ISSN: 2278 – 909X
International Journal of Advanced Research in Electronics and Communication Engineering (IJARECE)
Volume 5, Issue 4, April 2016

Improvement of the Ultra Long-Haul Distances in UW-DWDM Optical Communication Networks With Raman Gain Amplifiers

Abd El Naser A. Mohamed[1], Mohamed A. metawe e[2], Mostafa Moftah Ali[3]
[1]Electronics and Electrical Communications Engineering Department
Faculty of Electronic Engineering, Menouf 32951, Menoufia University, EGYPT
[2] Communications and Computers Engineering Department
Faculty of Engineering, Delta University for science and Technology EGYPT
[3] Higher Institute of Engineering and Technology in El-Arish, Egypt

Abstract— ***In the present paper, increase the optical long-haul distances with ultra-wide wavelength division multiplexing (UW-WDM) where Raman gain of multi-pumping optical amplifier has been modeled and parametrically investigated over wide ranges of affecting parameters are employed with Raman pumping powers, Rpo = 0.2 W), optical signal wavelengths*** $1.42 \leq \lambda_s, \mu m \leq 1.72$, ***the pumping wavelengths*** $1.42 \leq \lambda_R, \mu m \leq 1.52$, ***and the relative refractive index difference*** $0.004 \leq \Delta n \leq 0.01$. ***The problem is cast into two coupled nonlinear differential equations of first order taking into account both pump-pump interactions and signal-signal interactions along the fiber. The cross coupling terms among channels of UW-WDM are negligible. The total number of channels*** $3600 \leq N_t \leq 14400$ ***are handled in ultra-wide space division multiplexing (UW-SDM) to transmitted through optical link*** $30 \leq N_L \leq 480$, ***The multi-pumping amplifiers, NR = {4,5,6,8,10} pumps are processed with equal spectral spacing. The effective fiber core area, the gain coefficient and the amplified spontaneous emission power ASE (as a measure of the minimum detectable power), the signal-to-noise ratio at the effective length, the channel spacing are cast and calculated over the operating wavelength. The obtained results are employed to find the average optical distances over the spectral range under the processing. It is concluded that for repeater spacing, the total injected Raman powers are the vital factor rather than the number of amplifiers, while for the gain spectral width, the number of amplifiers is the vital factor. The central wavelength of the subset of channels that propagates in a link indicates the order of link. The total number of links in the core determines the ultimate values of different effects.***

Key Word- Multi-Pumping Raman Amplifiers, Ultra-Long Haul Optical Communication Systems, Ultra-Wide Wavelength Division Multiplexing

I. Introduction

Distributed Fiber Raman Amplifier (FRA) using the long haul transmission line as a Raman gain medium to amplify optical signals in fibers, based on transferring the power from the pump beam to the signal via Raman interaction between the light and vibrational modes of the glass, especially for ultra wide dense Wavelength Division Multiplexing (UW-DWDM) to increase the repeater distance as well as the capacity of the communication systems [1-3].

The optical characteristics of a DFRA in a laboratory environment can be precisely estimated by numerical simulation when the fiber parameters, such as core radius, numerical aperture, and attenuation coefficient, are given with the Raman gain coefficient measured experimentally [4-6]. Raman fiber lasers and amplifiers will play an increasing role in future optical fiber communication systems. In the most common configuration, several pump lasers are launched into the transmission span and counterpropagate with signals. These pumps are high-power lasers and undergo nonlinear interactions. The simplest of these interactions is a transfer of power from the short pump wavelengths due to Raman scattering [7-10].

Distributed Raman amplifiers improve the optical-signal-to-noise ratio (OSNR), the noise figure and reduce the nonlinear penalty of fiber systems performance, allowing for longer amplifier spans, higher bit rates, closer channel spacing, and operation near the zero-dispersion wavelength [11-13].

A comprehensive experimental investigation of an all-Raman ultra wide single-band transmission system for both 10 and 40 Gb/s line rates was done [14-15].

In the present paper, the multi-pumping Raman amplifiers employed in ultra-high capacity and ultra-long haul applications will be deeply and parametrically investigated over wide ranges of affecting parameters.

II. Basic Model and Analysis

The total number of optical channels, N_t are transmitted through the optical link, N_L . The multi-pumping Raman amplifiers are employed via the use of N_R pumps of equal l powers and equal spectral spacing . The following characteristics are processed at the total number of pumps, N_R = {4,5,6,8,10}: i) The net effective gain constant, G_c, ii) The average effective area, $A_{eff.}$, iii) The average amplified spontaneous emission, ASE, iv) The average signal-to-noise ratio, SNR, v) The average optical distances, L_{sa}. vi) The channel spacing , and finally vii) The Four wave mixing , FWM

II.1. Numerical data

The following numerical data are employed to obtain the best performance of the present paper for the following:

$$3600 \leq N_t, \text{total optical channels} \leq 14400$$

$$30 \leq N_L, \text{optical links} \leq 480$$

$$0.004 \leq \Delta n, \leq 0.01$$

$$1.42 \leq \lambda_s, \text{optical signal wavelength}, \mu m \leq 1.72$$

$$1.42 \leq \lambda_R, \text{pumping signal wavelength}, \mu m \leq 1.52$$

Signal power, S_{po} = 10 mW,
Pumping power, R_{po} = 0.2 Watt/pump.

The number of channels per link, $N_{chL} = N_t / N_L$, these N_{chL} possess a central wavelength λ_{cL} given by:

$$\lambda_{cL} = \lambda_i + \delta\lambda (N_{oL} - 0.5) N_{chL} \quad (1)$$

$$\delta\lambda = (\lambda_f - \lambda_i)/(N_t - 1), \quad (2)$$

with λ_i = 1.42 µm , λ_f = 1.72 µm , and N_{oL} is the order of link {1,2,3,….., N_L}.

$$\Delta\lambda = \lambda_f - \lambda_i = 300 \text{ nm} \quad (3)$$

II.2. Four wave mixing and channel spacing Channel assignment for links

Analyzed the propagation of total number of channels N_t, through number of links N_L with any squeezed total chromatic dispersion coefficient, D_t.

The efficiency of Four-wave mixing depends on the channel spacing and the fiber dispersion, to reduce the effects of Four-wave mixing, the channels in a link will be selected with large spectral spacing. The $\Delta\lambda$ is divided into N_L subgroups according to the number of links, each of width $\Delta_s\lambda$ as shown in Fig.1.

Where: $\Delta_s\lambda$ is the link spacing:

$$\Delta_s\lambda = \frac{\Delta\lambda}{N_L} \quad (4)$$

In order to overcome the four-wave mixing (FWM) effect, the channel spacing , $\delta\lambda$ in each link is largely selected on the following bases.

1) Each link of order N_L is occupied with N_{chL} , starting from $\lambda_i(N_L)$ up to $\lambda_f(N_L)$ where:

$$\lambda_i(N_L) = \lambda_i + \delta\lambda (N_L - 1) \quad (5)$$

$$\lambda_f(N_L) = (N_L - 1)\Delta_s\lambda + \delta\lambda (N_L - 1) + \lambda_i \quad (6)$$

where :

$$\delta\lambda = \frac{\lambda_f - \lambda_i}{N_t - 1} \text{ nm}, \quad N_{chL} = N_t / N_L \quad (7)$$

Then channel spacing:

$$\delta\lambda = \frac{\Delta_s\lambda}{N_{chL}} \quad (8).$$

2) New design of channel spacing

The Fig.2 designed for used channel 1 in L_1 , channel 1 in L_2, …..,also on, and used channel 2 in L_1 , channel 2 in L_2, …….,also on, from this design we get the channel spacing is very large than in item (1) because:

$$\delta\lambda = \Delta_s\lambda \quad (9)$$

Each link of order N_L possesses a central wavelength $\lambda_{cL}(N_L)$ where:

$$\lambda_{cL}(N_L) = (\lambda_i(N_L) + \lambda_f(N_L))/2$$
$$= \lambda_i(N_L) + 0.5(\lambda_f - \lambda_i) \quad (10)$$

Also we have the channel spacing Δf in GHz as [5]:

$$\Delta f = 3x10^5 \Delta_s\lambda / N_L \lambda_{cL}^2 (N_L) \quad (11)$$

II.2. Governing Equations

The major two rate nonlinear coupled differential equations for multi-pumping Raman amplifiers, that describe the optical (signals and Raman pump) powers for propagation of both in the optical fiber cables and negligible the interaction of the stokes power, are described [16-17]:

$$\frac{dS_p}{dL_s} + \sigma_s S_p = \frac{g}{A_{eff}} R_p S_p \quad (12)$$

$$\frac{dR_p}{dL_s} + \sigma_R R_p = \frac{g}{A_{eff}} \frac{\lambda_s}{\lambda_R} R_p S_p \quad (13)$$

For increase the transmission information's in the optical fiber cables and the average optical distances for using the UW-DWDM with multi-Raman pump powers, thus we cast and derived the following:

$$\frac{dS_{Pi}}{dL_s} + \sigma_{si} P_{si} = [G_o R_{pi}] S_{pi}, \quad \lambda_{si} > \lambda_{Rj} \quad (14)$$

$$\frac{dR_{pi}}{dL_s} + \sigma_{Rj} R_{pi} = [-G_1 S_{pi}] R_{pj}, \quad \lambda_{si} > \lambda_{Rj}, \quad (15)$$

where:

$$G_o = \sum_{j=1}^{N_R} \frac{g_j}{A_{effj}} = \frac{g}{A} N_{RR}, \quad km^{-1}W^{-1}, \quad \lambda_{si} > \lambda_{Rj}, \quad (16)$$

$$G_1 = \sum_{\substack{j=1 \\ i=1}}^{\substack{N_{ch} \\ N_R}} \left(\frac{g_i}{A_{effi}}\right) \left(\frac{\lambda_{si}}{\lambda_{Rj}}\right), \quad km^{-1}W^{-1}, \quad (17)$$

Where N_{RR} is the number of amplifiers of wavelengths λ_{Rj} less than λ_{si}, where:

N_{RR} = 1,2,3,…….,N_R. (18)

Recast the two coefficients (G_o , G_1) under the forms:

$$G_o = N_{RR} G_c, \quad (19)$$

$$G_1 = G_c [N_{chL} \lambda_{sa1} / \lambda_{si}] = N_1 G_c, \quad (20)$$

The average gain coefficient over a link , $G_c =< g / A_{eff} >$, (20)

$$\lambda_{sa1} = (\lambda_{NchL} + \lambda_{i+1})/2, \quad (21)$$

$$\lambda_{sa2} = (\lambda_{s1} + \lambda_{schL})/2, \quad \lambda_{si} \geq \lambda_{Rj} \quad (22)$$

Then, the transmission signals and pump powers in the optical cables as the forms [18-19]:

$$S_{pi}(L_s) = S_{poi}(L_s) e^{-\sigma_{si} L_s}, \quad \text{and} \quad (23)$$

$$R_{pj}(L_s) = R_{poj}(L_s) e^{-\sigma_{Rj} L_s}. \quad (24)$$

The solution of the Eqs.(14,15) with respect to L_s, one gets:

$$S_{pi}(L_s) = \frac{S_{poi} G_3 e^{-\sigma_{si} L_s}}{(S_{poi} + G_3)(e^{-P_T G_c L_{eff}}) - 1} = G_T(L_s) S_{poi} e^{-\sigma_{si} L_s}, \quad (25)$$

$$P_T = N_{RR} P_{Rjo} + N_2 P_{sio}. \quad (26)$$

$$N_2 = N_{chL}\left(\lambda_{sa2}/\lambda_{Rj}\right) \quad (27)$$

where: $G_T(L) = G_3\left(\left(S_{poi} + G_3\right)e^{-P_T G_c L_{eff}} - S_{poi}\right)^{-1}$
is a dimensionless variable.

In the above equations $S_{pi}(L)$, G_c, R_{poi}, S_{poi}, L_{eff}, σ_{si} are respectively signal power at a distance L_s, effective total Raman gain coefficient, Raman pump power at L_s=0.0, signal power at L_s=0.0, effective length, and the spectral losses in km^{-1}. G_c is given by [19]:

$$G_c\left(\lambda_{cL},\lambda_{RA},g_o\right) = g\left(\lambda_{cL},\lambda_{RA}\right)/\left[A_e\left(\lambda_{cL},\lambda_{RA}\right)\right] \quad (28)$$

where $g\left(\lambda_{cL},\lambda_{RA}\right)$ and $A_e\left(\lambda_{cL},\lambda_{RA}\right)$ are functions of both the central wavelength and the average Raman pumps wavelengths.

The net effective gain $G_c\left(\lambda_{cL},\lambda_{RA}\right)$, and both $g\left(\lambda_{si},\lambda_{RA}\right)$ and $A_e\left(\lambda_{si},\lambda_{RA}\right)$ are computed based on the data of each link N_{oL} where $\lambda_{1L} \le \lambda_{si} \le \lambda_{2L}$ and

$$\lambda_{1L} = \lambda_i + \delta\lambda\left(N_{oL} - 1\right)N_{chL}, \quad (29)$$

$$\lambda_{2L} = \lambda_{1L} + \delta\lambda N_{chL} = \lambda_i + N_{oL}N_{chL} \quad (30)$$

$$\lambda_{si} = \lambda_{1L} + \delta\lambda\left(i-1\right)N_{chL}, \quad (31)$$

with i = {1,2,3,….., N_{chL}}.

Then, both $g\left(\lambda_{si},\lambda_{RA}\right)$ and $A_e\left(\lambda_{si},\lambda_{RA}\right)$ are averaged to give:

$$g\left(\lambda_{cL},\lambda_{RA}\right) = \frac{1}{N_{chL}}\sum_{i=1}^{N_{ch}} g\left(\lambda_{si},\lambda_{RA}\right) \quad (32)$$

$$A_e\left(\lambda_{cL},\lambda_{RA}\right) = \frac{1}{N_{chL}}\sum_{i=1}^{N_{chL}} A_e\left(\lambda_{si},\lambda_{RA}\right) \quad (33)$$

In such a manner, we obtain both $A_e\left(\lambda_{cL},\lambda_{RA}\right)$ and $g\left(\lambda_{cL},\lambda_{RA}\right)$ and consequently we cast $G_c\left(\lambda_{cL},\lambda_{RA}\right)$. $ASE\left(\lambda_{cL},\lambda_{RA}\right)$, as a criterion of the minimum detectable power, is computed. The signal light must be amplified again before its level becomes less than that of the ASE. In order to obtain the ASE power at the output end of the fiber for signal power amplification,, ASE power in Watt is given by:

$$ASE = \frac{2.981326x10^{-8}\sqrt{\left(\pi\sigma_{Rj}/4.343\right)/R_{poj}G_c}}{\lambda_{si}} \quad (34)$$

The average optical distances in link of order N_{oL}., $L_{SA}(N_{oL})$ is given by:

$$L_{SA}\left(N_{oL}\right) = \frac{1}{N_{chL}}\sum_{i=1}^{N_{ch}} L_{si}, \quad (35)$$

where L_{si} satisfies:

$$S_{pi}\left(L_{si}\right) = G_T\left(L_{si}\right)S_{poi}e^{-\sigma_{si}L_{si}} = ASE\left(\lambda_{si},\lambda_{RA}\right) \quad (36)$$

with

$$L_{eff} = \left(1 - e^{-\sigma_a L_{si}}\right)/\sigma_a, \text{ km.} \quad (37)$$

The average SNR per link are given are defined as:

$$SNR = \frac{\sum_{i=1}^{N_{chL}} 10Log_{10}\left(S_{pi}\left(L_s,R_p\right)/ASE\right)}{N_{chL}} \quad .(38)$$

In the present study, we have considered:

$$L_s = L_{eff} = 1.5/\sigma_{si}, \text{ km} \quad (39)$$

III. Results and Discussion

In the present paper both the causes and the resulted effects are as follows: i) Causes are N_t, N_L, $N_{oL}(\lambda_{cL})$, N_{chL}, Δn, N_R, S_{poi}, R_{poj}, and R_{pT}, where the set of major interest is {N_t, N_L,N_R,R_{pT}}, and ii) Effects are G_c, A_e, ASE, SNR, L_s (maximum theoretical limit) [19]. The given effects are investigated at the propagation distances: L_s which equals to $1.5/\sigma_{si}$ which is considered as L_{eff}. Based on AllWave fiber of spectral losses $\sigma_s(\lambda_s)$, where we have cast:

$$\sigma_{sd}\left(\lambda_s\right) = 0.19319 + 6.234\lambda_m^2 + 27.902\lambda_m^3$$
$$-9.1542\lambda_m^4 - 341.85\lambda_m^5 - 525.81\lambda_m^6 \text{ dB/km}, \quad (40)$$

Where:

$$\lambda_m = \lambda_s - 1.55, \text{ and}$$

$$\sigma_{sk}\left(\lambda_s\right) = \sigma_{sd}\left(\lambda_s\right)/4.343 \text{ km}^{-1}$$

Variations of the set of effects {G_c SNR, L_s} against variations of the subset of causes {Δn,N_R, $N_{oL}(\lambda_{cL})$} are depicted in Figs. 3-16 and will be discussed in the following subsections.

III.2. Variations of Average Optical Distance, L_{sa}

a) For the total number of channels, N_t = 3600 channels

The variations of the average optical distances , L_{sa} with the optical signal powers, S_{po} and the relative refractive index difference, Δn at the number of pumping powers , N_R = {5,10}, pumping power, R_{po} = 0.2 W over set of the controlling parameters, shown in Figs.(3-6). These figures clarify the following:

i) As S_{ps} increases L_{sa} increase, whatever the other controlling sets of parameters.
ii) N_L and L_{sa} are in positive correlations, whatever, the other controlling sets of parameters.
iii) L_{sa} and Δn are in positive correlations, whatever, the other controlling sets of parameters, due to the amplifier gain
iv) As the number of pumps N_R increases, R_{ra} increases also.

b) For the total number of channels, N_t = {7200, 14400 channels}

The variations of the average optical distances , L_{sa} with the number of links, N_L at N_R = {4,6,8}, S_{po} = 10 mW, R_{po}= 0.2W and Δn = 0.0075, shown in Figs. (7-9). These figures clarify the following:

i) L_{sa} and any subset of the set of causes {N_L,R_{pT},Δn} are in positive correlations,
ii) L_{sa} and N_t are in negative correlations,

iii) The total injected Raman powers are the vital factor rather than the number of amplifier.

III.2. Variations of G_c

Variation of Raman gain constant, G_c against N_L , and optical wavelength as a major cause are portrayed in Figs.10-14 at the effective length. These figures assure the sort of variations of L_{sa} whatever the controlling sets of causes.

III.3. Variations of SNR

Variations of signal-to-noise S/N, also at the effective length are displayed in Figs.15-16 where the following are clarified:

i) S/N increases as N_L increases, or Δn increases, or N_{chL} decreases or both, and

ii) The total Raman injected power R_{pT} possesses remarkable effect also on the ratio S/N.

IV. Conclusions

In the present paper, the net effective gain of multi-pumping Raman amplifier in ultra-wavelength division multiplexing (WDM) and ultra long-haul optical communication systems has been modelled and parametrically investigated over wide ranges of affecting parameters, taking into account the polarization effect.

Average optical distances, L_{sa}, net Raman gain, G_c and signal-to-noise ratio, SNR, effects are as major parametrically investigated under variations of major sets of causes employing multi-pumping Raman amplifier at different pumping conditions. The investigation indicates the following integrated conclusions: i) Both the total number of links in the core N_L and the total Raman injected power of pumps R_{pT} are causes of vital effects, ii) L_s, G_c, and SNR, as a criterion to account the minimum detectable power, and any subset of the following set $\{N_L, R_{pT}, \Delta n, N_{chL}\}$ are in positive correlations, iii) SNR and either N_R or N_{chL} or both are in negative correlations.

REFERENCES

[1] L. Xue and L.Yan-He, " Optimal Bandwidth for Distributed Multi-pump Raman Amplifier Based on Hybrid genetic Algorithm" Chin. Phys. Lett., Vol. 21, No. 1, pp. 84-86, 2004.

[2] Abd El-Naser A. Mohammed, Mohammed M. E. El-Halawany, Ahmed Nabih Zaki Rashed, and Mohamoud M. Eid "Recent Applications of Optical Parametric Amplifiers in Hybrid WDM/TDM Local Area Optical Networks ", IJCSIS International Journal of Computer Science and Information Security, vol. 3, no. 1, pp. 14-24, July 2009.

[3] C. Headley and G.P. Agrawal, Raman Amplification in Fiber Optical Communication Systems, Elsevier AP, USA, 2005

[4] Z. Xu, K Roltwitt, C. Peucheret, and D. Jeppesen, "Optimization of Pumping Schemes for 160 Gb/s Single-Channel Raman Amplified Systems, " IEEE Photonics Technol. Lett., Vol.16, No.1, pp.329-331, Jan. 2004.

[5] J. C. Baoutealler, L. Leng, and C. Headley., "Pump-Pump Four Wave Mixing in Distributed Raman Amplified Systems," J. Lightwave Technol., Vol.22, No.3, pp.723-731, March., 2004.

[6] Abd El-Naser A. Mohammed, and Ahmed Nabih Zaki Rashed, Comparison Performance Evolution of Different Transmission Techniques with Bi-Directional Distributed Raman Gain Amplification Technique in High Capacity Optical Networks, International Journal of Advanced Engineering & Applications, Vol. 1, No. 1, pp. 1-9, Jan. 2010.

[7] Gerima Aroram Sangeev Dewra,"DWDM Transmission using Hybrid Optical Amplifiers,", I.J. of Advanced Research and communication Engineering, Vol.3, Issue 4, pp.6174-6177, April 2014

[8] Abd El-Naser A. Mohammed, Ahmed Nabih Zaki Rashed, "Efficient Distributed Raman Gain Amplification technique in Modern metro Passive Optical Networks", I.J. of Academic library and Information Science, Vol.1(1), pp.10-23, August 2013

[9] Q. Han, J. Ning, and Z. Chen, "Novel Shooting Algorithm for Highly Efficient Analysis of Fiber Raman Amplifiers," J. Lightwave Technol., Vol.24, No.4, p.4946, April 2006.

[10] Silvia Dias, et. al., "Wavelength Division multiplexed Distributed Fiber Raman Amplifier Bus network for sensors", SPIE vol.5820, Bellingham, WA, , pp.242-245, 2005

[11] J. Hu, et al., "Flat-Gain Fiber Raman Amplifiers Using Equally Spaced Pumps", J. Lightwave Technol., Vol.22, No.6, pp.1519-1522, June., 2004.

[12] Abd El-Naser A. Mohammed, Ahmed Nabih Zaki Rashed and Mahmoud A. Eid, "Recent Advances of Distributed Optical Fiber Raman Amplifiers in Ultra Wide Wavelength Division Multiplexing Telecommunication networks", I.J. Computer network and Information Security, 2012,4,63-74

[13] M. V. Raghavendra, and P. L. H. Vara Prasad, "Estimation of Optical Link Length for Multi Haul Applications," International Journal of Engineering Science and Technology, Vol. 2, No. 6, pp. 1485-1491, 2010

[14] D.F. Grosz, A. Agarwal, S. Banerjee, D.N. Maywar, A.P. Kung, "All-Raman Ultra-Long-Haul Single-Wideband DWDM Transmission Systems with OADM Capability," J. Lightwave Technol., Vol.22, No.2, pp.423-432, Feb. 2004.

[15] Sasanthi Peiris, Ncholas Madanopoudos, Neophytos A. Antoniades," Performane Analysis of a Hybrid Raman Optical parametric Amplifier in the O-and E-Bands for CWMPONs", Photonics, 2014, 1,473-487, dii:10.3390 photonics 1040473

[16] Abd El-Naser A. Mohammed, Abd El-Fattah A. Saad, and Ahmed Nabih Zaki Rashed and Mahomud M. Eid, " Characteristics of Multi-Pumped Raman Amplifiers in Dense Wavelength Division Multiplexing (DWDM) Optical Access Networks" IJCSNS International Journal of Computer Science and Network Security, vol. 9, no. 2, pp. 277-284, Feb. 2009.

[17] Ahmed Nabih Zaki Rashed, "New Trends of Forward Fiber Raman Amplification for Dense Wavelength Division Multiplexing Photonic Communication Networks", International Journal of Soft Computing, vol. 6, no. 2, pp. 26-32, 2011.

[18] B. Bala Subbanna, L.P. Divya Meenakshi,"{ The Role of Amplifiers in Optical Fiber Communication," I.j of

Eng. and Advanced Tech., Vol.2, Issue 4 , pp. 730-733, April 2013

[19] J. Bromage, "Raman Amplification for Fiber Communications Systems," J. Lightwave Technol., Vol. 22, No. 1, pp. 79-93, Jan 2004.

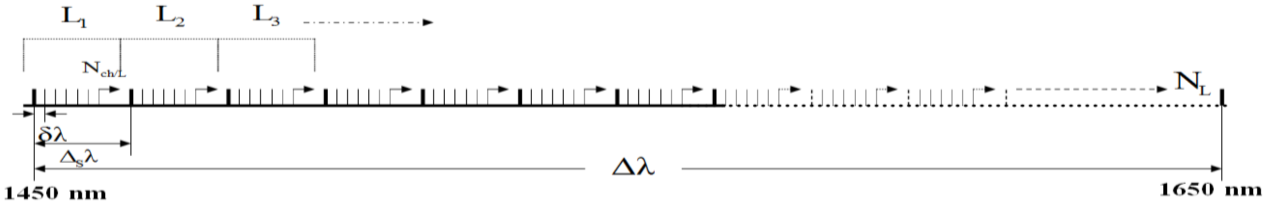
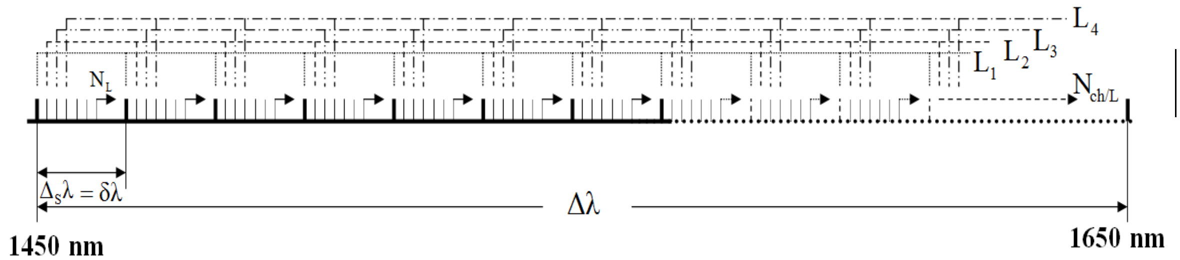


Fig. 1 The subgroups of the employed spectral width.



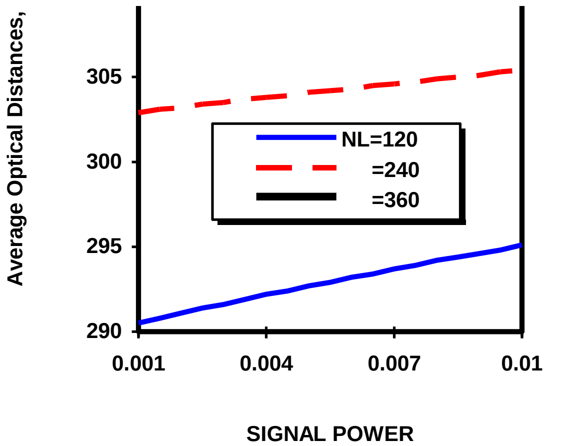


Fig. 3. Variations of average optical distances, L_{sa}, km against variations of signal power, P_{so}, Watt at the assumed set of parameters.

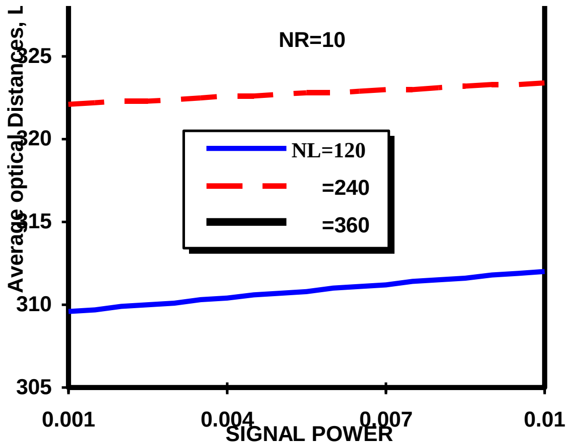


Fig. 4. Variations of average optical distances, L_{sa} km against variations of signal power, P_{so}, Watt at the assumed set of parameters

$1.42 \leq \lambda_S$, μm≤ 1.72		**$1.42 \leq \lambda_R$, μm≤ 1.52**
N_t=3600 ch	**N_R=5 ,**	**N_L=360 link**

$1.42 \leq \lambda_S$, μm≤ 1.72		**$1.42 \leq \lambda_R$, μm≤ 1.52**
N_t=3600 ch.	**N_R=10 ,**	**N_L=360 link**

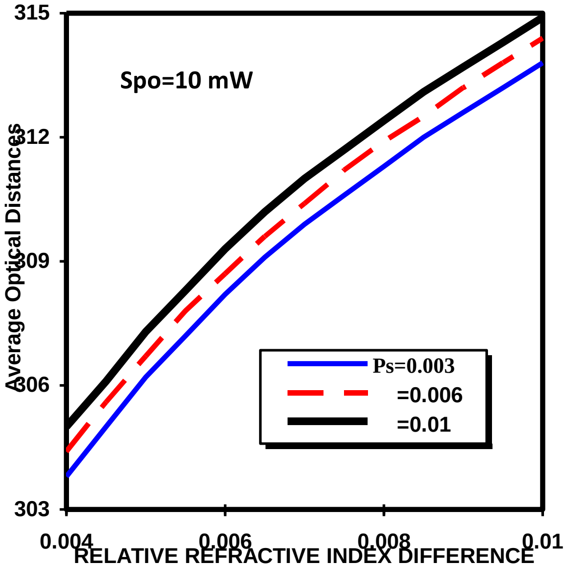


Fig. 5. Variations of average optical distances, L_{sa} km against variations of relative refractive index difference at the assumed set of parameters.

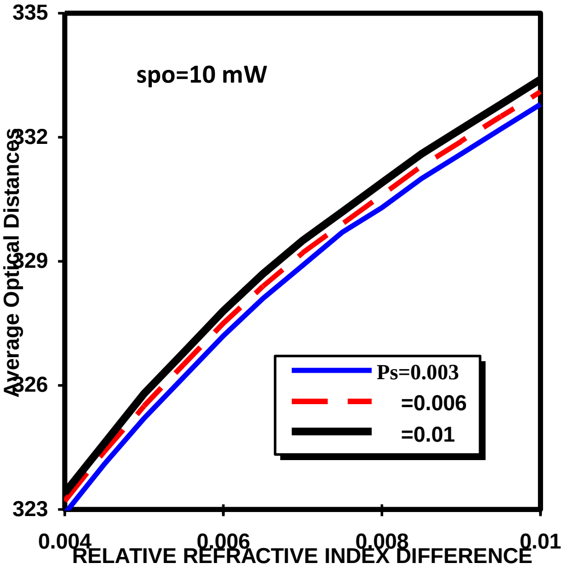


Fig. 6. Variations of average optical distances, L_{sa} km against variations of relative refractive index difference at the assumed set of parameters.

N_T =7200 channels		N_T = 14400 channels	
N_R= 4,6,8	1.42 < λ, μm < 1.72,	P_S=10 mW	Δn=0.0075,
g_o =0.74x10^{-13},	$P_{RT}(N_R = 4)$ = 1.07 Watt ,	$P_{RT}(N_R = 6)$ = 1.3965 Watt,	$P_{RT}(N_R = 8)$ = 0.409 Watt

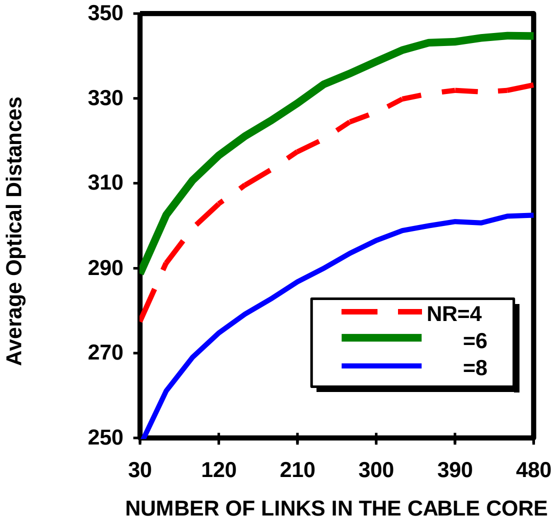


Fig.7. Variations of average optical distances, $L_{sa\,s}$, km with number of links in the cable core, N_L, at the assumed set of parameters.

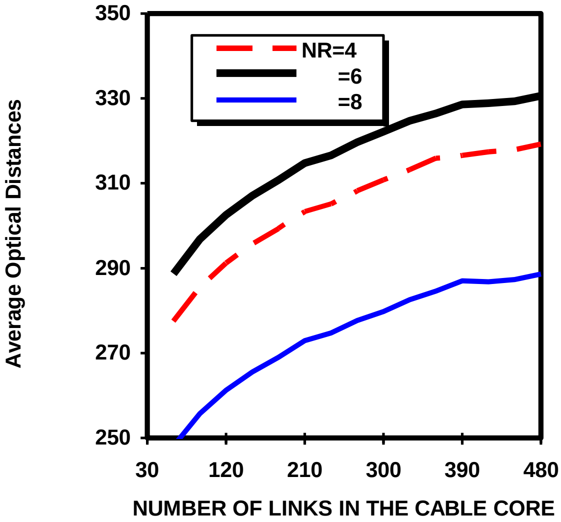


Fig.8. Variations of average optical distances, L_{sa}, km with number of links in the cable core, N_L, at the assumed set of parameters.

N_t =14400 Channel		N_R= 4,8, 10	1.42< λ, μm < 1.72
P_S=10 mW	Δn=0.0075,	P_{RT} = 0.96 Watt	1.42 < λ_R μm < 1.52

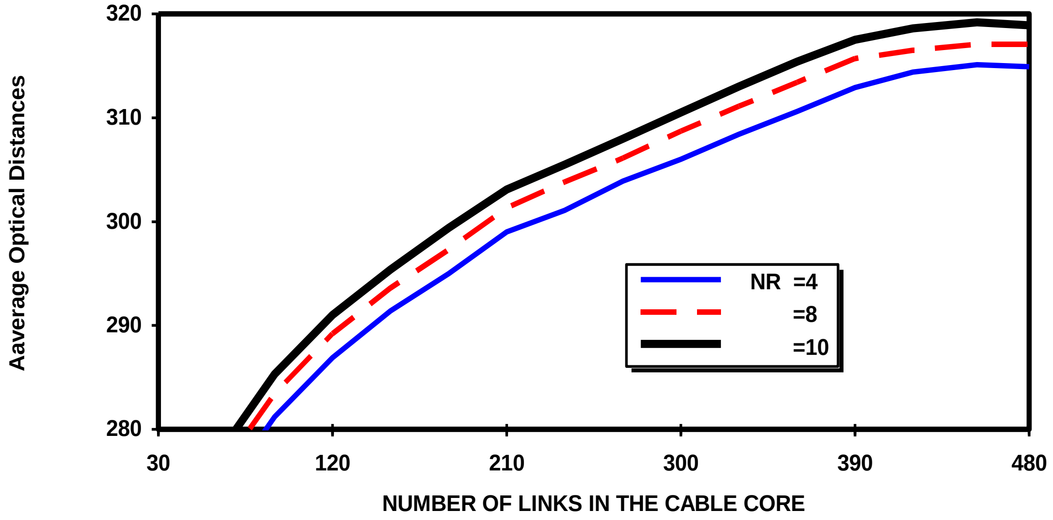


Fig.9. Variations of average optical distances, L_{sa}, km with number of links in the cable core, N_L, at the assumed set of parameters.

N_T =7200 channels		N_T = 14400 channels	
N_R= 4,6,8	1.42 < λ, μm < 1.72	P_S=10 mW	Δn=0.0075,
g_o =0.74X10^{-13}	$P_{RT}(N_R = 4)$ = 1.07 Watt ,	$P_{RT}(N_R = 6)$ = 1.3965 Watt,	$P_{RT}(N_R = 8)$ = 0.409 Watt

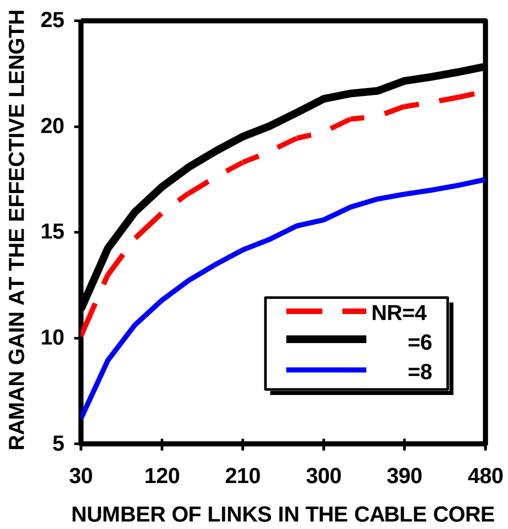


Fig.10. Variations of Raman gain at the effective length, dB with number of links in the cable core, N_L, at the assumed set of parameters.

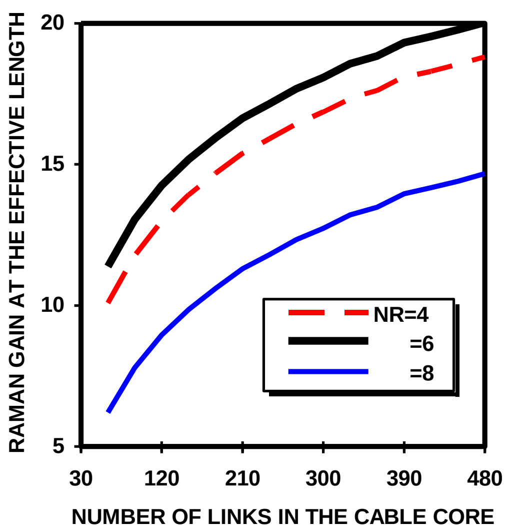


Fig.11. Variations of Raman gain at the effective length, dB with number of links in the cable core, N_L , at the assumed set of parameters

N_T =14400 channel		N_R= 4,8, 10	1.42< λ, μm < 1.72
P_S=10 mW	Δn=0.0075,	P_{RT} = 0.96 Watt	1.42< $λ_R$ μm < 1.52

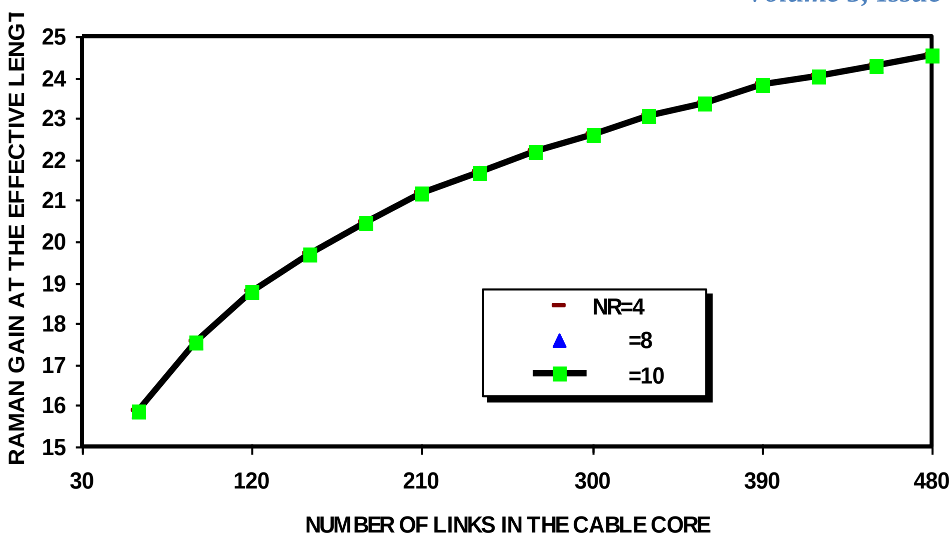


Fig.12. Variations of average Raman gain, dB with number of links in the cable core, N_L, at the assumed set of parameters.

$1.42\le\lambda_S$, μm≤1.72		$1.42\le\lambda_R$, μm≤1.52	$1.42\le\lambda_S$, μm≤1.72		$1.42\le\lambda_R$, μm≤1.52
N_T=3600 ch.	N_R=5,	N_L=360 link	N_T=3600ch.	N_R=10 ,	N_L=360 link

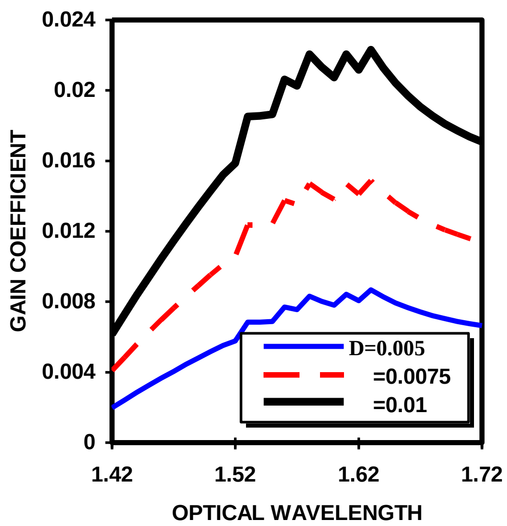


Fig.13. Variations of gain coefficient, G_c, $Watt^{-1}$ km^{-1} against variations of optical wavelength,λ_s, μm at the assumed set of parameters.

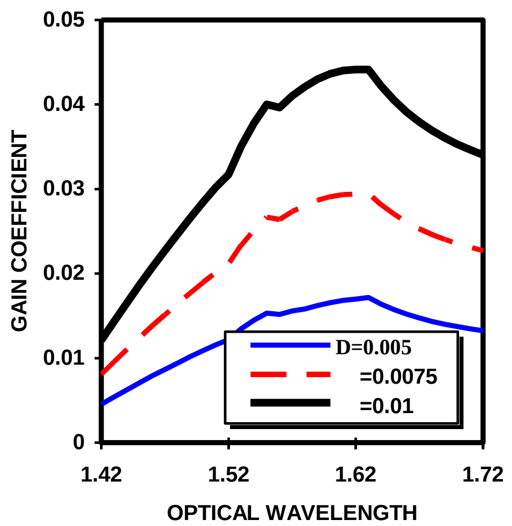


Fig.14. Variations of gain coefficient, G_c, $Watt^{-1}$ km^{-1} against variations of optical wavelength,λ_s, μm at the assumed set of parameters.

N_T =7200 channels			N_T = 14400 channels
N_R= 4,6,8	$1.42 < \lambda$, μm < 1.72	P_S=10 mW	Δn=0.0075,
g_o =0.74X10^{-13}	$P_{RT}(N_R = 4)$ = 1.07 Watt ,	$P_{RT}(N_R = 6)$ = 1.3965 Watt,	$P_{RT}(N_R = 8)$ = 0.409 Watt

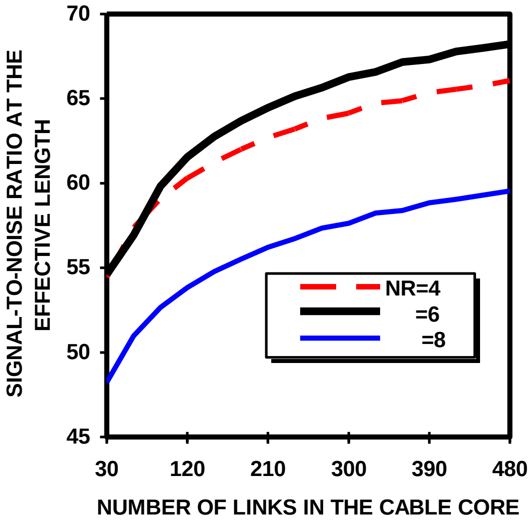


Fig.15. Variations of signal-to-noise ratio at the effective length with number of links in the cable core, N_L, at the assumed set of parameters.

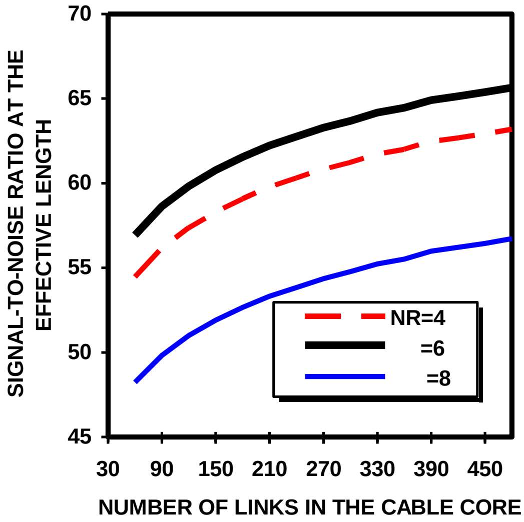


Fig.16 Variations of signal-to-noise ratio at the effective length with number of links in the cable core, N_L , at the assumed set of parameters