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Efficient Raman Amplifiers within Propagation and Multiplexing Techniques for High Capacity and Ultra Long Haul Transmission Systems

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***Abstract*— Optical amplifiers are key elements of any fiber-optic communication system. Even though modern optical fibers have losses below 0.2 dB/km, a repeated amplification of the transmitted signal to its original strength becomes necessary at long enough distances. 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. This paper has proposed the investigation of the soliton and MTDM techniques to be processed to handle both bit rate and product either per link or per channel for cables of multi-links (40-240 links/core). Two multiplexing techniques are applied, ultra wide wavelength division multiplexing (UW-WDM) and ultra wide space division multiplexing (UW-SDM), where maximum number of transmitted channels is processed to handle the product of bit rate either per channel or per link for cables of multi-links. The soliton and MTDM transmission bit rates and products either per link or per channel are also treated over wide range of the affecting parameters. The amplification process is essentially independent of the details of the spectral channel layout, modulation format or data rate of the transmission.**

***IndexTerms*— Optical Fiber Communication, High Transmission Capacity, Fiber Raman Amplifier, Long Transmission Distances Multiplexing Techniques and Propagation Techniques**

I. INTRODUCTION

THE technology of wavelength-division multiplexing (WDM) has recently resulted in a considerable increase in the transmission capacity of fiber optic communication systems up to several terabits per second [1]. 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. Raman fiber amplifiers (RFAs) hold much promise for telecommunication systems [2], since they can operate within the transparency window of optical fibers with a practically arbitrary wavelength. Therefore, it is of considerable interest to analyze the ways of optimizing the type of optical fibers for RFAs operating within different spectral ranges. Single-mode optical fibers with a high content of germanium in the core offer much promise for discrete Raman fiber amplifiers. Such optical fibers allow the pump power and the length of the employed fiber segment to be minimized. On the other hand, it seems quite natural to consider standard communication optical fibers as possible elements for distributed Raman amplifiers [3].

In an optical communication system, the optical signals from the transmitter are attenuated by the optical fiber as they propagate through it. Also multiplexers and couplers (and other optical components) add loss [4]. The cumulative loss of signal strength causes the signal to become too weak to be detected. So the signal strength must be restored, before this happens. Before optical amplifiers, the only option was to regenerate the signal. So the signal is received and then retransmitted. This process is accomplished by regenerators. First the regenerator converts the optical signal to an electrical signal, then regenerator cleans the signal and finally regenerator converts the signal back into an optical signal for onwards transmission. Because of all this, optical amplifiers have become essential components in high performance optical communication systems [5]. There are though some downsides in amplifiers. They introduce additional noise, and this noise accumulates as the signal passes through multiple amplifiers along its path because of the analog nature of the amplifier. The spectral shape of the gain, the output power, and the transient behavior of the amplifier are also important considerations for system applications. Also the gain should be flat over the operating wavelength range and the gain should be insensitive to variations in input power of the signal [6].

In the present study, we have investigated deeply the different transmission techniques such as soliton and maximum time division multiplexing with distributed Raman amplification technique to handle the bit rates and products either per link or per channel to improve the capacity of optical communication systems over wide range of the affecting parameters. Also, two multiplexing techniques are taken in to account such as UW-WDM and UW-SDM in order to increase total number of transmitted channels and then to increase number of subscribers in high capacity and ultra long distance transmission in optical communication systems.

II. SYSTEM MODEL AND ANALYSIS

It is assumed that the power of the first pump source is SP_P and the second source pump is $(1\text{-}S)\ P_P$ respectively, where P_P is the pump power and S is a coefficient showing the power that is being pumped in the signal direction. The evolution of the signal power (P_s) and the power of the pump source propagating along the standard single mode optical fiber can be quantitatively described by different equations called propagation equations [7]:

$$\pm\frac{dP_P}{dz}=-\frac{\nu_P}{\nu_S}g_R\,P_P P_S-\alpha_P P_P \quad , \tag{1}$$

$$\frac{dP_S}{dz}=g_R\,P_P P_S-\alpha_S P_S \quad , \tag{2}$$

Where g_R 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, ν_S and ν_P are the optical signal and pump frequencies. The signs of "+" or "-" are corresponding to forward and backward pumping. In the general case, when a bi-directional pumping [9] is used (S =0-1) the laser source work at the same wavelength at different pump power. To calculate the pump power at point z it can be used for forward and backward direction configurations as discussed efficiently in Ref. [8]. With P_0 being the pump power at the input end. Hence the signal intensity at output of amplifier, fiber length L is determined by the following expression [9]:

$$P_S(L)=P_S(0)\exp\left(\frac{g_R\,P_0\,L_{eff}}{A_{eff}}-\alpha_S\,L\right) \quad , \tag{3}$$

The maximum allowed transmit power per channel, as a function of fiber cable length can be expressed [10]:

$$P_T\approx\frac{40000}{N_{ch}(N_{ch}-1)\Delta\lambda_S\,L} \quad , \tag{4}$$

Where N_{ch} be the number of transmitted channels, $\Delta\lambda_S$ be the channel spacing in nm, and L is to be the length of the fiber cable link in km.

III. DIFFERENT PROPAGATION TECHNIQUES

A. Soliton propagation technique

The term soliton has recently been coined to describe a pulse-like non-linear wave having unchanged shape and speed. In an ideal lossless medium, the soliton would have also the same amplitude during propagation. The balance between the non-linearity effects from one side and the dispersion effects from the other side creates a solitary wave. The dispersion of a medium (in the absence of non-linearity) makes the various frequency components propagate at different velocities; while the non-linearity (in the absence of dispersion) causes the pulse energy to be continually injected, via harmonic generation, into higher frequency modes. That is to say, the dispersion effect results in broadening the pulse while the non-linearity tends to sharpen it. The main types of soliton are the bright (light) soliton and the dark soliton. The standard single mode optical fiber cable is made of the silica material which the investigation of the spectral variations of the waveguide refractive-index require equation under the form [11]:

$$n^2=1+\frac{S_1\lambda^2}{\lambda^2-S_2^2}+\frac{S_3\lambda^2}{\lambda^2-S_4^2}+\frac{S_5\lambda^2}{\lambda^2-S_6^2} \tag{5}$$

The parameters of Sellmeier equation coefficients for silica material, as a function of ambient temperature as: S_1= 10.668422193, S_2= 0.0301516485 $(T/T_0)^2$, S_3= 3.043474218x 10^{-3}, S_4= 1.1347511235 $(T/T_0)^2$, S_5= 1.54133408, S_6= 1.104x10^3. Where T is the ambient temperature in °C, and T_0 is the room temperature. The second differentiation of empirical equation w. r. t λ as discussed in Ref. [12]. The total bandwidth is based on the total chromatic dispersion coefficient D_t where: D_t= D_m + D_w. Both D_m, and D_w are given by (for the fundamental mode):

$$D_m=-\frac{\lambda}{c}\left(\frac{d^2n}{d\lambda^2}\right), \quad n\sec/nm.km \tag{6}$$

$$D_W=-\left(\frac{n_{cladding}}{c\,n}\right)\left(\frac{\Delta n}{\lambda}\right)Y \ , \quad n\sec/nm.km \tag{7}$$

Where c is the velocity of the light, 3 x 10^8 m/sec, n is the refractive-index of the fiber cable core, Y is a function of wavelength, the relative refractive-index difference Δn is given by the following expression:

$$\Delta n=\frac{n-n_{clad}}{n} \quad , \tag{8}$$

In any infinitesimal segment of fiber, dispersion on one hand and non linearity of the refractive-index on the other hand produce infinitesimal modulation angles which exactly compensate reciprocally. In the sense that their sum is an irrelevant constant phase shift. Under such conditions the pulse shape is the same everywhere. All this provided that a soliton waveform be used with a peak power [12]:

$$P_1=\frac{\Delta\lambda^3 D_t A_{eff}}{4\pi^2 c\,n_2\,t_0^2} \ , \tag{9}$$

Where n_2 is the nonlinear Kerr coefficient, 2.6 x 10^{-20} m^2/Watt, Δλ is the spectral line width of the optical source in nm, P_1 is the peak power in watt, A_{eff} is the effective area of the cable core fiber in μm^2, D_t is the total chromatic dispersion coefficient in nsec/nm.km. Then the pulse intensity width in nsec is given by:

$$t_0=\sqrt{\frac{\Delta\lambda^3 D_t\,A_{eff}}{4\pi^2\,P_1\,n_2\,c}} \ , \quad n\sec \tag{10}$$

Then the Soliton transmission bit rate per channel is given as follows [13]:

$$B_{rsc}=\frac{1}{10t_0}=\frac{0.1}{t_0}, \quad Gbit/\sec/channel \tag{11}$$

Then the Soliton transmission bit rate/link is given:

$$B_{rsl}=\frac{0.1\ N_L}{t_0}, \quad Gbit/\sec/link \tag{12}$$

Also in the system model analysis, the transmitted channels per link is given by the following:

$$\Delta N_{ch}=\frac{N_{ch}}{N_L} \quad , \tag{13}$$

Where N_L is the total number of links in the fiber cable core, and N_{ch} is the total number of channels. The available soliton transmitted bit rate B_{rs} is compared as the fiber cable length, L, and consequently the soliton product P_{rsc} per channel is computed as the following expression:

$$P_{rsc}=B_{rsc}\ L \ , \tag{14}$$

Also, in the same way, the soliton product P_{rsl} per link is computed as the following expression:

$$P_{rsl}=B_{rsl}\ \ L \ , \tag{15}$$

B. MTDM Propagation Technique

To achieve a high data transmission bit rate in the telecommunication field is the goal of UW-WDM technology. The maximum bit rates are determined by numerous factors, including the signal modulation rate, the transmission bandwidth through the transmission media, and the response time of the optoelectronic devices. In optical communication systems, the UW-WDM system is simply one part of the transmission regime. The pulse broadening of grating-based UW-WDM imposes inherent limitations on the data transmission bit rates. According to our assumption that the standard single mode optical fiber cable is made of the pure silica material which the investigation of the spectral variations of the waveguide refractive-index (n) is shown in Eq. (5), Then the first and third differentiation of Eq. (5) w. r. t λ as discussed in Ref. [12]. The total chromatic dispersion in standard single mode fiber (SSMF) that limits the transmission bit rates in system based UW-WDM communication can be calculated as follows [14]:

$$D_t = \frac{\Delta\tau}{\Delta\lambda.\ L} = -\left(M_{md} + M_{wd}\right),\ n\sec/\,nm.km \qquad (16)$$

Where M_{md} is the material dispersion coefficient in nsec/nm.km, M_{wd} is the waveguide dispersion coefficient in nsec/nm.km, Δτ is the total pulse broadening due to the effect of total chromatic dispersion, Δλ is the spectral linewidth of the used optical source in nm, and L is the fiber cable length in km. The material dispersion coefficient is given as:

$$M_{md} = -\frac{\lambda_s}{c}\frac{d^2n}{d\lambda^2} - \frac{\Delta\lambda}{2c}\left(\lambda\frac{d^3n}{d\lambda^3} + \frac{d^2n}{d\lambda^2}\right), \qquad (17)$$

The waveguide dispersion coefficient is given by the following expression:

$$M_{wd} = -n_{cladding}\left(\frac{\Delta n}{c\,\lambda_s}\right)F(V), \qquad (18)$$

Where n_{clad} is the refractive-index of the cladding material, Δn is the relative refractive-index difference, λ_s is the optical signal wavelength, F (V) is a function of V number or normalized frequency. Based on the work [16], they designed the function F (V) is a function of V as follows:

$$F(V) = 1.38V - 6.98V^2 + 13.45V^3 - 4.84V^4 - 1.48V^5\ , \qquad (19)$$

When they are employing V-number in the range of (0 ≤ V ≤ 1.15) yields the above expression. In our simulation model design, we are taking into account V-number as unity to emphasis single mode operation. The MTDM transmission bit rate per channel can be expressed as follows [15]:

$$B_{rmc} = \frac{1}{4\Delta\tau} = \frac{0.25}{\Delta\tau}, \qquad (20)$$

Then the MTDM transmission bit rate per link is given as:

$$B_{rml} = \frac{0.25\ N_{link}}{\Delta\tau}, \qquad (21)$$

The available MTDM transmitted bit rate B_{rm} is compared as the fiber cable length, L, and consequently the MTDM product P_{rmc} per channel is computed as:

$$P_{rmc} = B_{rmc}\ L\ , \qquad (22)$$

Also, in the same way, the MTDM product P_{rml} per link is computed as the following expression [16]:

$$P_{rml} = B_{rml}\ \ L\ , \qquad (23)$$

IV. SIMULATION RESULTS AND DISCUSSIONS

In the analysis of our results, we have deeply investigated the different transmission techniques with distributed Raman amplification for allowing high capacity and long distance transmission communication systems in the interval of 1.45 μm to 1.65 μm under the set of controlling parameters of temperature ranges varied from (25 °C-45 °C). The following set of the numerical data of our simulation system model design are employed to obtain the high capacity and long distance transmission for wired optical communication networks within different transmission and propagation techniques with distributed Raman amplification technique as the following operating parameters: 1.5 ≤ λ_{si}, optical signal wavelength, μm ≤ 1.65, 1.4 ≤ λ_p, pumping wavelength, μm ≤ 1.55, α_{si}=0.2 dB/km, α_P=0.35 dB/km, Pumping power: P_P= 0.25 Watt/pump, 4 ≤ P_{si}, optical signal power, mwatt ≤ 30, A_{eff}= 85 μm^2, N_L: total number of links up to 240 links, $\Delta\lambda_s$ =0.25 nm, 0.001 ≤ Δn, relative refractive-index difference ≤ 0.009, N_t: total number of channels up to 6000 channels, n_2= 1.445, Raman gain coefficient: g_R=0.75 W^{-1}. km^{-1}.

Based on the set of Figs (1-12), the following facts and obtained features are assured to present the high capacity and long haul transmission optical communication networks within transmission, propagation, multiplexing and amplification techniques as the following:

i) As shown in Figs. (1, 2), both soliton and MTDM bit rates per channel increase as the optical signal wavelength increases at the same relative refractive-index difference (Δn). But as Δn increases, both soliton and MTDM bit rates per channel decrease at the same optical signal wavelength. While we can find that soliton transmission technique yields higher bit rate/channel than MTDM transmission technique at the same relative refractive-index difference, Δn.

ii) Figs. (3, 4) have indicated that as the number of links in the fiber cable core increases, both soliton and MTDM bit rates per link increase at the same number of transmitted channels. But as number of transmitted channels increases, both soliton and MTDM bit rates/link decrease at the same number of links in the fiber cable core. Moreover, we can conclude that soliton transmission technique yields higher bit rate/link than MTDM transmission technique at the same number of transmitted channels.

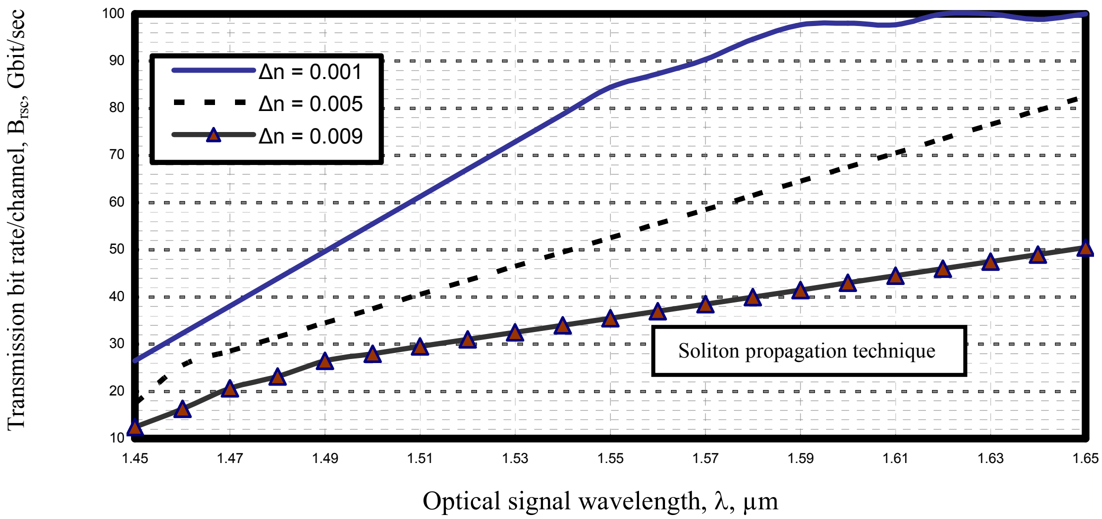

Fig. 1. Variations of the soliton bit rate per channel with the optical signal wavelength at the assumed set of parameters.

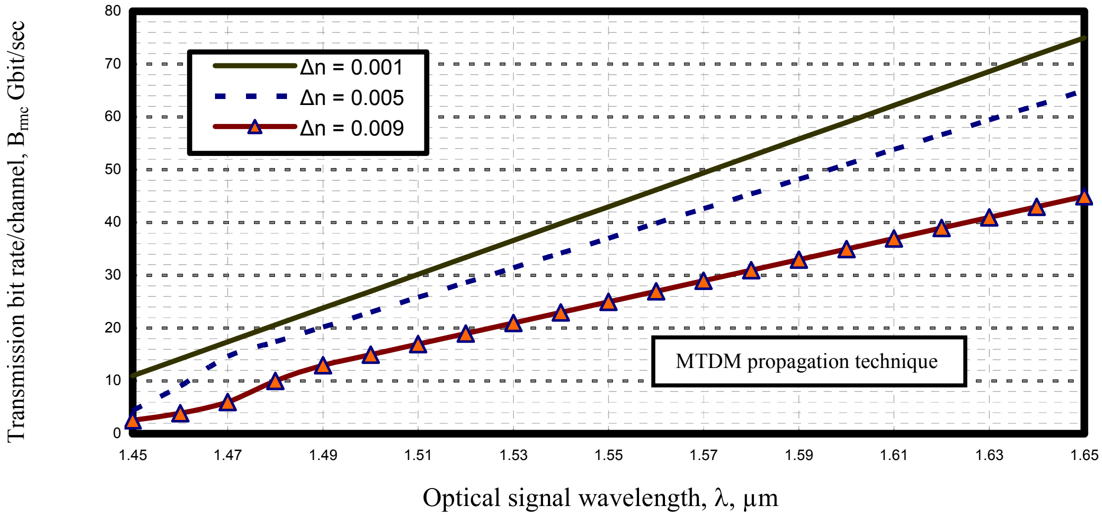

Fig. 2. Variations of the MTDM bit rate per channel with the optical signal wavelength at the assumed set of parameters.

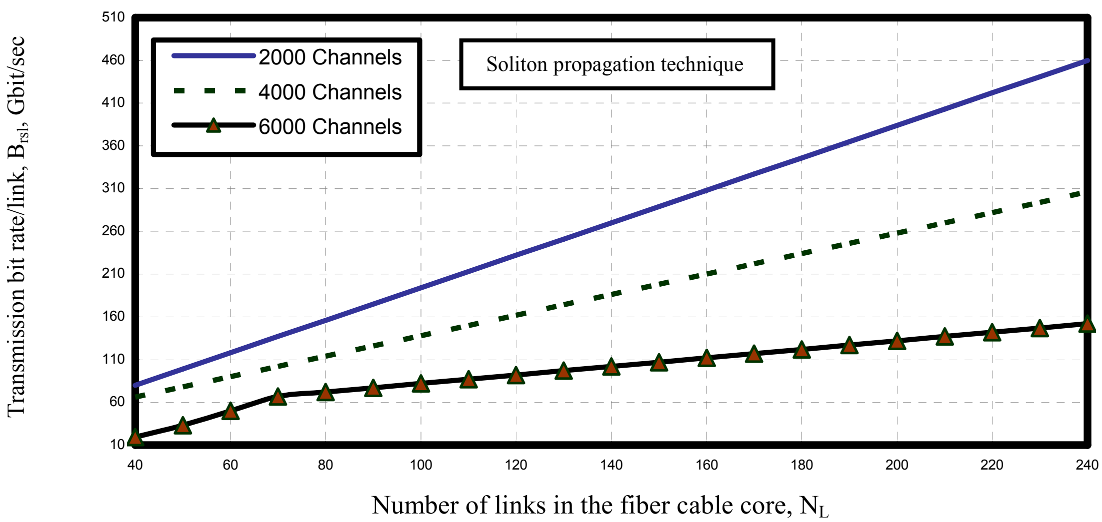

Fig. 3. Variations of the soliton bit rate per link with the number of links in the fiber cable core at the assumed set of parameters.

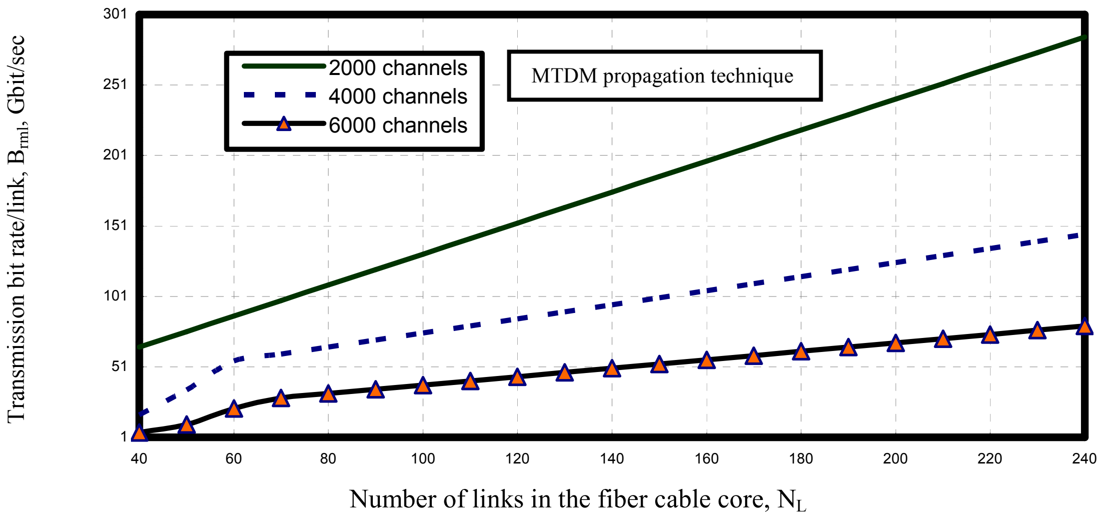

Fig. 4. Variations of the MTDM bit rate per link with the number of links in the fiber cable core at the assumed set of parameters.

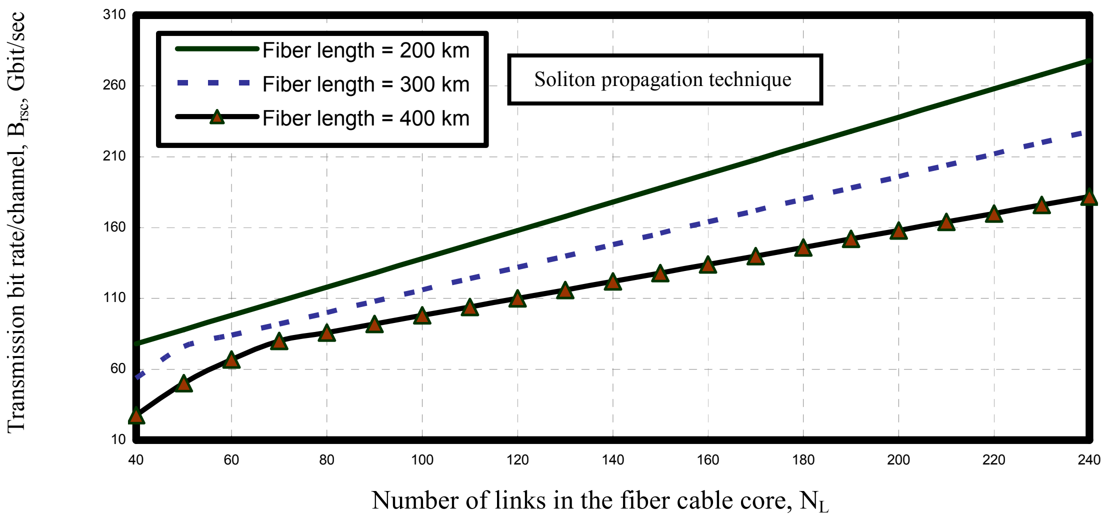

Fig. 5. Variations of the soliton bit rate per channel with the number of links in the fiber cable core at the assumed set of parameters.

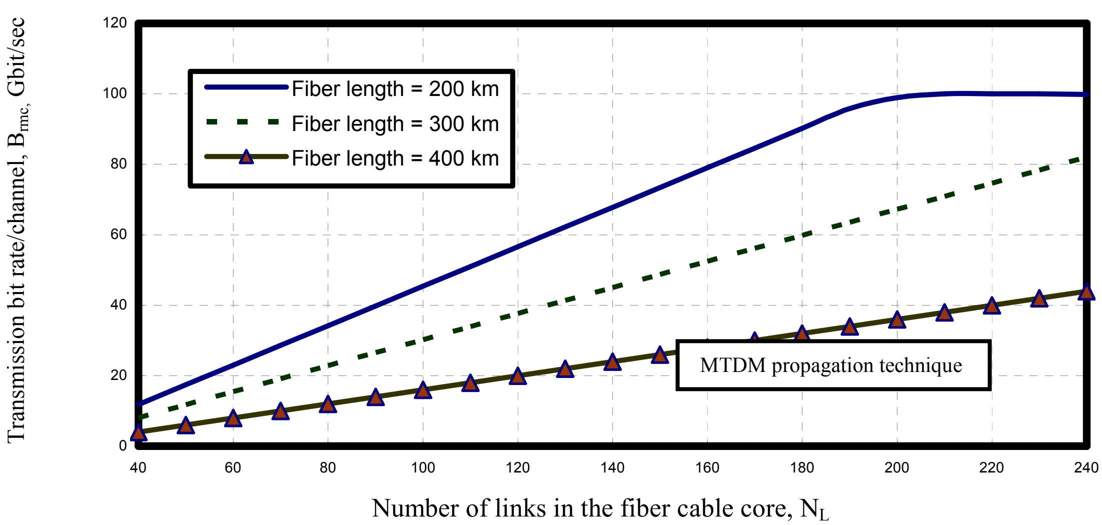

Fig. 6. Variations of the MTDM bit rate per channel with the number of links in the fiber cable core at the assumed set of parameters.

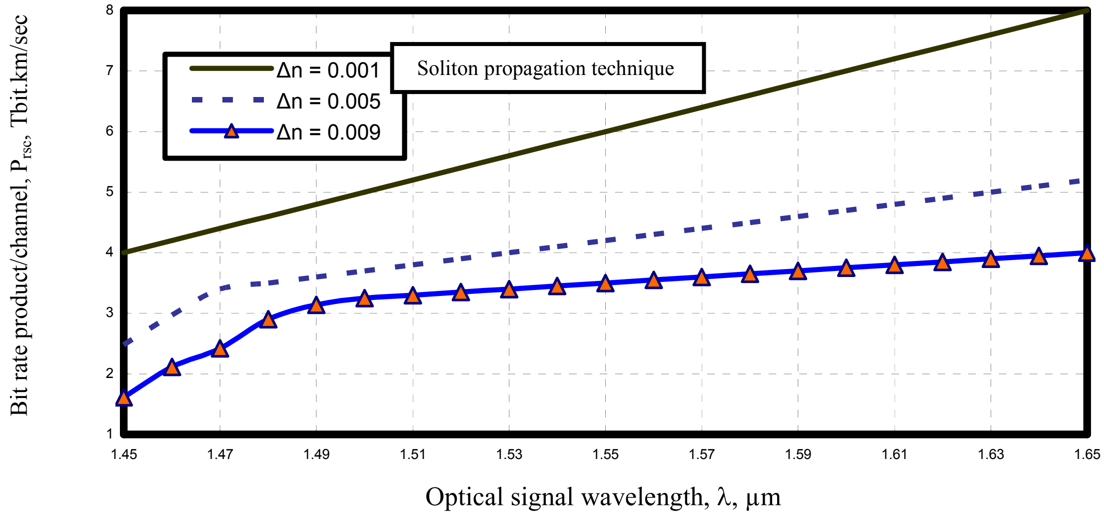

Fig. 7. Variations of the soliton product per channel with the optical signal wavelength at the assumed set of parameters.

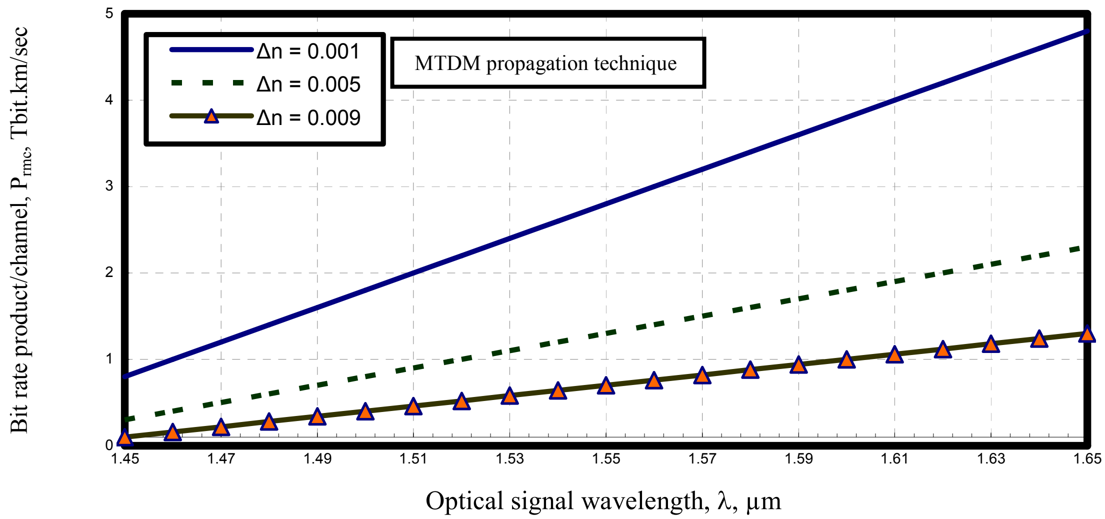

Fig. 8. Variations of the MTDM product per channel with the optical signal wavelength at the assumed set of parameters.

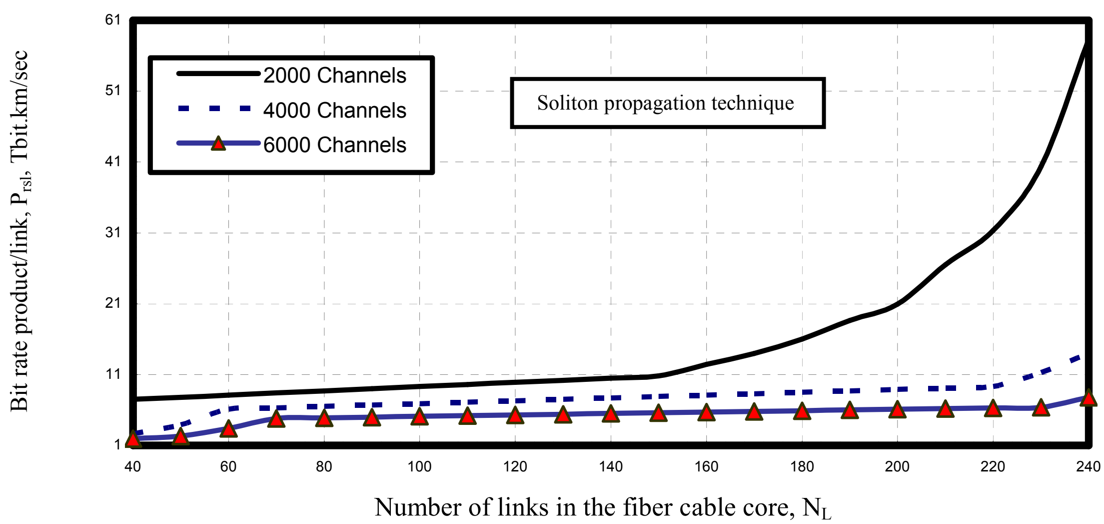

Fig. 9. Variations of the soliton product per link with the number of links in the fiber cable core at the assumed set of parameters.

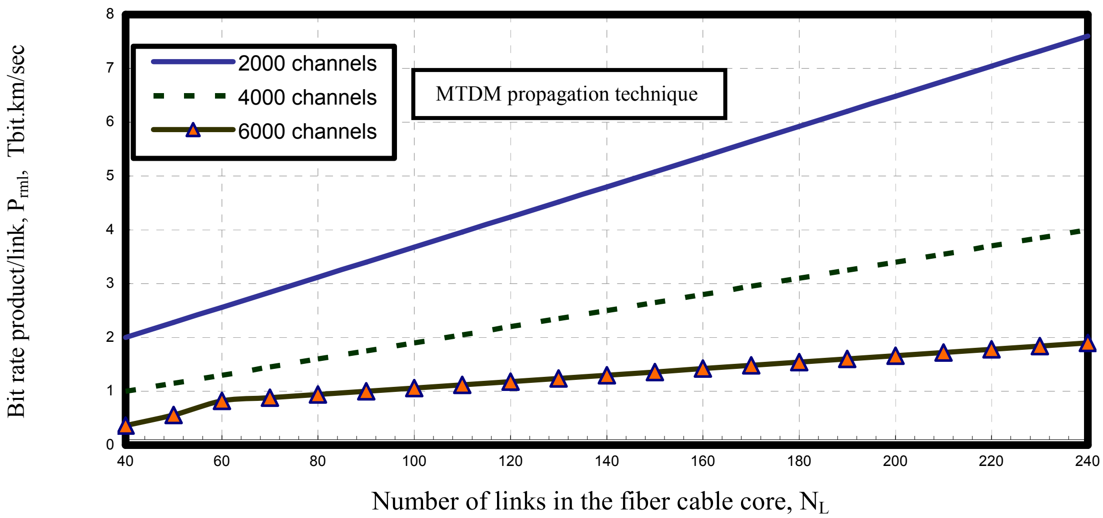

Fig. 10. Variations of the MTDM product per link with the number of links in the fiber cable core at the assumed set of parameters.

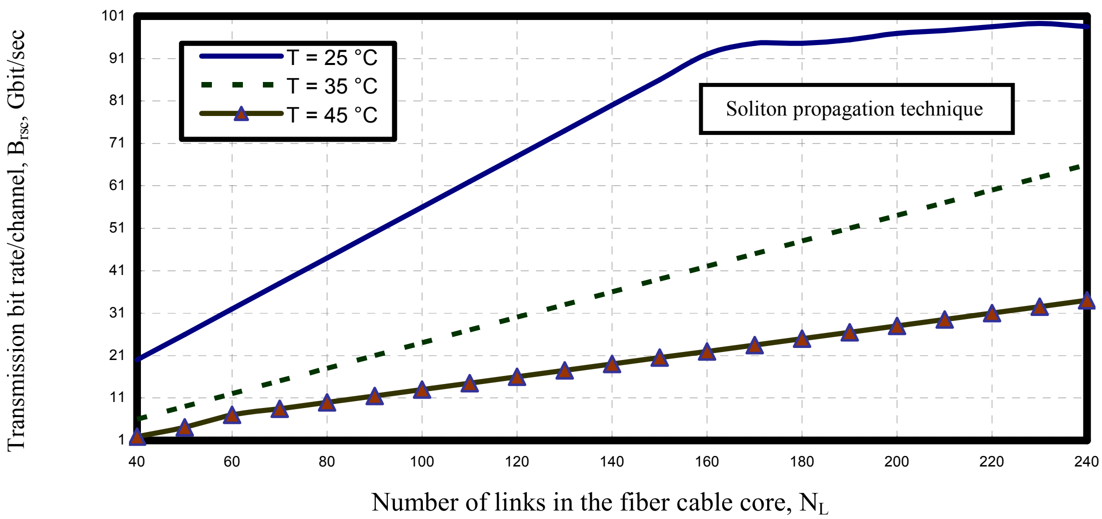

Fig. 11. Variations of the soliton bit rate per channel with the number of links in the fiber cable core at the assumed set of parameters.

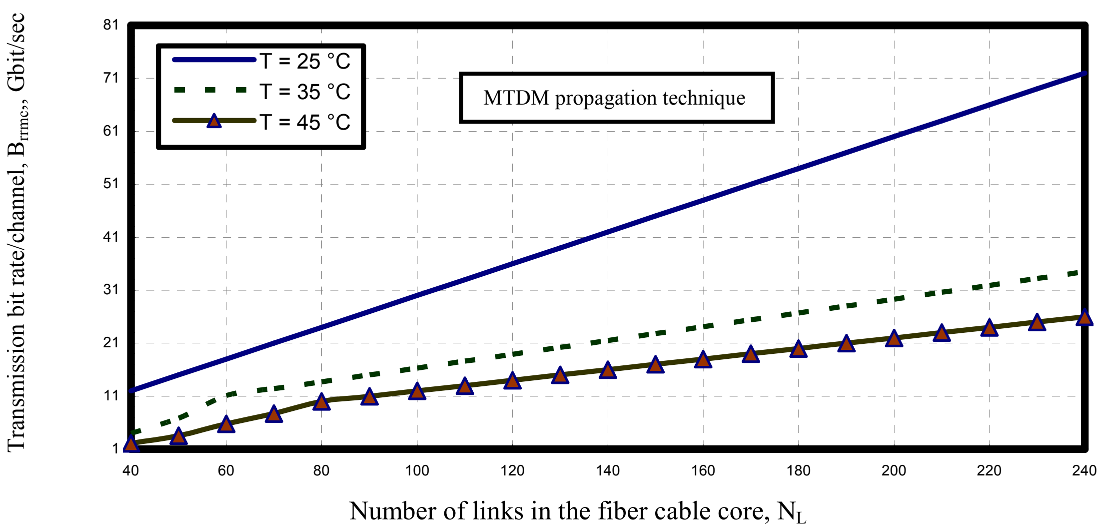

Fig. 12. Variations of the MTDM bit rate per channel with the number of links in the fiber cable core at the assumed set of parameters.

iii) Figs. (5, 6) have assured that as the number of links in the fiber cable core increases, both soliton and MTDM bit rates per channel increase at the same fiber cable length. But as the fiber cable length increases, both soliton and MTDM bit rates/channel decrease at the same number of links in the fiber cable core. Moreover, we can find that soliton transmission technique yields higher bit rate/channel than MTDM transmission technique at the same fiber cable length.

iv) As shown in Figs. (7, 8), both soliton and MTDM products per channel increase as the optical signal wavelength increases at the same relative refractive-index difference (Δn). But as Δn increases, both soliton and MTDM products per channel decrease at the same optical signal wavelength. While we can find that soliton transmission technique yields higher product/channel than MTDM transmission technique at the same relative refractive-index difference, Δn.

v) Figs. (9, 10) have indicated that as the number of links in the fiber cable core increases, both soliton and MTDM products per link increase at the same number of transmitted channels. But as number of transmitted channels increases, both soliton and MTDM products/link decrease at the same number of links in the fiber cable core. Moreover, we can conclude that soliton transmission technique yields higher product/link than MTDM transmission technique at the same number of transmitted channels.

vi) As shown in Figs. (11, 12), both soliton and MTDM bit rates per channel increase as the number of links in the fiber cable core increases at the same ambient temperature (T). But as ambient temperature (T) increases, both soliton and MTDM bit rates per channel decrease at the same fiber cable length. While we can find that soliton transmission technique yields higher bit rate/channel than MTDM transmission technique at the same ambient temperature.

V. CONCLUSIONS

The fiber Raman optical amplifier is quickly emerging as an important part of long distance, high capacity, and high speed optical communication systems. The decreasing cost of high power semiconductor lasers and the increasing need in optical fiber transmission for more gain bandwidth, lower gain ripple, and lower noise figures make Raman amplifiers a more attractive technology than the traditional erbium doped fiber amplifier. we have developed the different transmission techniques within distributed Raman optical amplifiers for upgrading high capacity and long haul transmission telecommunication systems. It is found theoretically and demonstrated that the lower number of transmitted channels, ambient temperature and relative refractive-index difference, the higher soliton and MTDM bit rates and products either per link or per channel at the same optical signal wavelength, and number of links in the fiber cable core. Moreover, we have assured that the increased fiber cable length, the higher soliton and MTDM product either per link or per channel at the same relative refractive-index difference. It is theoretically found for the complete analysis that the nature of the Raman effect in conventional silica glass fibers results in the fact that the peak of the relatively broad gain contour of stimulated Raman scattering depends only on the pump wavelength, not on the fiber dopant. It is evident from simulation results that the soliton transmission technique has presented higher bit rates and products either per link or per channel than MTDM transmission technique at the assumed set of the affecting parameters.

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