

New Trends of Forward Fiber Raman Amplification for Dense Wavelength Division Multiplexing (DWDM) Photonic Communication Networks

Ahmed Nabih Zaki Rashed

Department of Electronics and Electrical Communication Engineering,
Faculty of Electronic Engineering, Menoufia University, 32951 Menouf, Egypt

Abstract: The technology of Dense Wavelength-Division Multiplexing (DWDM) has recently resulted in a considerable increase in the transmission capacity of fiber-optic communication systems up to several terabits per second. The further improvement of the transmission capacity of such systems can be achieved through the expansion of the spectral range of WDM transmission toward the short-wavelength region. Therefore, this present study has proposed and investigated the new trends and progress of fiber Raman amplification for dense wavelength division multiplexing photonic communication networks over wide range of the affecting parameters. As well as we have deeply studied the transmission distances and transmission bit rates within Raman amplification technique in forward pumping direction configuration through standard single-mode fiber using Shannon transmission technique to handle transmission bit rate and product per channel in this direction for upgrading network performance and efficiency to provide maximum amount of transmission data rate to the supported maximum number of users.

Key words: Photonic networks, raman amplification, forward direction, transmission data rate, DWDM, Egypt

INTRODUCTION

Optical amplifiers are key elements of any fiber-optic communication system. Even though modern optical fibers have losses below 0.2 dB km^{-1} , a repeated amplification of the transmitted signal to its original strength becomes necessary at long enough distances (Chen and Wong, 2001). One solution for signal regeneration is the conversion of the optical signal into the electrical domain and subsequent re-conversion into a fresh optical signal. However, purely optical amplifiers are usually preferred. They simply amplify the electromagnetic field of the signal via stimulated emission or stimulated-scattering processes in a certain optical frequency range. The amplification process is essentially independent of the details of the spectral channel layout, modulation format or data rate of the transmission span (Felinskyi and Korotkov, 2008) thus permitting the system operator to later re-configure these parameters without having to upgrade the amplifiers (Fugihara and Pinto, 2008). Multi-wavelength pumped Raman Amplifiers (RAs) have attracted more and more attention in recent years (Gest and Chen, 2007). In this type of amplification a widely used concept, for high capacity long distance Wavelength Division Multiplexing (WDM) transmission systems was used. They have been already used in many ultra long-haul dense WDM (DWDM) transmission

systems. It supports high bit rate data transmission over long fiber spans due to its benefits such as proper gain and Optical Signal to Noise Ratio (OSNR). In addition, it can be used for increasing the bandwidth of Erbium Doped Fiber amplifiers (EDFAs) in hybrid systems. Another important feature of Ras is its gain bandwidth which is determined by pump wavelength. Multi-wavelength pumping scheme is usually used to increase the gain flattening and bandwidth for high capacity WDM transmission systems. In backward-pumped fiber Raman amplifiers, other noise sources such as the Relative Intensity Noise (RIN) transfer are minimized because this scheme can suppress the related signal power fluctuation. OSNR of this excitation is tilted and channels with longer wavelength have longer OSNR respect to the shorter wavelength channels (Jordanova and Topchiev, 2008; Karasek and Menif, 2002)

In the present study, researchers have integrated and deeply studied the fiber Raman amplification with the transmission media fibers and pumped at any wavelength to provide wide gain bandwidth and improve optical signal to noise ratio of the transmitted optical signals in order to allow both ultra long transmission bit rate distance and high capacity in DWDM photonic networks in forward direction configuration over wide range of the affecting parameters (Fig. 1).

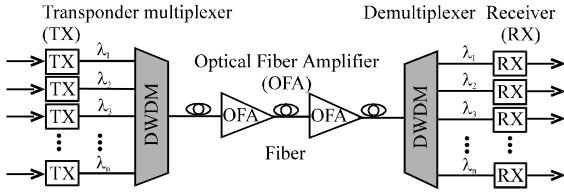


Fig. 1: DWDM photonic networks

SCHEMATIC VIEW OF DWDM PHOTONIC NETWORKS

This study shows multichannel DWDM transmission system when various 10 Gbit sec⁻¹ signals are fed to optical transmission modules (Karasek *et al.*, 2004). An optical DWDM coupler (multiplexer) then bunches these optical signals together on one fiber and forwards them as a multiplexed signal to an Optical Fiber Amplifier (OFA). A DWDM system can be described as a parallel set of optical channels, each using a slightly different wavelength but all sharing a single transmission medium of fiber. Depending on path length and type of fiber used, one or more optical fiber amplifiers can be used to boost the optical signal for long fiber links. At termination on the receiving side, the optical signals are preamplified then separated by using optical filters (demultiplexer) before being converted to electrical signals in the receiving modules (Lee *et al.*, 2009).

MODEL DESCRIPTION AND ANALYSIS

The signal and pump power interaction along fiber cable length can be expressed as (Mohammed *et al.*, 2009a):

$$\frac{dP_s}{dL} = g_0 P_p P_s - \alpha_s P_s \quad (1)$$

$$+ \frac{dP_p}{dL} = -\frac{\lambda_s}{\lambda_p} g_0 P_p P_s - \alpha_p P_p \quad (2)$$

where, g_0 in $W^{-1}m^{-1}$ is the Raman gain coefficient of the fiber cable length, α_s and α_p are the attenuation of the signal and pump power in silica-doped fiber, λ_s and λ_p are the signal and pump wavelengths. The sign of + is corresponding to forward pumping. Since, $P_p \gg P_s$, therefore, Eq. 2 can be solved when both sides of the equation are integrated. When using forward pumping ($S = 1$), the pump power can be expressed as the following expression:

$$P_p(L) = P_p(0) \exp(-\alpha_p L) \quad (3)$$

If the values of P_p are substituted in differential Eq. 1 and it is integrated from 0-L for the signal power in the forward pumping direction can be written as:

$$P_s(L) = P_s(0) \exp \left[g_0 S P_0 \frac{1 - \exp(-\alpha_p L)}{\alpha_p} - \alpha_s L \right] = G_F P_s(0) \quad (4)$$

where, G_F is the net gain in the forward pumping. With P_0 being the pump power at the input end. Hence the signal intensity at output of amplifier, fiber cable length L is determined by the following expression (Mohammed *et al.*, 2009b):

$$P_s(L) = P_s(0) \exp \left(\frac{g_0 P_0 L_{eff}}{A_{eff}} - \alpha_s L \right) \quad (5)$$

The effective length, L_{eff} is the length over which the nonlinearities still holds or Stimulated Raman Scattering (SRS) occurs in the fiber and is defined as:

$$L_{eff} = \frac{1 - \exp(-\alpha_p L)}{\alpha_p} \quad (6)$$

Hence, the amplification gain defined as the ratio of the power signal with and without Raman amplification is given by the following expression:

$$G_A = \frac{P_s(L)}{P_s(0) \exp(-\alpha_s L)} \quad (7)$$

The Noise Figure (NF) is the determination of the signal denigration over the length of the transmission span. It is the signal to noise ratio of input over that of the output and in fiber Raman amplifier. It is dependent upon the pumping power and the gain of the optical system as (Mohammed *et al.*, 2009c):

$$NF \approx \frac{2g_0}{A_{eff}} \int_0^L \frac{P_p dL}{G_A(L)} + \frac{1}{G_{net}(L)} \quad (8)$$

Where:

- $G_A(L)$ = The net gain at distance L along the fiber cable length
- A_{eff} = The effective area of the fiber cable core
- $G_{net}(L)$ = The net gain at the end of the fiber cable length

The maximum allowed transmit power per channel (P_T) as a function of fiber cable link length can be expressed as follows (Mohammed *et al.*, 2009d-f):

$$P_T \approx \frac{4 \times 10^4}{N_{ch}(N_{ch}-1)\Delta\lambda_s L} \quad (9)$$

Where:

- N_{ch} = The number of channels
- $\Delta\lambda_s$ = The channel spacing in nm
- L = The length of the fiber cable link in km

The maximum transmitted power per channel decreases. This is because the lowest wavelength channel which is also the worst affected channel, now interacts with more number of channels through the process of SRS. Thus, SRS is not a serious effect for small number of channels but can be serious for higher number of channels. To reduce the effect of SRS for higher number of channels, the spacing is thus reduced. If the spacing is fixed, the power launched decreases with N_{ch} inversely with a square term (Mohammed *et al.*, 2009d). The standard single mode fiber cable is made of the pure silica material which the investigation of the spectral variations of the waveguide refractive-index require empirical equation under the form (Mohammed *et al.*, 2009e):

$$n = \sqrt{1 + \frac{A\lambda^2}{\lambda^2 - B^2} + \frac{C\lambda^2}{\lambda^2 - D^2} + \frac{E\lambda^2}{\lambda^2 - F^2}} \quad (10)$$

The parameters of empirical equation coefficients for silica material as a function of ambient Temperature (T) and room Temperature (T_0) (Mohammed *et al.*, 2009d). Differentiation first and second order of empirical equation w, r, t λ yields (Nicholson, 2003). The total bandwidth is based on the total chromatic dispersion ($D_t = D_m + D_w$) where:

$$D_t = -\frac{\lambda}{c} \left(\frac{d^2 n}{d\lambda^2} \right) - \left(\frac{n_2}{cn} \right) \left(\frac{\Delta n}{\lambda} \right) Y, \quad \text{nsec nm.km}^{-1} \quad (11)$$

Where:

- λ = The operating signal wavelength
- c = The velocity of the light, 3×10^8 m sec⁻¹
- n = The refractive-index of the fiber cable core
- n_2 = The refractive-index of cladding material
- Y = The function of wavelength
- Δn = The relative refractive-index difference

Assuming the receiver is at the room temperature and feeds a matched preamplifier with Noise Figure (NF) in dB, then for a transmitted power P_T in Watts, the Optical Signal to Noise Ratio at the receiver (OSNR) is (Nicholson, 2003):

$$\text{OSNR} = \frac{P_T L}{NF k T \alpha_s} \quad (12)$$

Where:

- k = The Boltzmann's constant (1.38×10^{-23} J K⁻¹)
- α = The total attenuation coefficient in dB km⁻¹
- L = The fiber link length in km

The total pulse broadening $\Delta\tau$ due to total dispersion coefficient can be determined by:

$$\Delta\tau = D_t \Delta\lambda_s L, \quad \text{nsec} \quad (13)$$

The allowable signal bandwidth in standard single mode fiber can be expressed as (Raghuwanshi *et al.*, 2006):

$$\text{B.W}_{\text{sig}} = \frac{0.44}{\Delta\tau L}, \quad \text{Ghz} \quad (14)$$

As well as the Shannon transmission bit rate can be expressed as the following formula:

$$B_{\text{sh}} = 3.3219 \text{B.W}_{\text{sig}} \log_{10}(1 + \text{OSNR}), \quad \text{Gbit sec}^{-1} \quad (15)$$

Moreover the Shannon bit rate-distance product can be expressed as a function of Shannon transmission bit rate and fiber link length as the following expression:

$$P_{\text{sh}} = B_{\text{sh}} \cdot L, \quad \text{Gbit.km sec}^{-1} \quad (16)$$

The BER essentially specifies the average probability of incorrect bit identification. In general the higher the received SNR, the lower the BER probability will be. For most PIN receivers, the noise is generally thermally limited which independent of signal current. The BER is related to the OSNR as follows (Wasfi, 2009):

$$\text{BER} = 0.5 \left[1 - \text{erf} \left(\frac{\sqrt{\text{OSNR}}}{2\sqrt{2}} \right) \right] \quad (17)$$

where, erf is the error function and OSNR is the signal to noise ratio in absolute value.

SIMULATION RESULTS AND DISCUSSION

In the analysis of the results, we have investigated the new trends of fiber Raman amplification in DWDM photonic communication networks under the set of affecting operating parameters are shown in Table 1.

Based on the set of Fig. 2-19, the following facts and obtained features are assured as follows: Figure 2 and 3 have assured that as fiber link length increases, this results in decreasing in pumping power that leads to

Table 1: The suggested operating parameters in DWDM photonic networks

Operating parameters	Symbol	Values
Operating signal wavelength	λ_s	1.45-1.65 μm
Ambient temperature	T	300-340 K
Room temperature	T_0	300 K
Channel spacing	$\Delta\lambda_s$	0.1-0.8 nm
Pumping wavelength	λ_p	1.4-1.55 μm
Signal attenuation	α_s	0.2-0.5 dB km^{-1}
Pump attenuation	α_p	0.35 dB km^{-1}
Pumping power	P_p	0.25-0.5 W/pump
Transmitted signal power	$P_s = P_T$	2-20 mW
Effective area	A_{eff}	85 μm^2
Raman gain coefficient	g_0	0.7 Watt. km^{-1}
Relative refractive-index difference	Δn	0.003-0.009
Fiber link length	L	100-1000 km
Number of transmitted channels	N_{ch}	100-1000 channel
On-off Raman gain	G_A	5-50 dB
Noise figure	NF	2-5 dB

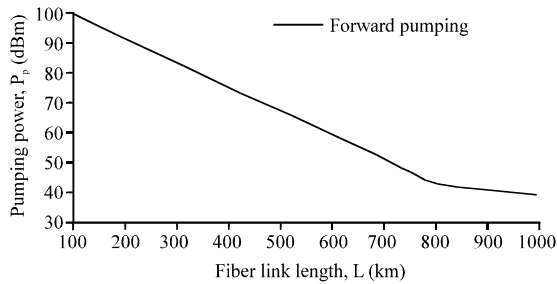


Fig. 2: Variations of the pumping power against the fiber link length at the assumed set of parameters

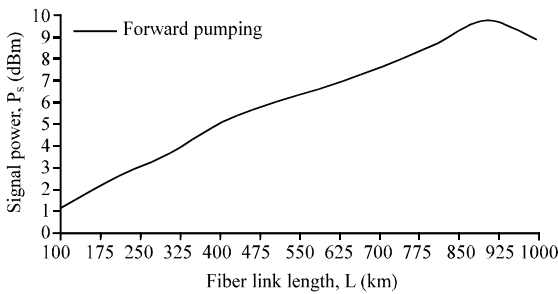


Fig. 3: Variations of the signal power against the fiber link length at the assumed set of parameters

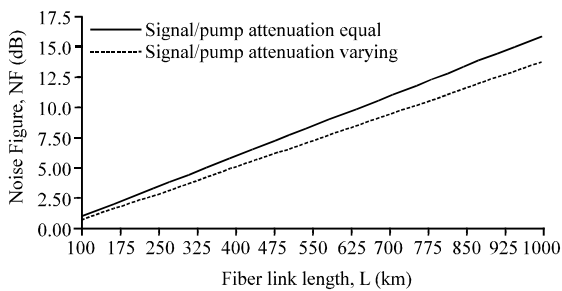


Fig. 4: Variations of noise figure against the fiber link length at the assumed set of parameters

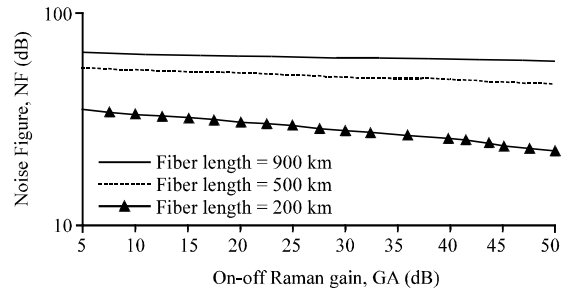


Fig. 5: Variations of noise figure with the on-off Raman gain at the assumed set of parameters

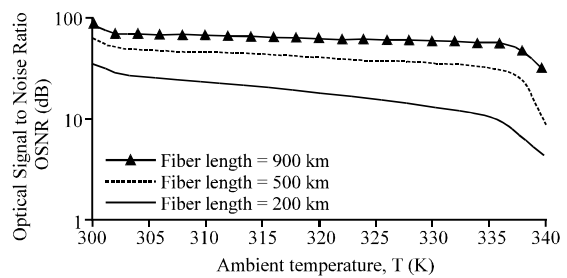


Fig. 6: Variations of the optical signal to noise ratio versus ambient temperature at the assumed set of parameters

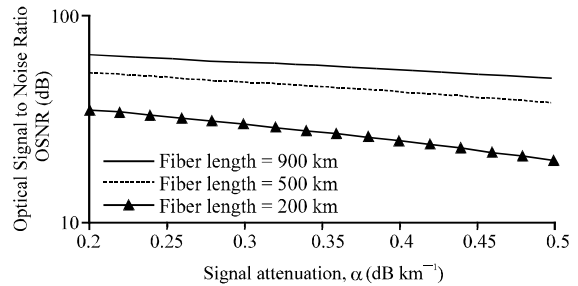


Fig. 7: Variations of the optical signal to noise ratio versus signal attenuation at the assumed set of parameters

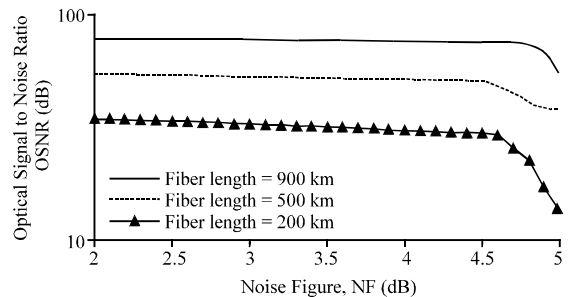


Fig. 8: Variations of the optical signal to noise ratio versus noise figure at the assumed set of parameters

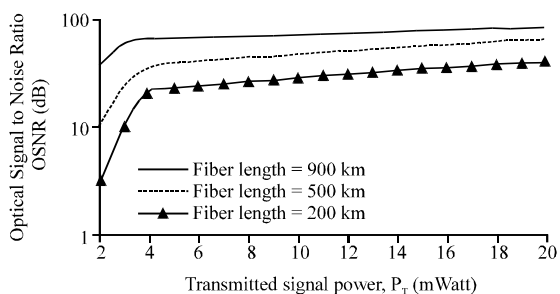


Fig. 9: Variations of the optical signal to noise ratio against signal power at the assumed set of parameters

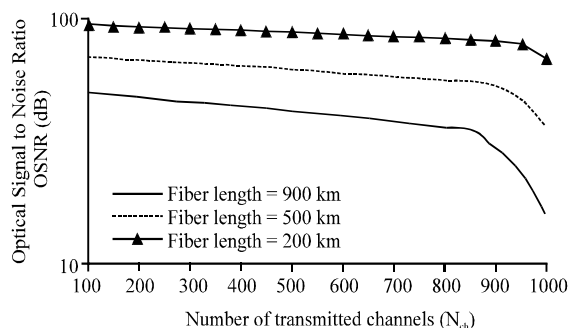


Fig. 12: Variations of the signal to noise ratio against number of transmitted channels at the assumed set of parameters with amplification

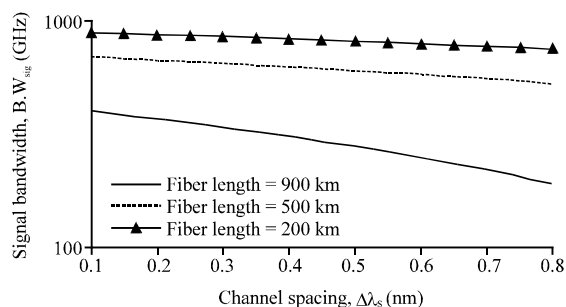


Fig. 10: Variations of the signal bandwidth against channel spacing at the assumed set of parameters with amplification

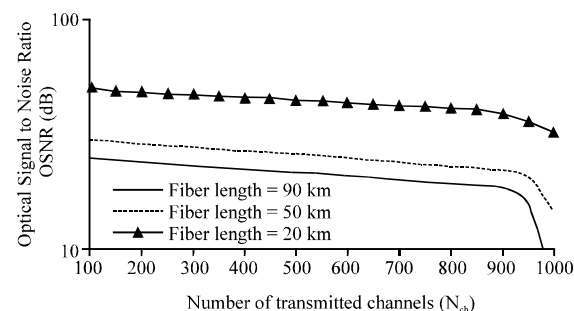


Fig. 13: Variations of the signal to noise ratio against number of transmitted channels at the assumed set of parameters without amplification

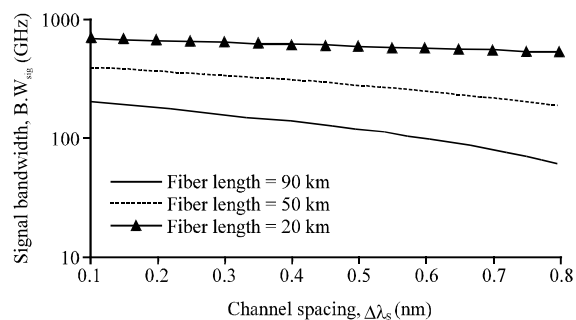


Fig. 11: Variations of the signal bandwidth against channel spacing at the assumed set of parameters without amplification

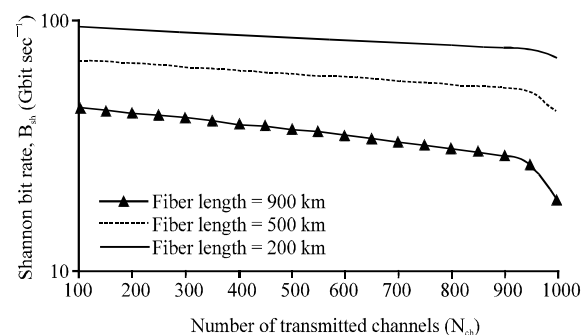


Fig. 14: Variations of Shannon bit rate against number of transmitted channels at the assumed set of parameters with amplification

increase in signal power. Figure 4 has demonstrated that as the fiber link length increases this leads to increase in noise figure. As well as at signal pump⁻¹ attenuation equal presents higher noise figure than signal pump⁻¹ attenuation varying. Figure 5 has proved that as on-off Raman gain increases this leads to decrease in noise figure at constant fiber link length. Moreover as fiber link length increases this results in increasing in noise figure.

In the series of Fig. 6-9 have indicated that as ambient temperature, signal attenuation and noise figure increase, this result in decreasing optical signal to noise ratio at constant fiber link length. But as both fiber link length and transmitted signal power increase, this lead to increase in optical signal to noise ratio.

As shown in Fig. 10 and 11 have assured that as channel spacing increases this results in decreasing in

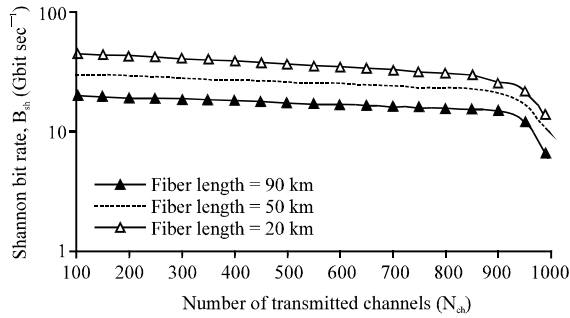


Fig. 15: Variations of Shannon bit rate against number of transmitted channels at the assumed set of parameters without amplification

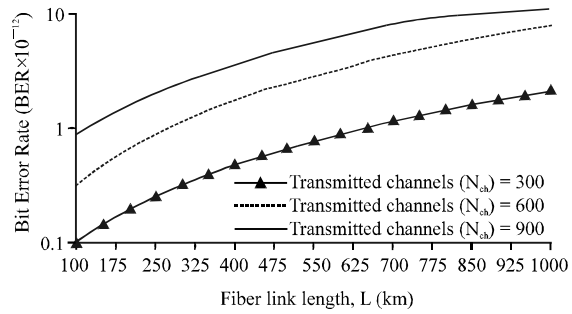


Fig. 18: Variations of received bit error rate against fiber link length at the assumed set of parameters with amplification

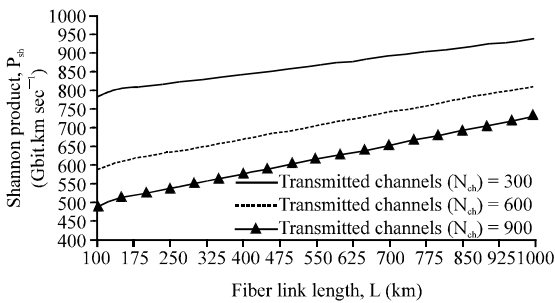


Fig. 16: Variations of Shannon bit rate-distance product versus fiber link length at the assumed set of parameters with amplification

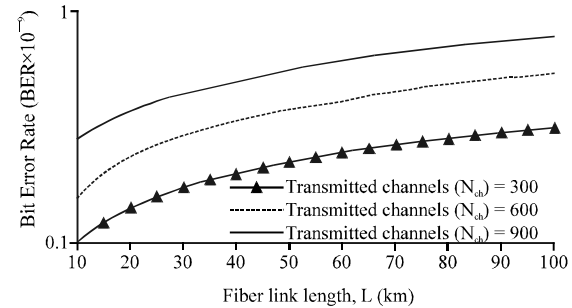


Fig. 19: Variations of received bit error rate against fiber link length at the assumed set of parameters without amplification

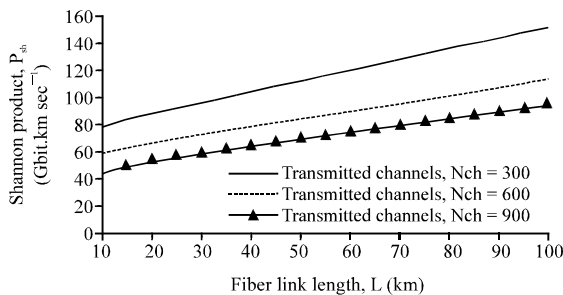


Fig. 17: Variations of Shannon bit rate-distance product versus fiber link length at the assumed set of parameters without amplification

signal bandwidth at constant fiber link length. With forward Raman amplification technique presents both higher fiber link length and signal bandwidth than without amplification case. As shown in Fig. 12-15 have demonstrated that as number of transmitted channels increases this result in decreasing in both optical signal to noise ratio and Shannon bit rate at constant fiber link length. With forward Raman amplification technique presents higher fiber link length, optical signal to noise ratio and Shannon bit rate than without amplification case.

As shown in Fig. 16-19 have assured that as fiber link length increases this results in increasing in both Shannon bit rate-distance product and bit error rate at constant number of transmitted channels. With forward Raman amplification technique presents higher Shannon bit rate-distance product than and lower bit error rate without amplification case.

CONCLUSION

In the study, researchers have been investigated and modeled forward Raman gain amplification technique for DWDM photonic networks over wide range of the affecting parameters. It is observed that the increased fiber link length, the increased of both signal power and noise figure and the decreased pumping power. As well as the increased on-off Raman gain, the decreased noise figure.

Moreover, the decreased ambient temperature, signal attenuation and noise figure, the increased Optical Signal to Noise Ratio (OSNR). The increased of both transmitted signal power and fiber link length, the

increased OSNR. With forward Raman amplification presents higher fiber link length, signal bandwidth, Shannon bit rate, OSNR, Shannon bit rate-distance product and the lower Bit Error Rate (BER) without amplification case.

REFERENCES

- Chen, C.J. and W.S. Wong, 2001. Transient effects in saturated Raman amplifiers. *Electr. Lett.*, 37: 371-373.
- Felinskyi, G.S. and P.A. Korotkov, 2008. Raman threshold and optical gain bandwidth in silica fibers. *J. Semiconductor Phys. Quantum Electr. Optoelectronics*, 11: 360-363.
- Fugihara, M.C. and A.N. Pinto, 2008. Low-cost Raman amplifier for CWDM systems. *Microwave Optical Technol. Lett.*, 50: 297-301.
- Gest, J. and L.R. Chen, 2007. Impact of the all-optical gain-clamping technique on the transience characteristics of cascaded discrete fiber Raman amplifiers. *Optics Commun.*, 273: 138-148.
- Jordanova, L.T. and V.I. Topchiev, 2008. Improvement of the optical channel noise characteristics using distributed Raman amplifiers. *ICEST*, 12: 20-23.
- Karasek, M. and M. Menif, 2002. Channel addition/removal response in Raman fiber amplifiers: Modeling and experimentation. *J. Lightwave Technol.*, 20: 1680-1687.
- Karasek, M., J. Kanka, P. Honzatko and P. Peterka, 2004. Time-domain simulation of power transients in Raman fibre amplifiers. *Int. J. Numerical Modell.: Electr. Networks Devices Fields*, 17: 165-176.
- Lee, B.G., A. Biberman, A.C. Turner-Foster, M.A. Foster, M. Lipson, A.L. Gaeta and K. Bergman, 2009. Demonstration of broadband wavelength conversion at 40 Gb/s in silicon waveguides. *IEEE Photonics Technol. Lett.*, 21: 182-184.
- Mohammed, A.E.N.A., A.E.F.A. Saad and A.N.Z. Rashed, 2009e. High channel Arrayed Waveguide Grating (AWG) in wavelength division multiplexing passive optical networks (WDM-PONs). *Int. J. Comp. Sci. Network Security*, 9: 253-259.
- Mohammed, A.E.N.A., A.E.F.A. Saad and A.N.Z. Rashed, 2009d. Matrices of the thermal and spectral variations for the fabrication materials based arrayed waveguide grating (awg) devices. *Int. J. Phys. Sci.*, 4: 205-211.
- Mohammed, A.E.N.A., A.E.F.A. Saad and A.N.Z. Rashed, 2009c. Thermal sensitivity coefficients of the fabrication materials based a thermal Arrayed Waveguide Grating (AWG) in wide area dense wavelength division multiplexing optical networks. *Int. J. Eng. Technol.*, 1: 131-139.
- Mohammed, A.E.N.A., A.E.F.A. Saad, A.N.Z. Rashed and M.M.A. Eid, 2009f. Characteristics of multi-pumped Raman amplifiers in Dense Wavelength Division Multiplexing (DWDM) optical access networks. *Int. J. Comp. Sci. Network Security*, 9: 277-284.
- Mohammed, A.E.N.A., A.N.Z. Rashed, G.E.S.M. El-Abyad and A.E.F.A. Saad, 2009a. High transmission bit rate of a thermal arrayed waveguide grating (AWG) module in passive optical networks. *Int. J. Comp. Sci. Inform. Security*, 1: 13-21.
- Mohammed, A.E.N.A., M.M.E. El-Halawany, A.N.Z. Rashed and M.M.A. Eid, 2009b. Recent applications of optical parametric amplifiers in Hybrid WDM/TDM local area optical networks. *Int. J. Comp. Sci. Inform. Secur.*, 3: 14-24.
- Nicholson, J.W., 2003. Dispersion compensating Raman amplifiers with pump reflectors for increased efficiency. *J. Lightwave Technol.*, 21: 1758-1762.
- Raghuwanshi, S.K., V. Gupta, V.K. Dinesh and S. Talabattula, 2006. Bi-directional optical fiber transmission scheme through Raman amplification: Effect of pump depletion. *J. Indian Inst. Sci.*, 86: 655-665.
- Wasfi, M., 2009. Optical fiber amplifiers review. *Int. J. Commun. Networks Inform. Security*, 1: 42-47.