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8 x 10 Gbps Green WDM-PON system and its Performance Analysis

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Abstract
In the 21st century, the emergence of advanced internet multimedia applications has significantly increased bandwidth demands at the access network level. Wavelength Division Multiplexed Passive Optical Networks (WDM-PONs) have emerged as a promising solution to meet these demands. Unlike traditional PON systems that utilize unidirectional traffic per fiber, implementing bidirectional fibers at the access level can reduce network costs and promote environmentally friendly ("green") systems. However, the efficiency of bidirectional fibers is challenged by nonlinear effects, such as Four-Wave Mixing (FWM), especially under fixed bandwidth constraints. This paper presents a comprehensive performance analysis of an 8 × 10 Gbps bidirectional green WDM-PON system, considering both linear and nonlinear effects. The study reveals that for a fixed transmission distance of 30 km, the input channel power should not exceed 18 dBm, as higher power levels lead to significant performance degradation due to FWM. Additionally, for a fixed channel power of 0 dBm, the maximum achievable transmission distances are 50 km for the uplink and 43 km for the downlink, ensuring acceptable system performance. These findings provide valuable insights for optimizing bidirectional WDM-PON systems to balance performance, cost, and environmental considerations.

Keywords: Bidirectional WDM-PON, four-wave mixing (FWM), green optical networks, transmission distance, channel power

1. Introduction

Optical communication systems offer unparalleled bandwidth, making them the ideal backbone for hybrid networks. At the access level, passive optical networks (PONs) are particularly well-suited for meeting high-bandwidth demands. Among the leading standards—Ethernet PON (EPON), Gigabit PON (GPON), and Wavelength Division-Multiplexed PON (WDM-PON)—each delivers optical connectivity directly to end users [1-2]. Compared to wired metallic and wireless systems, all-fiber PONs easily satisfies modern end-user bandwidth requirements.

Within fiber-optic access technologies, EPON and GPON allocate bandwidth via time-division multiplexing (TDM), which limits each user's throughput [3]. In contrast, WDM-PON assigns individual wavelengths (channels) per user, allowing dedicated high-bandwidth access regardless of the total number of users. Recent studies analyzing cost and energy consumption among EPON, GPON, and WDM-PON [4-7] indicate that EPON struggles to scale bandwidth-wise and also consumes the most energy [5-7], while GPON and WDM-PON are more energy-efficient. However, only WDM-PON can support next-generation, high-quality multimedia services, making it the preferred access-level technology moving forward.

Scaling WDM-PON to more users necessitates packing more closely spaced channels within a fixed spectrum. This high channel density, however, amplifies nonlinear effects like Stimulated Raman Scattering (SRS) and Four-Wave Mixing (FWM), which degrade system performance in Dense Wavelength Division Multiplexing (DWDM) environments [8]. To assess these effects, this paper analyzes an 8-channel, 10 Gbps per channel, bidirectional WDM-PON—including both linear and nonlinear impairments. Prior two-channel studies [7] failed to reveal in-band FWM degradation, as generated mixing products fell outside the signal bands. By contrast, our eight-channel configuration guarantees that FWM-induced distortion overlaps with a central channel, without excessively increasing SRS. In non-zero-dispersion fiber, FWM efficiency drops quickly once channel separation exceeds several tens of GHz [9], making our eight-channel design a suitable testbed for evaluating FWM impacts in bidirectional WDM-PON systems.

The previous demonstrations [10-13] like British telecom, Photonic Integrated Extended Metro and Access Network (PIEMAN) sponsored by the Information Society Technologies (IST) and ACTS-PLANET (Advanced Communication Technologies and Services - Photonic Local Access Network) used unidirectional traffic over the single fiber. The use of bidirectional fibers for such systems can significantly drop the installation cost of the system and efforts.

The organization of the paper is as follows. The theory of one of crucial nonlinearity for multichannel system i.e. FWM is given in section II. The design of the 8 × 10 Gbps WDM-PON system using bidirectional fiber is given in section III. The performance analysis of the 8 × 10 Gbps WDM-PON system is given in section IV. The performance of the system is analyzed in terms of the bidirectional fiber limited link length and limit on maximum input power of individual channel for the transmission. The impact of FWM is vivid in power analysis. The conclusion and future scope is discussed in section V.

Theory of Four Wave Mixing

The four wave mixing is the major problem for a dense wavelength division multiplexed system. It severely impacts the performance of the individual channels in consequence of the fact that the FWM fall exactly inband to the original channels. Hence it is the major reason of the crosstalk noise. It is defined as when two or more channel at different wavelengths interact with the fiber medium, the susceptibility [10-11] give rise to generation of additional new frequencies along with original frequency channels. The new frequencies fall as per equation $f_{ijk} = f_i + f_j - f_k \quad \forall\, i, j \text{ and } k \in (1 \text{ to } N)$. The N is the number of the channels. The power of each of the newly formed FWM component can be calculate easily by the linear equation [8-9] given as follows:

$$P_{ijk} = \frac{\eta_{ijk}}{9} D_{ijk}^2 \left(\frac{2\pi n_2}{\lambda_c A_{eff}}\right)^2 P_i P_j P_k \, e^{-\alpha l} {L_{eff}}^2 \qquad (1)$$

The $P_i P_j$ and P_k are the individual channel powers. For the analysis in this paper all the channels have the equal power. D is the degeneracy factor that have value either 3 for (i=j ≠k) and 6 for (i ≠ j ≠k). η_{ijk} is the efficiency of the individual FWM component. $\alpha, \lambda_c, A_{eff}$ and n_2 are the attenuation coefficient, central wavelength, effective area and nonlinear index of the fiber. The $L_{eff} = \frac{1-e^{-\alpha L}}{\alpha}$ is the effective length of the fiber. The generation of this FWM is mostly decided by the extent of the mixing efficiency that is further depends on the extent of the phase mismatch condition. The mixing efficiency (η_{ijk}) and phase mismatch $(\Delta\beta_{ijk})$ are generalized as follows.

$$\eta_{ijk} = \frac{\alpha^2}{(\alpha^2 + \Delta\beta_{ijk}{}^2)} \times \frac{1+4e^{-\alpha L}\sin^2(\Delta\beta_{ijk}.L/2))}{(1-e^{-\alpha L})^2} \qquad (2)$$

$$\Delta\beta_{ijk} = \left(\frac{2\pi\lambda_0^2}{c}\right)(f_i - f_k)(f_j - f_k) \times \left[D_C + \left(\frac{\lambda_0^2}{2c}\right)\left(\frac{dD_C}{d\lambda}\right)[(f_i - f_o) + (f_j - f_o)]\right] \qquad (3)$$

Where, the λ_0 is a zero-dispersion wavelength, c is the speed of electromagnetic wave in vacuum. $\frac{dD_C}{d\lambda}$ is the chromatic dispersion slop of the fiber.

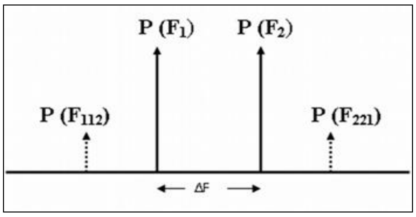


Fig 1: Two channel model of FWM [9]

The additional four wave mixing components are clearly visible in the two channel model given in fig. 1.

The architecture of an 8-channel WDM-PON system—each channel operating at 10 Gbps—employs a bidirectional non-zero-dispersion-shifted fiber, as outlined in this section. With optical circulators, uplink and downlink traffic traverse the same fiber strand, enabling communication for 16 end users. The system setup (illustrated in Fig. 2) was modeled via a commercial optical communications simulator, and key simulation parameters are summarized in Table I. Importantly, the simulation incorporates all relevant nonlinearities and receiver noise sources, with system parameters specifically tuned to highlight the impact of Four-Wave Mixing performance degradation. Bidirectional transmission is achieved by isolating directional flows with circulators, a standard technique in single-fiber designsdesign and Methodology of WDM-PON system

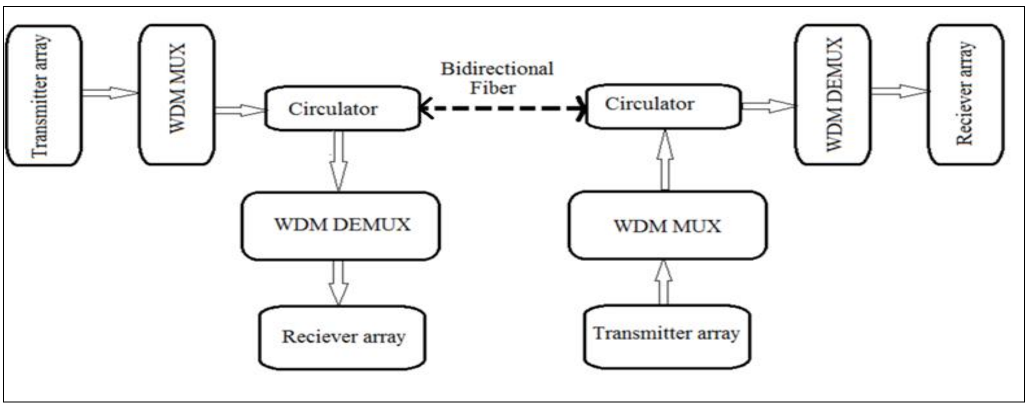


Fig 2: Architecture of bidirectional WDM-PON based on circulator.

Table 1: Parameters used for simulation

S.no.	Parameters	Values	Units
1	Reference wavelength	1550	nm
2	Length varried	15 - 51	Km
3	Attenuation	0.2	dB/km
4	Dispersion	16.75	ps/nm-Km
5	Dispersion slope	0.075	ps/nm^{2}-Km
6	Effective area	80	um^2
7	n2	2.60E-20	m^2/W
8	Power per channel	-8 to 20	dBm
9	Bit rate per channel	10	Gbps
10	Bandwidth filter	10	GHz
11	Filter type	Bessel	-
12	Filter order	2	-
13	β2(second order dispersion)	-20	ps^2/km

The fig. 2 shows the communication between two transponders with their own receivers and transmitters. For the sake of effective analysis of FWM, only two transponder have been considered. The choice of the bidirectional fiber has really reduced the resource requirements therefore it has evolved the green design of the communication problem.

Table 2: Frequencies designated for uplink and downlink channels

S.No.	Uplink channels (nm)	Downlink Channels (nm)
1	1552.4	1313.4
2	1553.2	1314.2
3	1554	1315
4	1554.8	1315.8
5	1555.6	1316.6
6	1556.4	1317.4
7	1557.2	1318.2
8	1558	1319

The uplink and downlink problem is realized using two circulators that isolate the uplink and downlink streams. For the provision of simultaneous data transportation between the 16 users, two different set of frequency bands have been assigned. The channel frequencies for the uplink (from transponder 1 to 2) operation and downlink operation (from transponder 2 to 1) are given in table II.

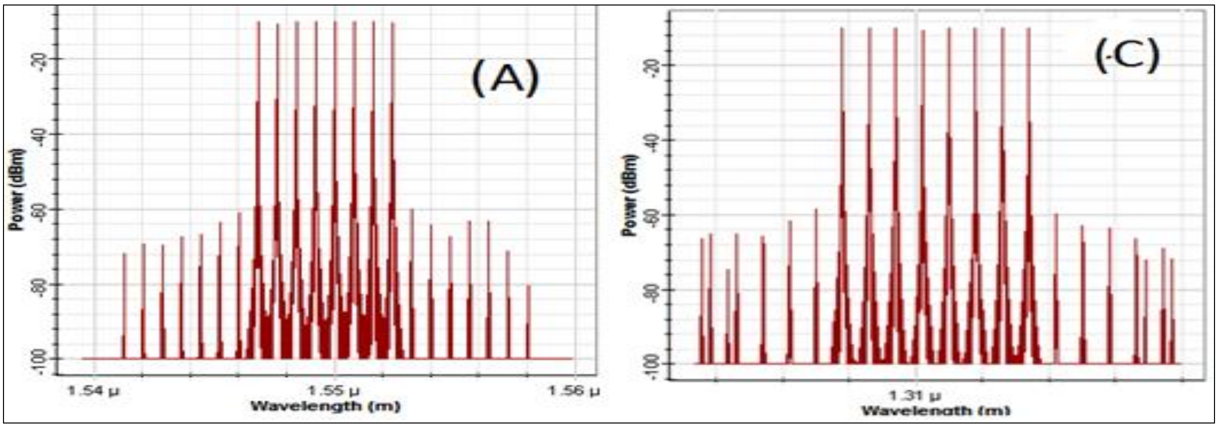
Performance Analysis of WDM-PON System

This section presents the performance analysis of the green 8 × 10 Gbps bidirectional WDM-PON system, focusing on two key metrics: the maximum allowable input channel power and the maximum link length. We define the link-limited length as the fiber length at which the bit error rate (BER) of the central channel just reaches the acceptable threshold of 10^{-9}. This analysis was performed keeping the individual channel powers fixed at 0 dBm. The subsections below explore each of these parameters in detail. Impact of Four Wave Mixing

The detrimental impact of Four-Wave Mixing (FWM) on channel performance was evaluated by sweeping the input channel power from -8 dBm to +20 dBm. Figures 3-5 clearly reveal the trade-off between increasing signal strength and rising FWM-induced noise. FWM is a power-dependent nonlinear effect that scales approximately with the cube of input power, making it exponentially more pronounced at higher launch levels

At moderate power levels near 0 dBm, the desired channels exceed FWM-generated noise by over 50 dB, ensuring strong signal quality. However, at elevated input powers of 20 dBm, this margin shrinks considerably, indicating that FWM noise can encroach significantly on channel performance.

These observations underscore the critical balance between boosting launch power to improve signal reach and limiting it to prevent FWM-induced interference.



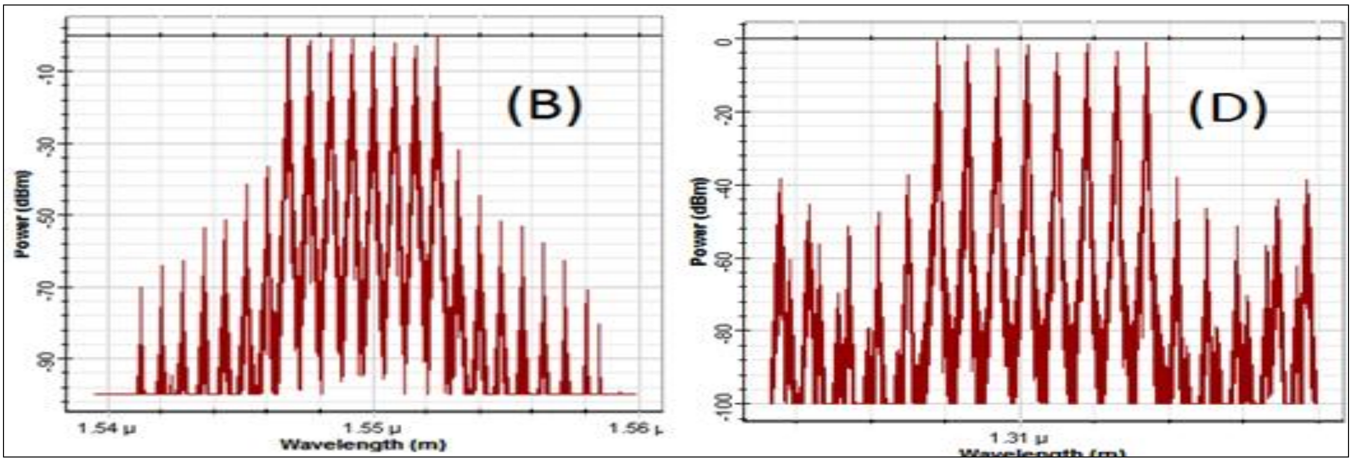


Fig 3: Spectrum of uplink and downlink with different input powers A) uplink at input channel power of 0 dBm B) uplink at input channel power of 10 dBm. C) Downlink at input channel power of 0 dBm. D) Downlink at input channel power of 10 dBm.

The deference is reduced to a value of 32 dB. The BER is related to Q factor as follows: BER=0.25*erfc (Q/sqrt(2)) [4]. For a BER of 10^{-09} the corresponding quality factor is around 5.9. The signal to noise ratio is a complex problem. With increase in input signal power the FWM crosstalk also increases. So, the tradeoff between the signal power and generation of four wave mixing is clearly showing its presence as shown in fig. 4 and 5. The signal remains stronger in comparison to FWM generation within -4 dBm to 19 dBm power as shown in fig. 5. The signal thereafter 19 dBm increases the extent of four wave mixing such that the signal to noise ratio drops corresponding BER value below the acceptable value. In between -4 dBm to 10 dBm value the performance get enhanced as shown in fig. 4. For the parameters given in table I and II, the system best performs for the input channel power varying between 4 to 12 dBm. The analysis have been performed for a fixed length problem (L=30 km).

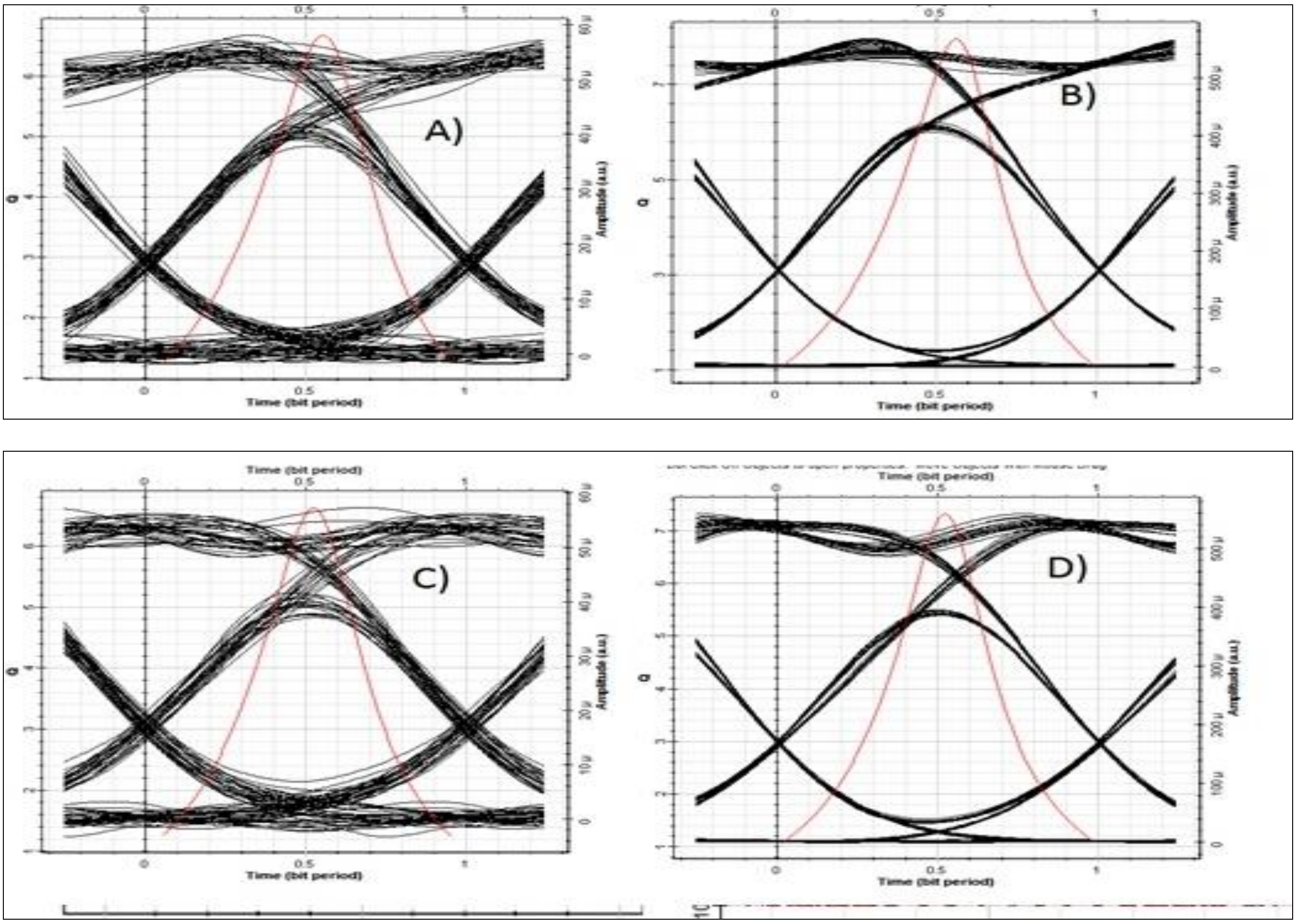


Fig 4: Eye diagram of uplink and downlink with different input powers A) uplink at input channel power of 0 dBm B) uplink at input channel power of 10 dBm. C) Downlink at input channel power of 0 dBm. D) Downlink at input channel power of 10 dBm.

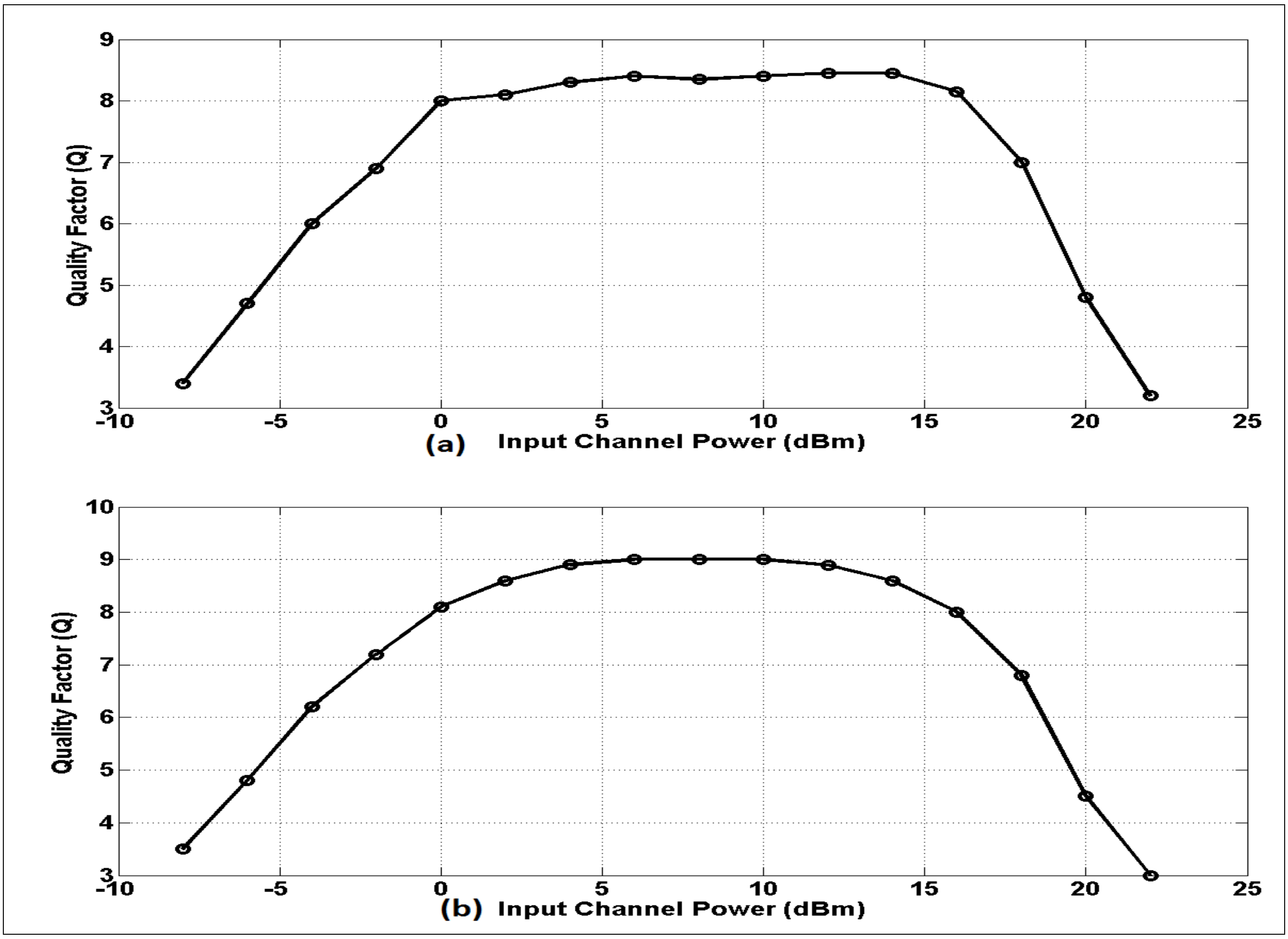


Fig 5: Input channel power analysis depicting effect of FWM on Downlink and Uplink traffic. The performance of the 4th channel is monitored as it is acting central channel among all the 8 channels.

Impact of System Length: Under this subsection the performance limited link length is evaluated. A simple methodology is adopted for it. The system length is increased in steps of 1 km until the performance of the central 4th channel drops below the acceptable value of BER (10^{-9}). This analysis has been presented for the fixed input channel power of 0 dBm for both of the uplink and downlink traffic streams as shown in fig. 6.

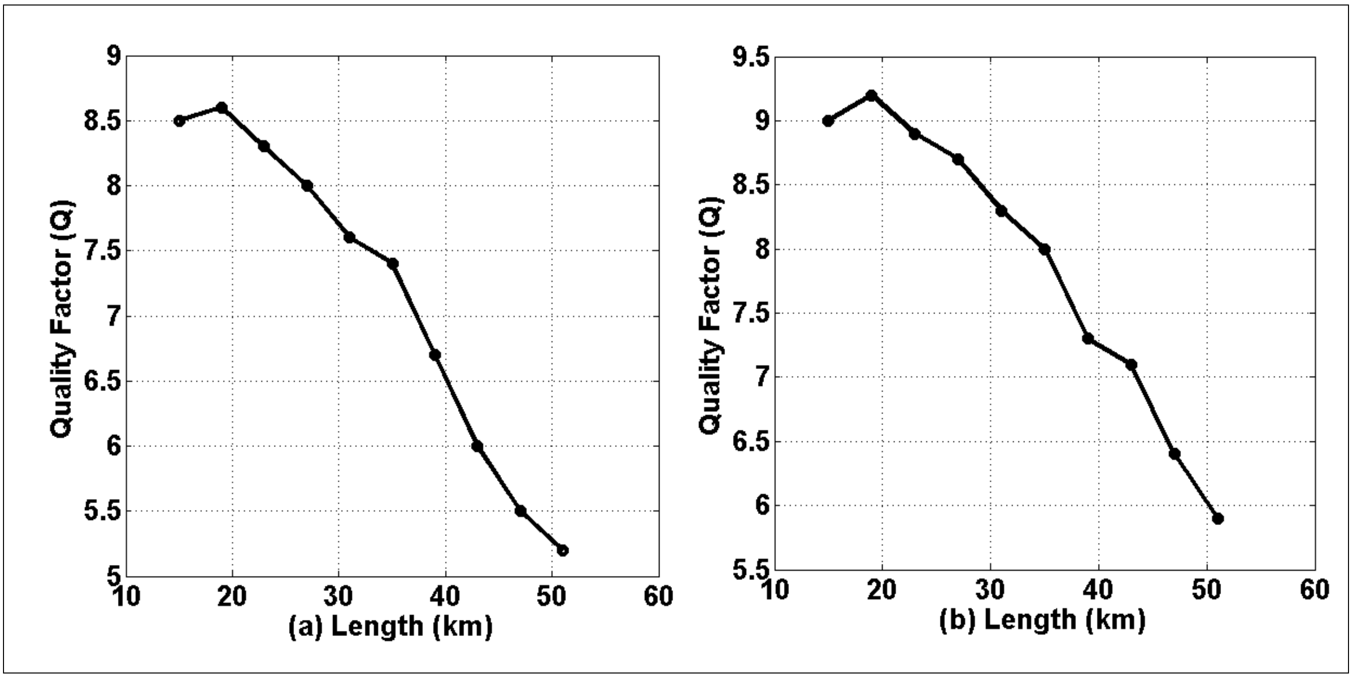


Fig 6: Q-factor and BER vs. Length (Km) at fixed power A) for downlink and B) for uplink

It has been noticed that performance limiting link length for the upstream and downstream traffic are 50 km and 43 km respectively for the same set of the parameters given in table I and II.

Conclusion

At the access layer of optical networks (AONs), technologies such as Ethernet Passive Optical Network (EPON), Gigabit Passive Optical Network (GPON), and Wavelength Division Multiplexed Passive Optical Network (WDM-PON) deliver high-speed data services to end users. Among these, WDM-PON stands out as a promising solution for future bandwidth demands due to its superior scalability and improved energy efficiency compared to EPON and GPON. However, WDM-PON systems face limitations when it comes to supporting a large number of users, primarily due to the fixed spectral bandwidth and the resulting constraint on the number of available wavelength channels. As user count increases, the system becomes more susceptible to nonlinear impairments, particularly Four-Wave Mixing (FWM), which significantly degrades individual channel performance. The performance evaluation of an 8 × 10 Gbps green WDM-PON system highlights the dominant impact of FWM, imposing strict limitations on both the maximum allowable launch power and the link length for reliable transmission. Simulation results indicate that for a fixed transmission distance of 30 km, optimal performance is maintained when the input channel power remains within the range of -4 dBm to +18 dBm. Furthermore, under a fixed input power of 0 dBm, the maximum transmission distances achievable for uplink and downlink are 50 km and 43 km, respectively.

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