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Performance Analysis of Nonlinearities in WDM Systems

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Abstract

Wavelength division multiplexing (WDM) is a technology that enables the transmission of several optical signals simultaneously at different carrier wavelengths on a single fiber and the separation of the signals by wavelength at the receiving node. While WDM is very attractive, it has some disadvantages also. One such disadvantage is the appearance of fiber nonlinearities. With the use of multiple channels, several miliwatts are injected into the fiber. Such high powers lead to the appearance of different nonlinear effects in the fiber, mainly the Stimulated Raman scattering (SRS), Stimulated Brillouin scattering (SBS), Four wave mixing (FWM), and the Cross Phase Modulation (CPM). These nonlinear effects lead to the degradation of system performance.

In this work the performance analysis of nonlinearities in the WDM systems was implemented using Mat lab-(7).

تحليل الأداءِ الغير الخطي في منظومات المزج بالتقسيم الموجي (WDM)

الخلاصة

أن المزج بالتقسيم الموجي هي تقنية تمكن أرسال عدة أشارات ضوئية في ان واحد على حاملات باطوال موجية مختلفة على ليف ضوئي واحد . ويتم فصل الاشارات بواسطة الأطوال الموجية عند نقطة الأستلام وبالرغم من أن هذه التقنية فعالة ألاأن لديها مساوئ كذلك . واحدة من هذه المساوئ هو ظهور الحالات الغير الخطية لليف الضوئي .وبأستخدام عدة قنوات فأنه يحتاج الى قدرة ببعض الميلي واط لتغذية الليف , وأن هذه القدرة تؤدي الى ظهور عدة تاثيرات غير خطية في الليف مثل CPM . و SRS, SBS, FWM,

هذه التاثيرات غير الخطية تؤدي الى هبوط اداء المنظومة. في هذا العمل تحليل الآداء غير الخطي في منظومات المزج بالتقسيم الموجي قد نفذت باستخدام Mat lab- (7).

Introduction:

Wavelength Division Multiplexing (WDM) is a fiber-optic transmission technique that involves the process of multiplexing many different wavelength signals onto a single fiber simultaneously in the 1300-to-1600-nm spectral band. So each fiber has a set of parallel optical channels each using different light wavelengths [1]. Fig (1) shows a simple WDM link [2].

The minimum frequency separation between two different signals multiplexed is known as the Channel spacing. Since the wavelength of operation is inversely proportional to the frequency, a corresponding

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difference is introduced in the wavelength of each signal. The factors controlling channel spacing are the optical amplifier's bandwidth and the capability of the receiver in identifying two close wavelengths sets the lower bound on the channel spacing. Both factors ultimately restrict the number of unique wavelengths passing through the amplifier [1].

IN order to achieve higher data rates in long-haul optical fiber systems, higher signal-to-noise ratios (SNRs) are required at the receiver. However, as the signal intensity increases, the nonlinearities in the fiber affect the signal propagation. [3]

There are two categories of nonlinear effects Kerr effects and scattering effects. In an optical fiber the core in which the optical signals travel has a specific refractive index that determines how light travels through it. However, depending upon the intensity of light traveling in the core, this refractive index can change. This intensity dependence of refractive index is called the Kerr effect. It can cause Self-phase modulation (SPM) of a signal, whereby a wavelength can spread out onto adjacent wavelengths by itself. It can also cause cross-phase modulation (CPM) whereby several different wavelengths in a WDM system can cause each other to spread out. Finally, it can result in Four-wave mixing (FWM) in which two or more signal wavelengths can interact to create a new wavelength.

There are two nonlinear scattering effects. "Stimulated Raman Scattering" involves light losing energy to molecules in the fiber and being re-emitted at a longer wavelength (due to the loss of energy). In "Stimulated Brillouin Scattering" light in the fiber can create acoustic waves, which then scatter light to different wavelength [2].

Kerr Effect

The refractive index of silica fiber for communication is weakly dependent on optical intensity. Although the refractive index is a very weak function of signal power, the higher power from optical amplifiers and long transmission distances make it no longer negligible in modern optical communication systems. In fact, phase modulation due to intensity dependent refractive index induces various nonlinear effects, namely, Self-Phase Modulation (SPM), Cross-Phase Modulation (CPM), and Four-Wave Mixing (FWM) [4].

Four-Wave Mixing (FWM):

The Four-wave mixing is a nonlinear effect in which three optical waves at angular frequencies f_i , f_j and f_k mix to generate a new wave at angular frequency f_{ijk}. FWM induces signals at new frequencies that appear as crosstalk to the existing signals. The FWM effect is independent of the bit rate but is highly dependent on frequency channel spacing and is reduced when dispersion is present. Four-wave mixing (FWM), also known as four-photon mixing, is a parametric interaction among optical waves, which is analogous to intermodulation distortion in electrical systems. In a multi-channel system, the beating between two or more channels causes generation of one or more new frequencies at the expense of power depletion of the original channels. When three waves at frequencies f_i, f_j, and f_k are put into a fiber, new frequency components are generated at $f_{ijk} = f_i + f_j - f_k$ (where $i, j \neq k$) [5]. Figure (2) shows summary of all FWM terms falling on each frequency in an equally spaced three-channel system and power considerations.

The number and the optical power of the new generated signal are given by the relation [6]:

$$M = \frac{N^2}{2}(N-1) \qquad \text{… (1)}$$

Where N is number of channels and M is the number of newly generated sidebands for example: N= 3 then M= 9.

Self-Phase Modulation (SPM) and Cross-Phase Modulation (CPM):

SPM and CPM arise when fluctuations in the optical power of a signal cause changes in signal phase. Thus, different parts of a pulse undergo different phase shifts, which cause pulse chirping. This causes spectral broadening, which in turn increases dispersion penalties. The impairments due to SPM are significant mainly in high bit rate (over 10 Gb/s) systems. CPM becomes a problem if the wavelength channel spacing is tight (a few tens of GHz) [6].

Self-Phase Modulation (SPM):

The dependence of the refractive index on optical intensity causes a nonlinear phase shift while propagating through an optical fiber. The nonlinear phase shift is given by :

$$\Phi_{Nl} = \frac{2p}{l} n_2 I(t) z \qquad \text{…(2)}$$

Where l is the wavelength of the light wave, and z is the propagation distance.

Since the nonlinear phase shift is dependent on its own "pulse shape", it is called self-phase modulation (SPM). When the optical signal is time varying, such as an intensity modulated signal, the time-varying nonlinear phase shift results in a broadened spectrum of the optical signal [7].

Cross-Phase Modulation (CPM):

Another nonlinear phase shift originating from the Kerr effect is Cross-Phase Modulation (CPM), while SPM is the effect of a pulse on its own phase, CPM is a nonlinear phase effect due to optical pulses in other channels. Therefore, CPM occurs only in multi-channel systems. In a multi-channel system, the nonlinear phase shift of the signal at the center wavelength l_i is described by [8]:

$$\Phi_{Nl} = \frac{2p}{l} n_2 z \left[I_i(t) + 2\sum_{i \neq j} I_j(t) \right] \qquad \text{…(3)}$$

The first term is responsible for SPM, and the second term is for CPM. Equation (3) might lead to a speculation that the effect of CPM could be at least twice as significant as that of SPM. However, CPM is effective only when pulses in the other channels are synchronized with the signal of interest [8].

Nonlinear Scattering:

Stimulated raman scattering:

Stimulated raman scattering is an interaction between light waves and the vibration modes of silica molecules. If a photon with energy hv1 is incident on a molecule having a vibrational frequency υm ,the molecule can absorb some energy from the photon . In this interaction, the photon is scattered, thereby attaining a lower frequency υ2 and a corresponding lower energy hυ2. the modified photon is called

a stokes photon. Because the optical signal wave that is injected into a fiber is the source of the interacting photons, it is often called the pump wave, since it supplies power for the generated wave.

This process generates scattered light at a wavelength longer than that of the incident light. If another signal is present at this longer wavelength, the SRS light will amplify it and the pump-wavelength signal will decrease in power; Fig. (3) Illustrates this effect. Consequently, SRS can severely limit the performance of a multi-channel optical communication system by transferring energy from short wavelength channels to neighboring higher-wavelength channels. this is abroad-band effect that can occur in both directions [9].

Equation (4) displays the calculated Raman gain coefficient as function of the Raman frequency shift to the pump wavelength, for the experimentally available wavelength range.

$$G_r\,(l\,) = 4.35\left[\frac{1}{2}g_r(\,l\,)P_{pumps}\,(0)\frac{L_{eff}}{A_{eff}}\right] \quad \text{.... (4)}$$

Where PPumps(0) is the pumping power[10].

If Fout(j) is the fraction of power coupled from channel 0 to channel j , then the total fraction of power coupled out of channel 0 to all the other channels is

$$F_{out} = \sum_{j=1}^{N-1} F_{out}(j) = \sum_{j=1}^{N-1} g_{R,peak}\frac{j\Delta u_s}{\Delta u_c}\cdot\frac{PL_{eff}}{2A_{eff}}$$

$$= \frac{g_{R,peak}\Delta u_s PL_{eff}}{2\Delta u_c A_{eff}}\cdot\frac{N(N-1)}{2} \quad \text{.................(5)}$$

The power penalty for this channel then is -10log (1-Fout). To keep the penalty below 0.5dB, it needs to have Fout < 0.1. Using Eq.(2) , and with Aeff = 55μm2 , this gives the criterion

[NP][N-1]Δυs]Leff < 5 × 103 mW . THz . km …..(6)

Here, NP is the total power coupled into the fiber , (N-1)Δυs is the total occupied optical bandwidth ; and Leff is the effective length , which takes into account power absorption along the length of the fiber[10].

Stimulated Brillouin Scattering:

Stimulated Brillouin scattering arises when light-waves scatter from acoustic waves. The resultant scattered wave propagates principally in the backward direction in single-mode fibers. This backscattered light experiences gain from the forward- propagating signals, which leads to depletion of the signal power. The frequency of the scattered light experiences a Doppler shift given by

$$\upsilon B=2nVs/\lambda \quad .....(7)$$

where n is the index of refraction and Vs is the velocity of sound in the material .In silica , this interaction occurs over a very narrow Brillouin line width of $\Delta\upsilon B$ = 20 MHz at 1550 nm. For Vs = 5760 m/s in fused silica , the frequency of the backward-propagating light at 1550 nm is downshifted by 11GHz (0.09 nm) from the original signal . This shows that the SBS effect is confined within a single wavelength channel in a WDW system. Thus, the effect of SBS accumulates individually for each channel, and, consequently, occurs at the same power level in each channel as occurs in a single-channel system. System impairment starts when the amplitude of the scattered wave is comparable to the signal power. For typical fibers, the threshold power for this process is around 10 mW for single-fiber spans. In a long fiber chain containing optical amplitude, there are normally optical isolators to prevent backscattered signal from entering the amplifier. Consequentl, the impairment due to SBS is limited to the degradation occurring in a single amplifier-to-amplifier span. Criterion for determining at what point SBS becomes a problem is to consider the SBS threshold power Pth .

This is defined to be the signal power at which the backscattered light equals the fiber-input power. The calculation of this expression is rather complicated, but an

approximation is given by:

$$P_{th} \approx 2l\frac{A_{eff}b}{g_B L_{eff}}(1+\frac{\Delta v_{source}}{\Delta v_B}) \quad ....(8)$$

Here , Aeff is the effective cross-sectional area of the propagating wave , and the polarization factor b lies between 1 and 2 depending on the relative polarizations of the pump and stokes waves . The effective length Leff is given in Eq. (5) and gB is the Brillouin gain coefficient, which is approximately 4×10-11m/W, independent of the wave- length. Eq. (8) shows that the SBS threshold power increases as the source line width becomes larger [10].

Computer simulation and results:

Raman gain coefficient versus the wavelength channel separation:

In figures (4)-(6) the dashed line represents the Raman gain coefficient g r (10-14m/w) which is given by

$$g_R \approx g_{R.peak}\frac{\Delta v_s}{\Delta v_c} \quad ...(9)$$

This expression is used for computational simplicity for channel separations up to 8THz .This shows that ,owing to SRS ,the power transferred from a lower-wavelength channel to a higher–wavelength channel increases approximately linearly with channel spacing up to a maximum of about $\Delta\upsilon c$=14,16 and 20THz (in the 1550-nm window).

Maximum allowable power per channel versus the number of wavelength for three different channels spacing :

The limits indicated by equation (6) for systems with four and eight wavelength channels. The curves in figure (7) are for the power levels that insure an SRS degradation of less than 1db for all channels. When a fiber attenuation of 0.2 db/Km (or equivalently ,4.61×10-2km-1), a 125-Ghz frequency spacing is equivalent to a 1-nm wavelength spacing at 1550 nm and an amplifier spacing of 75 Km (which yields an effective length of Leff =22km).

Figure (8) represent system with five and ten wavelength channels and figure (9) for system with three and seven wavelength channel.

Conclusions

The effects of nonlinearities on network performance in WDM gives the following:

1-In SRS, the power transferred from a lower- wavelength channel to higher–wavelength channel increases approximately linearly with channel spacing.

2- The maximum allowable power per wavelength versus transmission length for three different channels spacing, when increasing the number of channels then the maximum allowable power per wavelength will be decreased

References

[1] M. Gandluru, "Optical Networking And Dense Wavelength Division Multiplexing (DWDM)," Ohio State University - white paper - www.cis.ohio-state.edu/~jain/cis788-99/dwdm/index.html 2000.

[2] M.Ghanim, “Study and Analysis of Hybrid WDM and CDMA Optical Networks” , M.Sc. thesis, UOT , 2005 .

[3] M. Taghavi , George C. Papen, “On the Multiuser Capacity of WDM in a Nonlinear Optical Fiber: Coherent Communication “, IEEE TRANSACTIONS ON INFORMATION THEORY, Vol.52, No. 11, November 2006.

[4] J. H. Lee, "Analysis and Characterization of Fiber Nonlinearities with Deterministic and Stochastic Signal Sources", Ph.D. Thesis, University of Virginia 2000.

[5] L. Auda, ”Ultra wideband WDM Long Distance WDM Transmission “ , PhD thesis , UOT , 2006 .

[6] M. Nissov and M. Mills " 765 Gb/s over 2,000 km Transmission Using C- and L-Band Erbium Doped Fiber Amplifiers " IEEE Photonics Technology Letters, 1999.

[7] Z. Al-Hashemy,”Crosstalk Reduction Investigation In WDM System”, M.Sc, Thesis, Dep. of Electrical and Electronic Engendering, University of Technology 2004.

[8] M.Shtaif, "Analytical description of cross-phase modulation in dispersive optical fibers," Optics Letters, vol. 23, no. 15, pp. 1191-1193, August 1998.

[9] G. Keiser, "Optical Fiber Communications," McGraw-Hill 3rd ed. 2000.

[10] Paulo Sergio de Brito André, Hypolito José Kalinowski, Luiz Mario ,"Measurement of Raman Gain Coefficient in Standard Single Mode Optical Fibers for DWDM Photonic Simulation Purposes " ,2003.

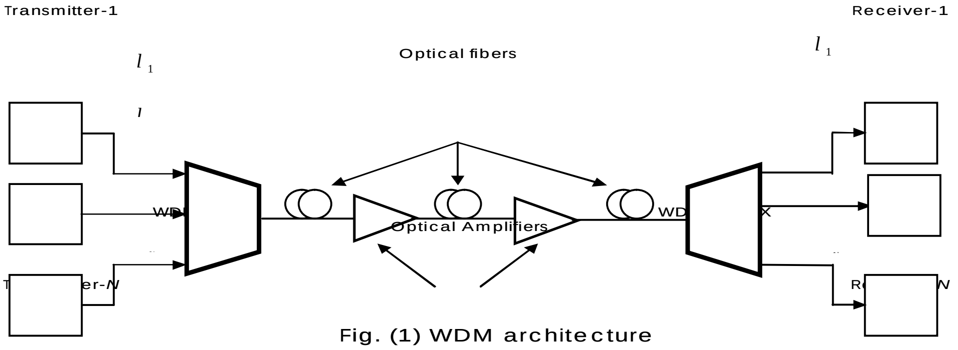


Fig. (1) WDM architecture

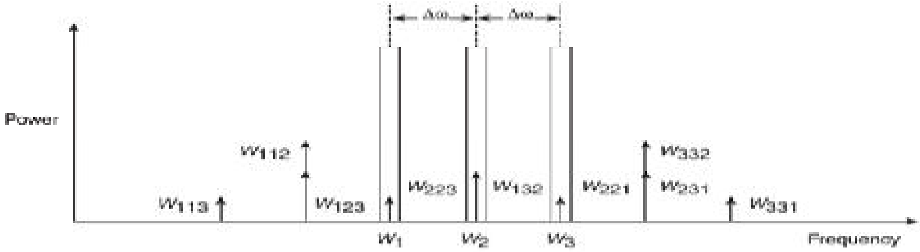
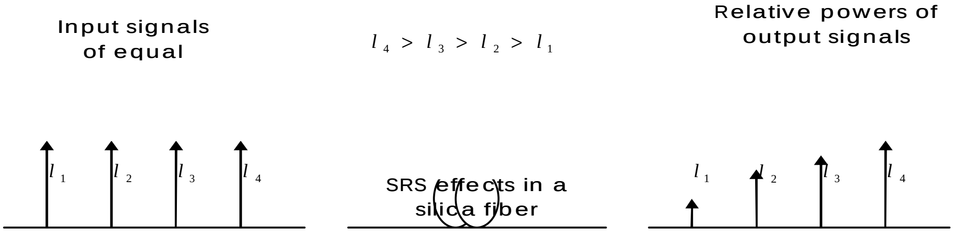
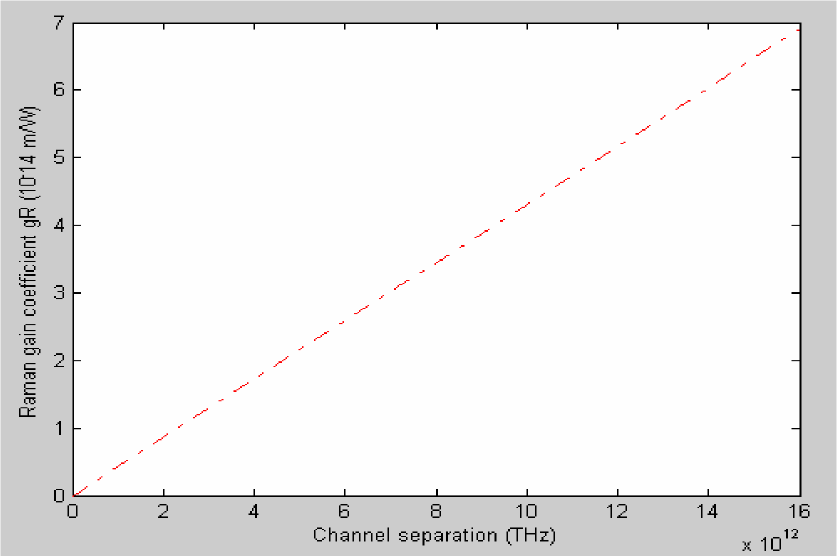


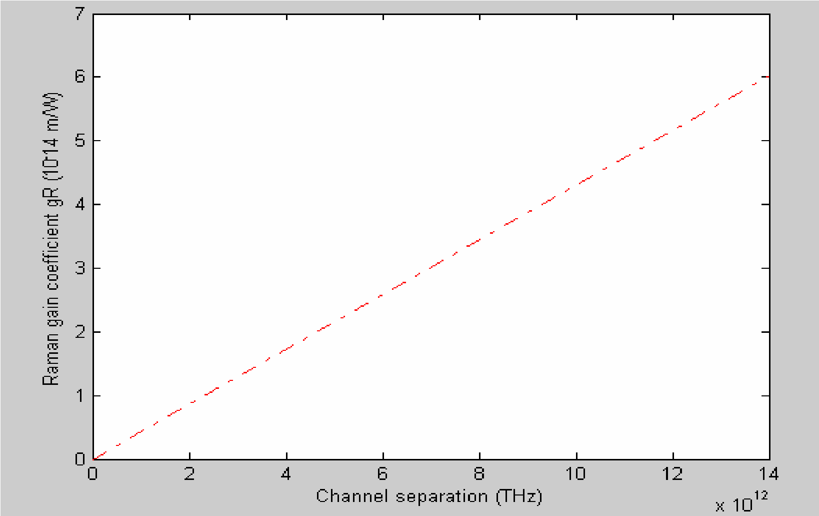
Figure (2) Three Equally Spaced Channels Generated Nine FWM Signals, Out of Which Three Fall on Top of the Signals [5]



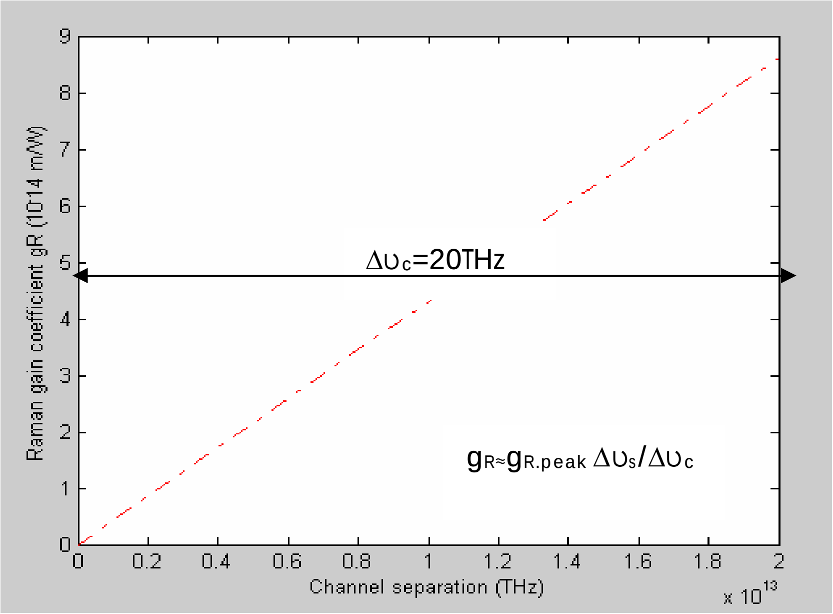
Figure(3) SRS transfers optical power from shorter wavelengths to longer wavelengths.6



Figure(4) Raman gain coefficient g_R as a function of the wavelength channel separation



Figure(5) Raman gain coefficient g_R as a function of the wavelength channel separation.



Figure(6) Raman gain coefficient g $_R$ as a function of the wavelength channel separation.

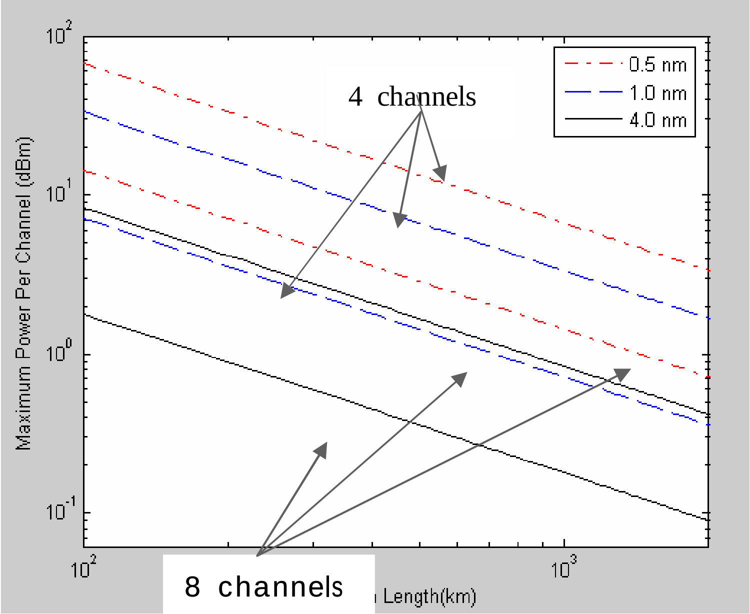


Figure (7) Maximum allowable power per wavelength versus transmission length for three different channels spacing.

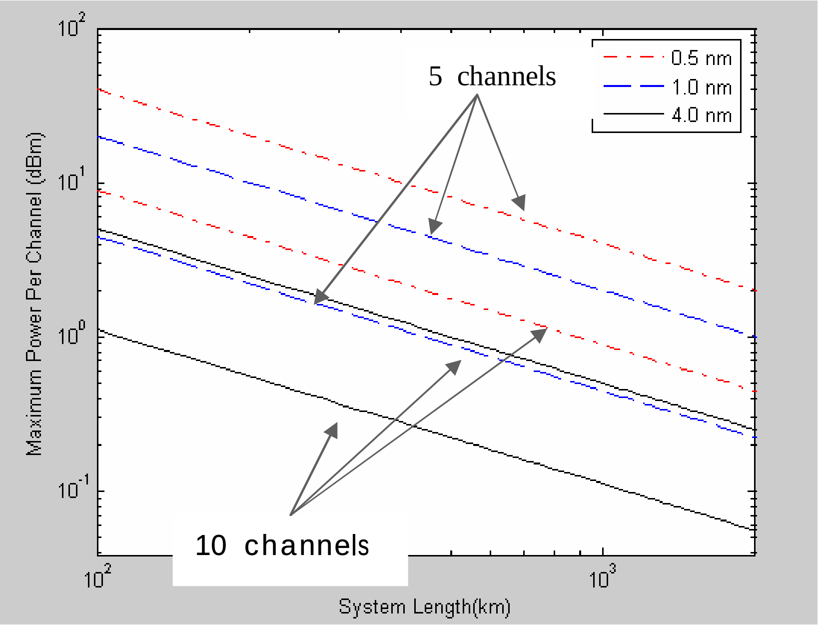


Figure (8) Maximum allowable power per wavelength versus transmission length for three different channels spacing.

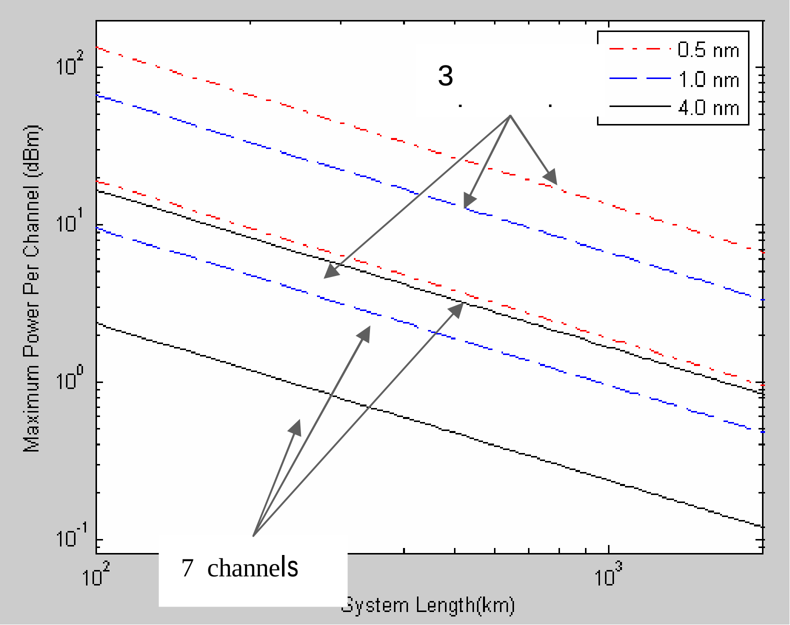


Figure (9) Maximum allowable power per wavelength versus transmission length or thre