 100 GHz due to the
(a) single impact of FWM (b) combined impact of SRS and FWM

Table 9. Comparative results for SXR values in center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems for different channel lengths and channel spacing values

Lengths (km)	DWDM-GPON Systems	Δf (GHz)	12.5	25	50	100
1	7-channel	SXR values in the center downlink channel due to the single impact of FWM (dB)	61.04	61.77	66.28	87.00
	15-channel		54.00	57.22	65.32	82.46
	31-channel		50.04	55.92	64.90	80.92
5	7-channel		49.01	54.85	67.94	78.83
	15-channel		44.99	53.91	66.60	78.04
	31-channel		44.12	53.48	66.07	77.69
10	7-channel		45.86	55.83	67.75	80.20
	15-channel		43.86	54.63	66.66	79.04
	31-channel		43.32	54.21	66.25	78.58
20	7-channel		45.36	57.54	68.71	84.94
	15-channel		44.15	56.16	67.70	82.65
	31-channel		43.64	55.61	67.28	81.81
30	7-channel		46.29	57.52	71.26	81.77
	15-channel		44.73	56.32	69.31	80.56
1	7-channel	SXR values in the center downlink channel due to the combined impact of SRS and FWM (dB)	61.06	61.91	67.25	91.77
	15-channel		54.37	59.52	73.52	99.08
	31-channel		54.20	67.35	85.08	110.10
5	7-channel		49.10	55.48	71.46	89.25
	15-channel		46.57	60.45	81.24	101.60
	31-channel		53.69	71.64	93.21	113.90
10	7-channel		46.04	57.01	73.20	93.44
	15-channel		46.60	63.67	84.23	105.60
	31-channel		55.65	75.35	96.39	117.80
20	7-channel		45.70	59.65	76.50	101.10
	15-channel		48.55	67.93	88.24	112.20
	31-channel		58.86	79.74	100.40	124.00
30	7-channel		46.78	60.39	80.56	99.64
	15-channel		50.33	69.75	91.60	111.90

50 GHz and 100 GHz channel spacings, respectively, for 31-channel DWDM-GPON systems under single impact of FWM while 5.72 dB and 7.00 dB at 50 GHz and 100 GHz channel spacings, respectively, for 31-channel DWDM-GPON systems under combined impact of SRS and FWM. It is clear that, generally, the combined impact of SRS and FWM enhances the maximum oscillation amplitude of the SXR variation in both 50 GHz and 100 GHz channel spacing values with respect to the case under the single impact of FWM.

4.4. Amplification factor of the Stokes wave-channel input power variations

In this subsection, simulation results displaying variation of amplification factor of the Stokes wave, i.e. G_R, with channel input powers for center downlink channels of 7-, 15- and 31-channel DWDM-GPON systems have been shown in Figs. 10-12.

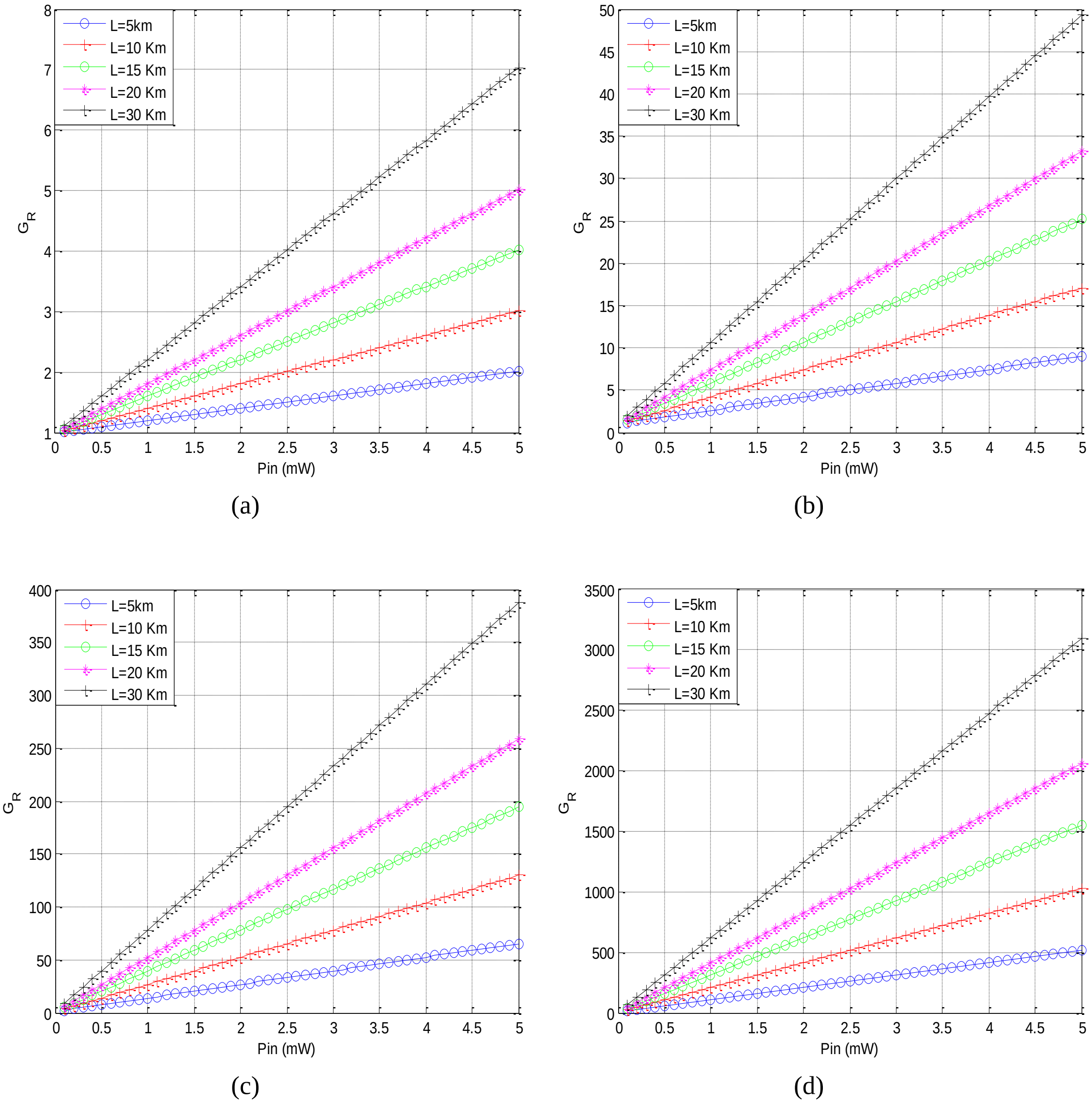


Figure 10:

G_R-channel input power variations in center downlink channels of 7-channel DWDM-GPON systems at different channel lengths for channel spacing values of
(a)12.5 GHz (b) 25 GHz (c) 50 GHz (d) 100 GHz

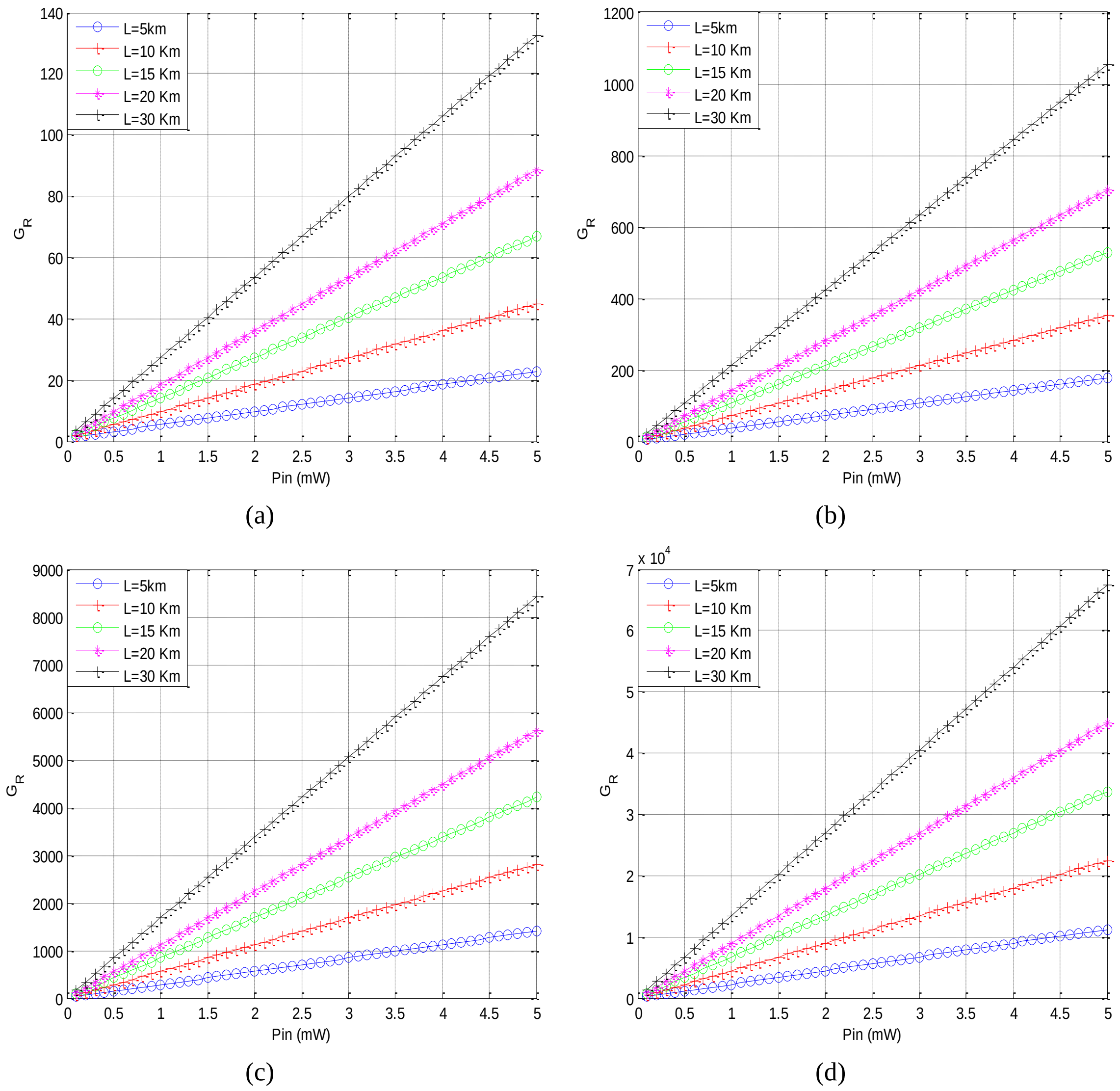


Figure 11:
G_R-channel input power variations in center downlink channels of 15-channel DWDM-GPON systems at different channel lengths for channel spacing values of (a)12.5 GHz (b) 25 GHz (c) 50 GHz (d) 100 GHz

Simulations have been performed for equal channel input powers in the range of 0.1-5 mW at channel lengths of 5 km, 10 km, 15 km, 20 km and 30 km for 7- and 15-channel DWDM-GPON systems and at channel lengths of 5 km, 10 km, 15 km and 20 km for 31-channel DWDM-GPON systems. It has been observed in Figs. 10-12 that the amplification factor of the Stokes wave, i.e. the Raman gain G_R, shows an approximately linear variation with the channel input power variation in the range of 0.1-5 mW. Furthermore, G_R increases with increasing fiber lengths, channel spacing values and channel numbers.

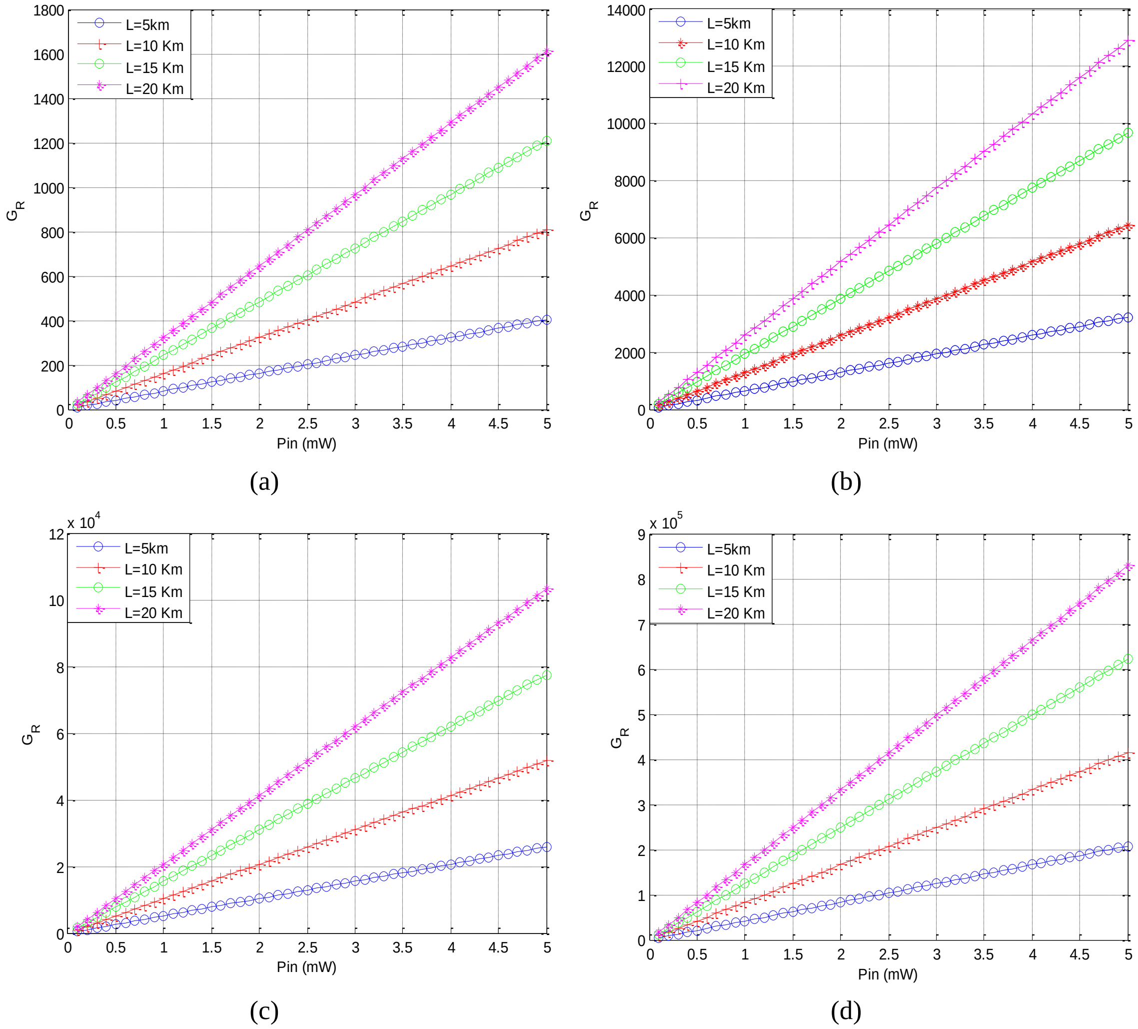


Figure 12:

G_R-channel input power variations in center downlink channels of 31-channel DWDM-GPON systems at different channel lengths for channel spacing values of (a)12.5 GHz (b) 25 GHz (c) 50 GHz (d) 100 GHz

5. CONCLUSION

Comparative analysis of the single impact of FWM and combined impact of SRS and FWM on the performance of center downlink channels of 7-, 15-, 31-channel DWDM-GPON systems have been carried out. The system performance has been evaluated by focusing on SXR variations with varying channel input powers, channel spacing values and channel link lengths under the single impact of FWM and the combined impact of SRS and FWM. Furthermore, variation of the amplification factor of the Stokes wave, i.e. the Raman gain G_R, with varying channel input powers has been also investigated.

The most remarkable point emphasized by comparative simulation results about SXR-channel input power variations is that SRS compensates negative impacts of FWM in center downlink channels of DWDM-GPON systems and significance of compensation enhances with increasing channel numbers and channel spacing values.

Simulation results obtained for SXR-channel spacing value variations show that at fixed channel input powers, channel spacing values have more considerable effects on SXR than channel numbers.

Simulation results of SXR-channel length variations state that a strong oscillatory behavior occurs on the SXR variation in very short channel length variations of 0.5 km especially at high channel spacing values of 50 GHz and 100 GHz. The combined impact of SRS and FWM enhances the maximum oscillation amplitude of the SXR variation with respect to the case under the single impact of FWM.

Simulation results display an approximately linear variation between the Raman gain and channel input powers in the range of 0.1-5 mW. Furthermore, the Raman gain increases with increasing fiber lengths, channel spacing values and channel numbers.

Results of this research exhibit that the combined impact of SRS and FWM on DWDM-GPON systems differs significantly from the single impact of FWM and give important hints for current DWDM-GPON implementations.

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