Characteristics of Multi Pumped Raman Amplifiers in Dense Wavelength Division Multiplexing (DWDM) Optical Access Networks

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Summary
In the present paper, the net effective gain of multi-pumped Raman amplifiers in dense wavelength division multiplexing (DWDM) optical access networks has been modeled and parametrically investigated over wide range of the affecting parameters, taking into account the polarization effect. The gain coefficients and the amplified spontaneous emission (ASE) are calculated over the operating wavelength. Also, in the same way, we have investigated to develop a design procedure for selecting the wavelengths and associated power of multiple pumps used in Raman amplifiers to obtain the pump laser selection criteria for applications in optical DWDM access networks. Finally, we have demonstrated that the maximum optical network channels (ONCs) bit rate or capacity is achieved within increasing pumping number and decreasing pumping wavelength respectively.

Key words:
Raman gain; stimulated Raman scattering (SRS); multiplexing; demultiplexing; access networks.

1. Introduction

It is more than 20 years since fiber-optic communications have been in commercial use and new technological developments are constantly being made [1]. Several years ago dense wavelength-division multiplex (DWDM) transmission using Erbium-doped fiber amplifiers became the mainstream technology for large-capacity long-haul systems [2], and more recently, to set new records, it has become indispensable to make use of Raman amplifiers, optimizing the dispersion characteristics of the transmission path. During the 1980s the Raman amplifier was extensively studied as a promising candidate for use in fiber-optic transmission but with the development of commercially viable EDFAs, they were allowed to languish for a period. When bit-rates were rising from 10 Gbit/sec to 40 Gbit/sec, it was not possible to design systems that used only discrete amplifiers like EDFAs and the advantages of distributed Raman amplification, in which the transmission path as a whole is the amplifying medium, again came to be recognized. We may further say that the concept of multi-wavelength pumping, in which high-reliability laser diodes are used as the pump source to achieve adequate gain over a broad band, was advanced to extend the applicability of Raman amplifiers. Backbone terrestrial systems must carry huge traffic volumes hundreds or thousands of kilometers between distribution nodes, and the demand for bandwidth is growing explosively [3]. In response to this, DWDM expands the capacity of each fiber dozens of times. The expense of the multiplexing hardware can be offset over long spans because chains of optical amplifiers can amplify all wavelengths simultaneously, with multiplexing and demultiplexing only at the ends. Although metro DWDM systems have come on the market recently for regional networks, long haul backbone transmission remains the primary application because it is ideally suited for DWDM systems [4].

The rapid traffic growth in the optical fiber communication network has encouraged the development of dense wavelength multiplexing (DWDM) to accommodate as many channels as possible within a single mode fiber cable. Distributed Raman amplifier using the transmission fiber as the gain medium is a promising technology available for the optical long-haul DWDM communication systems, where simultaneous amplification of all the light wave signals is required to compensate for the fiber loss [5]. As Raman amplifiers are distributed in nature rather then lumped like erbium doped fiber amplifiers (EDFAs), the signal power can be maintained at an approximately constant level along the fiber [6]. Pumps used for Raman amplification may be constructed from semiconductor laser diodes or all fiber lasers [7]. Raman amplifier is one of the enabling technologies for high capacity long distance DWDM transmission systems [8]. Raman amplifier provides wider amplification bandwidth, low noise characteristics, and simplicity [9]. Multi-wavelength pumping scheme is usually used to ensure gain bandwidth for high capacity DWDM transmission optical access networks. Raman gain bandwidth can be easily extended by adding pump wavelengths [10].

In the present study, dense wavelength division multiplexing (DWDM) optical access networks employ Raman Amplifiers to amplify optical signals, which uses the stimulated Raman scattering effect in the fiber medium. The amplifier is analyzed with employing four pump lasers to achieve gain from 1.45 μm wavelength to 1.65 μm with minimum possible gain ripple.

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2. Simplified DWDM Optical Access Networks Architecture

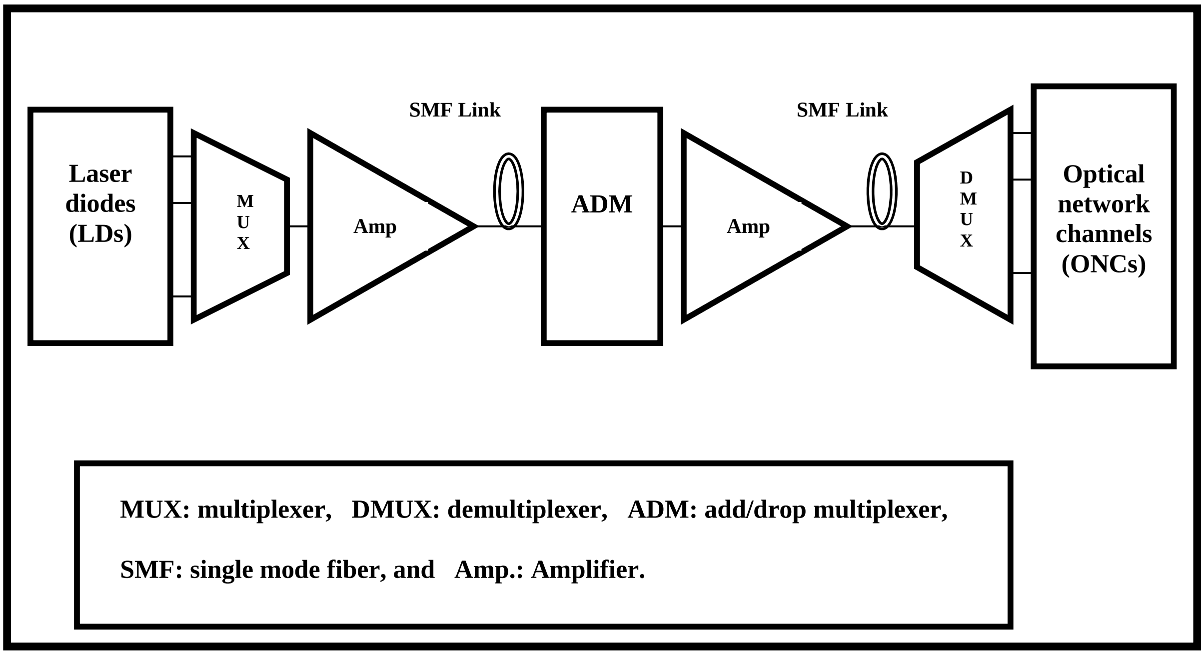
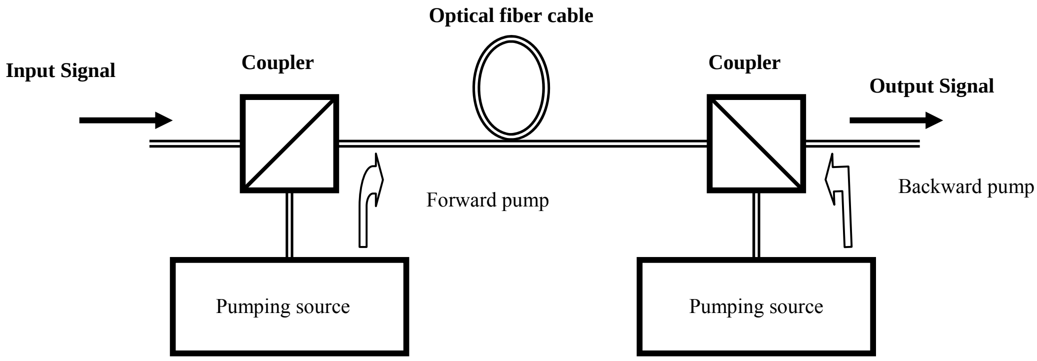


Fig. 1. Schematic view of DWDM optical access network system.

Figure 1 is a schematic view that shows a typical DWDM optical access network communications system. Signals having wavelengths λ_1 through λ_n from a plurality of laser diodes (LDs) are passed through a multiplexer and are aggregated on a single mode optical fiber. Raman amplifiers (marked Amp) are provided according to the length of the transmission path to amplify the power of the attenuated signal. The path may also be provided with an add/drop multiplexer (ADM), which can add or drop signals of any desired wavelength. The multiple signals transmitted on the single optical fiber are then demultiplexed into signals of the original wavelength. As in Fig. 1, makes clear, dense wavelength division multiplexing (DWDM) transmission requires a multiplexer/demultiplexer for the various signal wavelengths. When the number of optical network channels (ONCs) is increased, devices using a dielectric filter are too bulky and expensive, and their reliability drops. Thus for optical communication systems having a larger number of channels, there is a need for a practical multiplexer/demultiplexer of the AWG type [11]. Dense wavelength division multiplexing (DWDM) is well on its way to dominating the field of fiber optical access communication networks, and creating the need for higher capacity multiplexer/demultiplexers for the optical signals. Explosive growth in the Internet and other multimedia applications has created a need for larger optical access communication networks capacity. Dense wavelength division multiplexing (DWDM) represents a breakthrough in this area. DWDM mainly uses the 1.55 μm band, the gain window of multi pumped Raman fiber amplifiers, effecting simultaneous transmission of a number of different wavelengths on a single mode fiber (SMF) cable.

3. Paragraphs and Itemizations

As shown in Fig. 2, the basic configuration of Raman amplifier. It employs single mode fiber (SMF) cable as the gain medium. Pump lights are fed to the fiber through coupler which propagates in the forward or in the opposite direction (backward direction) to the information signals. Raman amplifier uses the stimulated Raman scattering (SRS) effect in an optical fiber cable, where a strong pump laser at shorter wavelength provides more gain to signals than longer wavelengths [12]. In our study, we have employed Raman amplifiers in dense wavelength division multiplexing (DWDM) optical access network for the benefits of Raman gain to improve the maximum bit rate or capacity of optical network channels (ONCs). Raman fiber amplifiers exhibit several attractive features for applications in transmission systems for DWDM optical access networks such as simplicity of amplifier architecture, low noise, broadband gain spectrum, flexibility of transmission window, higher saturation power, cheaper, only pump lasers are needed theoretically, wide range of pump wavelengths can be used and signal to noise ratio (SNR) is better than any amplifier.



F.g. 2. Schematic view configuration of Raman amplifier system.

The interaction between the pump and signal propagating in fiber is governed by the following two coupled equations [13]:

$$\frac{dP_{si}(f_{si},z)}{dz} = \frac{g_R(f_{si},f_p)P_{si}(f_{si},z)P_P(f_p,z)}{\Gamma A_{eff}} - \alpha_{si}P_{si}(f_{si},z) \quad (1)$$

$$\pm\frac{dP_P(f_p,z)}{dz} = -\frac{f_p}{f_{si}}\frac{g_R(f_{si},f_p)P_{si}(f_{si},z)P_P(f_p,z)}{\Gamma A_{eff}} - \alpha_P P_P(f_p,z) \quad (2)$$

where P_{si} (f_{si}, z) is the signal power at signal frequency f_{si} and distance z, P_P (f_p, z) is the pump power at pump frequency f_p and distance z, α_{si} is the attenuation constant for the signal, α_p is the attenuation constant for the pump, g_R (f_{si}, f_P): is the Raman gain coefficient which depends on frequency shift between the signal and pump, A_{eff} is the effective cross-section area of the single mode fiber (SMF), Γ is the polarization constant, which is 1 if the signal and pump are polarized and 2 if the signal and pump are not polarized and the signs of "+" or "–" correspond to forward and backward pumping. The first term in Eq. (2) represents the pump depletion due to the SRS effect, which can be neglected. Solving Eqs. (1) and (2), the Raman gain of a signal can be determined as:

$$G_R = \exp\left[\frac{g_R(f_{si},f_p)P_P(f_p,z)L_{eff}}{\Gamma A_{eff}}\right] \quad (3)$$

Then we can express the Raman gain of a signal in units of decibel as:

$$G_R(dB) = 4.343\frac{g_R(f_{si},f_p)P_P(f_p,z)L_{eff}}{\Gamma A_{eff}} \quad (4)$$

where L_{eff} =[1−exp(− α_p L)]/ L represents the effective fiber length taking into account the fiber loss at pump wavelength. A number of factors should be considered while designing a Raman amplifier with multi-wavelength pumps for DWDM systems, which include pump-to pump power transfer, signal-to-signal power transfer, pump depletion, Rayleigh back-scattering, amplified spontaneous emission (ASE) noise, in which loss due to noise emission, and four wave mixing (FWM) in signals and pumps [13]. The net effective gain G_{eff} (λ_{cL}, λ_P), and both g_R (λ_{si}, λ_P) and A_{eff} (λ_{si}, λ_P) are computed based on the data of each link N_{oL} where $\lambda_{1Link} \le \lambda_{si} \le \lambda_{2Link}$.

$$\lambda_{1Link} = \lambda_i + \Delta\lambda(N_{oL}-1)N_{ch} \ , \quad (5)$$

$$\lambda_{2Link} = \lambda_{1Link} + \Delta\lambda\, N_{ch} = \lambda_i + N_{oL}\, N_{ch} \ , \quad (6)$$

$$\lambda_{si} = \lambda_{1Link} + \Delta\lambda(i-1)N_{ch} \ , \quad (7)$$

With i = {1, 2, 3, ………………..…., N_{ch}}. Then, both g_R (λ_{si}, λ_P) and A_{eff} (λ_{si}, λ_P) are averaged to give [13]:

$$g_R(\lambda_{cL},\lambda_P) = \frac{1}{N_{ch}}\sum_{i=1}^{N_{ch}} g_R(\lambda_{si},\lambda_P) \ , \quad (8)$$

$$A_{eff}(\lambda_{cL},\lambda_P) = \frac{1}{N_{ch}}\sum_{i=1}^{N_{ch}} A_{eff}(\lambda_{si},\lambda_P) \ , \quad (9)$$

where the number of channels per link [N_{ch}=N_t/N_L], these N_{ch} possesses a central wavelength λ_{cL} given by:

$$\lambda_{cL} = \lambda_i + \Delta\lambda(N_{oL}-0.5)N_{ch} \ , \quad (10)$$

$$\Delta\lambda = (\lambda_f - \lambda_i)/(N_t - 1) \ , \quad (11)$$

with λ_i= 1.45 μm, λ_f = 1.65 μm, and N_{oL} is the order of the link {1, 2, 3, …………………………., N_L}.

The Raman gain coefficient becomes after number of pumps N_R as follows [14, 15, 16]:

$$G_{oR} = \sum_{j=1}^{N_R}\frac{g_{Rj}}{\Gamma A_{jeff}} \ , \quad (12)$$

We obtain both g_R (λ_{si}, λ_P) and A_{eff} (λ_{si}, λ_P) and consequently we cast G_{eff} (λ_{cL}, λ_P). Based on the model of [13], ASE (λ_{cL}, λ_P) as a criterion of the minimum detectable power is computed. The signal light must be amplified before its level becomes less than that of the amplified sponsnteous emission (ASE). In order to obtain the ASE power at the output end of the fiber for signal power amplification, the idea of effective input Stokes power $P_{Stokes-eff}$ at the ASE is employed:

$$P_{Stokes-eff} = h\, f_{Stokes}\, B_{eff} \quad , \qquad (13)$$

where $B_{eff} = \left(\sqrt{\pi}/2\right)\left(\Delta f_{FWHM} / \sqrt{P_P\, G_R / \alpha_P}\right),$ (14)

Raman amplifiers are based on stimulated Raman scattering (SRS) techniques to calculate the basic accumulated net Raman gain spectrum. During the long distance transmission, optical amplifiers are required so that the original transmitted signal is received at the receiving end with proper strength. Stimulated Raman scattering (SRS) techniques according to which the weak light signal gets amplified while passing through a Raman gain medium in the presence of a strong pump laser.

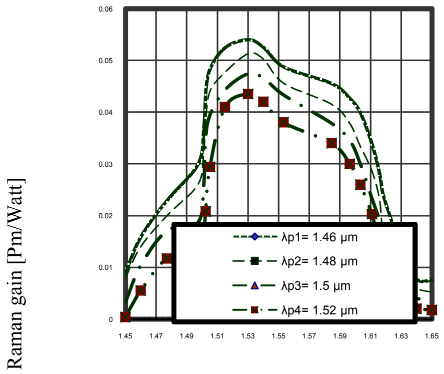


Fig. 3. Variations of Raman gain spectrum with pump lasers at 1.46 µm,1.48 µm, 1.5 µm and 1.52 µm at the assumed set of parameters.

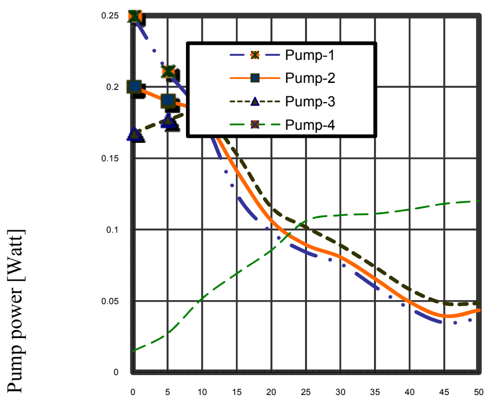


Fig. 4. Variations of pump power with the fiber cable length at the assumed set of parameters.

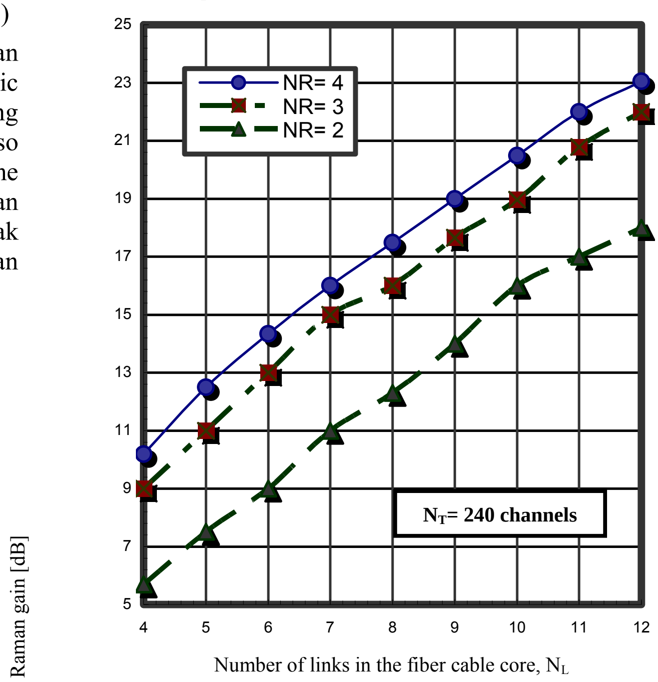


Fig. 5. Variations of Raman gain at the effective length with the number of links in the fiber cable core at the assumed set set of parameters.

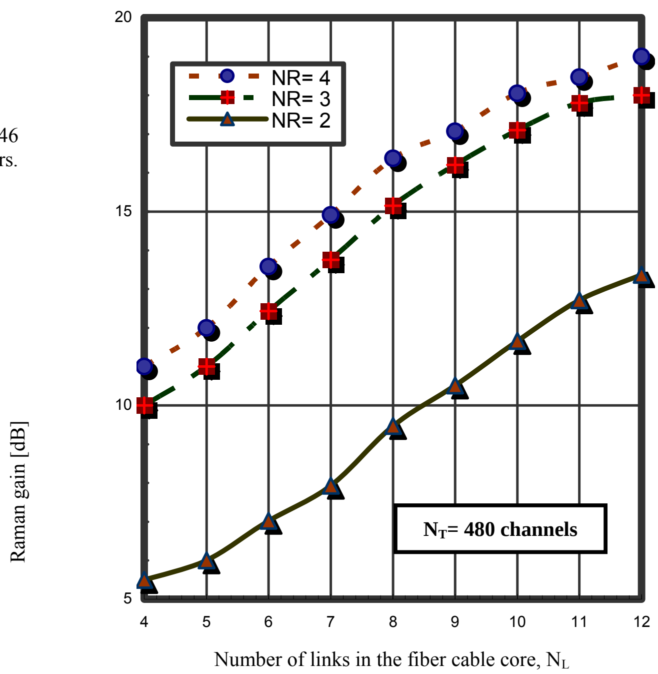


Fig. 6. Variations of Raman gain at the effective length with the number of links in the fiber cable core at the assumed set set of parameters.

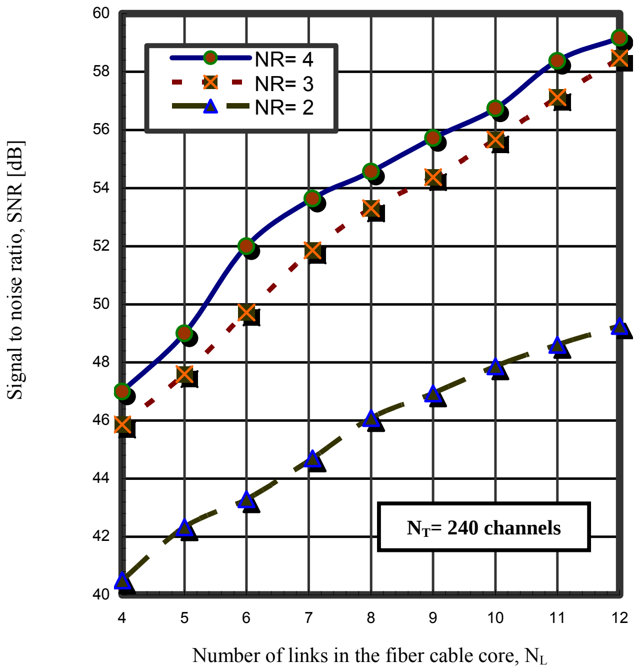


Fig. 7. Variations of signal to noise ratio (SNR) at the effective length with the number of links in the fiber cable core at the assumed set set of parameters.

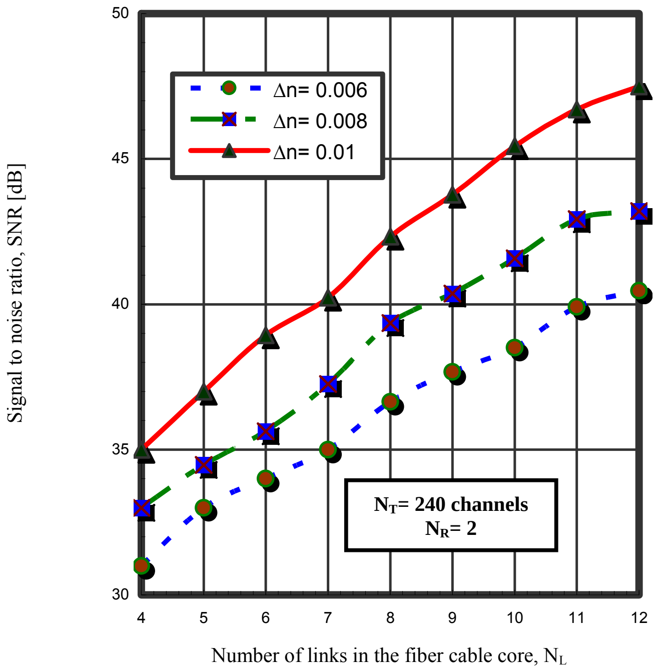


Fig. 9. Variations of signal to noise ratio (SNR) at the effective length with the number of links in the fiber cable core at the assumed set set of parameters.

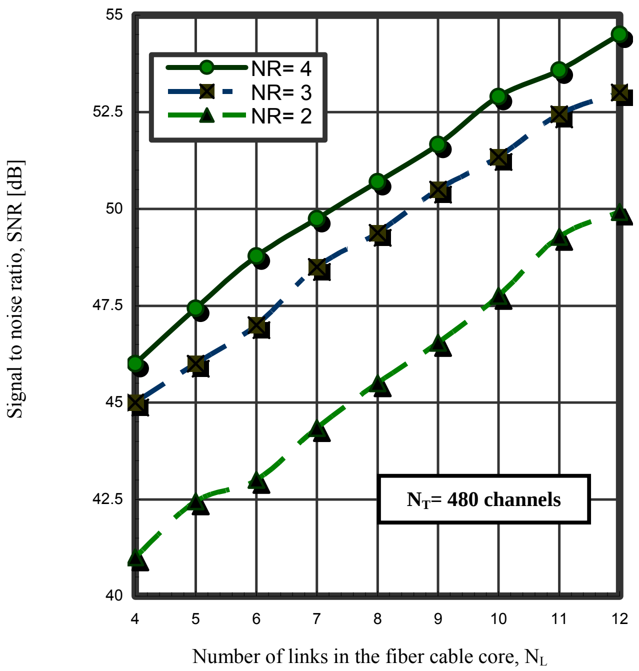


Fig. 8. Variations of signal to noise ratio (SNR) at the effective length with the number of links in the fiber cable core at the assumed set set of parameters.

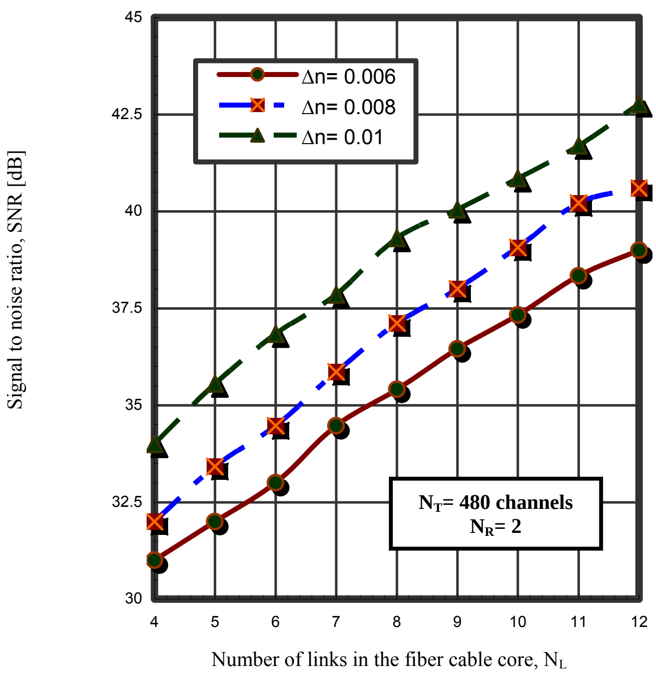


Fig. 10. Variations of signal to noise ratio (SNR) at the effective length with the number of links in the fiber cable core at the assumed set set of parameters.

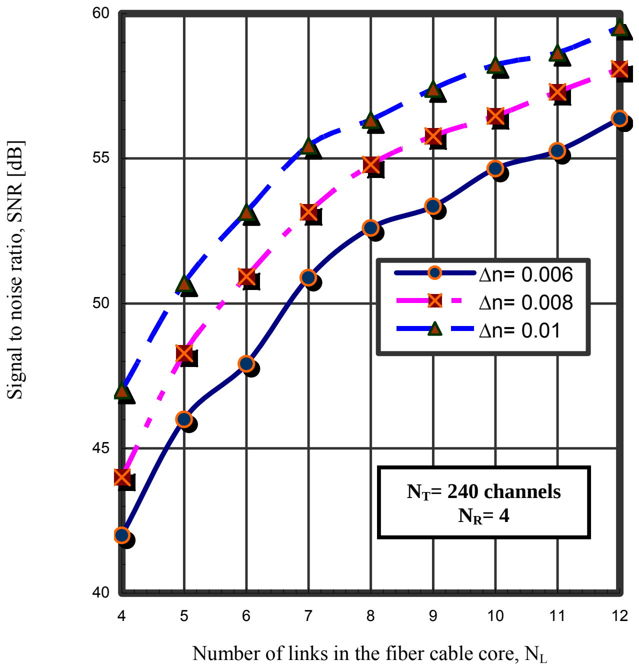


Fig. 11. Variations of signal to noise ratio (SNR) at the effective length with the number of links in the fiber cable core at the assumed set set of parameters.

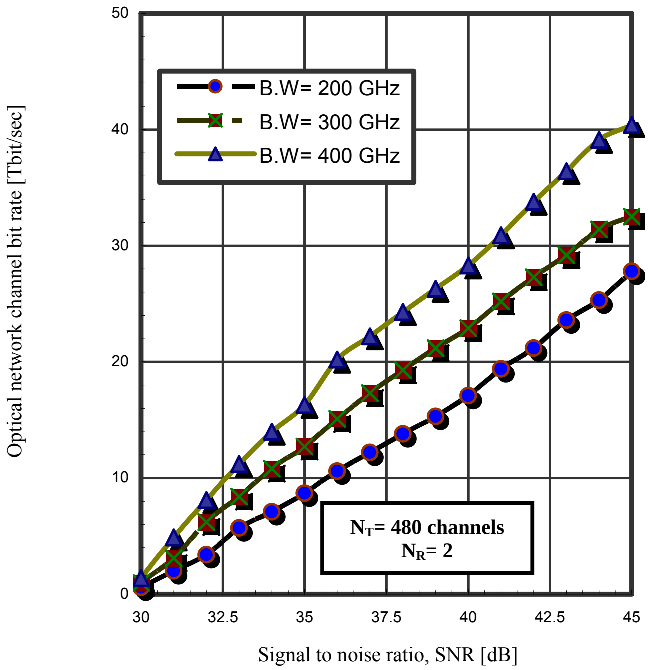


Fig. 13. Variations of optical network channel bit rate, C, with the signal to noise ratio (SNR) at the assumed set of parameters.

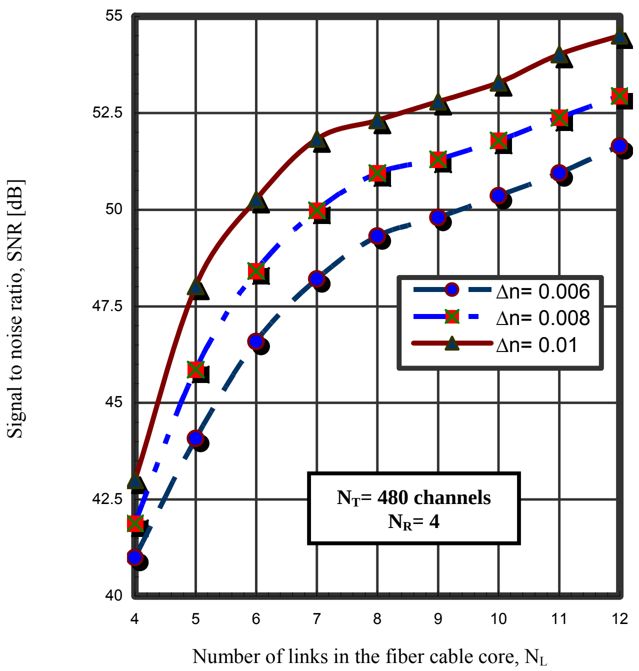


Fig. 12. Variations of signal to noise ratio (SNR) at the effective length with the number of links in the fiber cable core at the assumed set set of parameters.

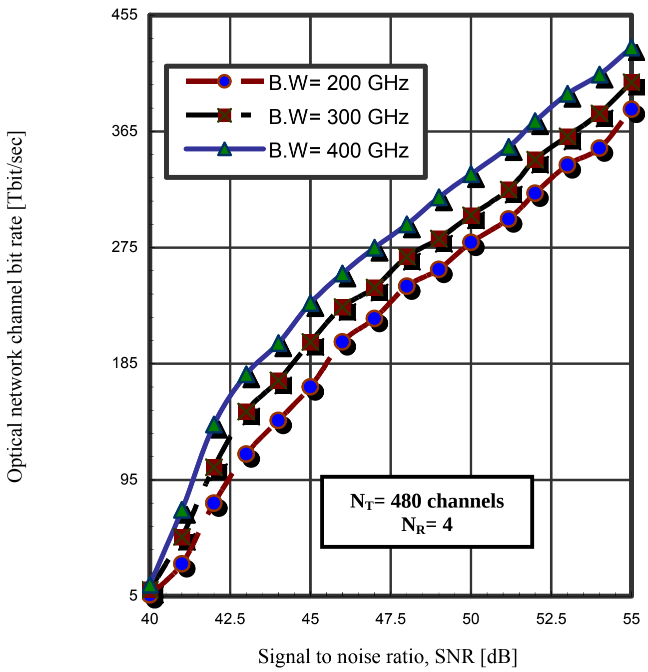


Fig. 14. Variations of optical network channel bit rate, C, with the signal to noise ratio (SNR) at the assumed set of parameters.

The net Raman gain [17, 18] is one of the most significant parameters of the Raman amplifier. It describes the signal power increase in the end of the transmission fiber cable and presents the ratio between the amplifier accumulated gain and the signal loss [19, 20]. Then the average Raman gain G_R and signal to noise ratio (SNR) per single mode fiber link is given as follows:

$$G_R = \frac{1}{N_{ch}} \sum_{i=1}^{N_{ch}} 10\log_{10}\left[P_{si}(L, P_R)/P_{si}(L, 0)\right] \quad , \quad (16)$$

$$SNR = \frac{1}{N_{ch}} \sum_{i=1}^{N_{ch}} 10\log_{10}\left[P_{si}(L, P_P)/P_{ASE}\right] \quad , \quad (17)$$

The maximum optical network channels (ONCs) bit rate or capacity according to Shannon theorem is given [21]:

$$C = B.W_{sig.}\log_2(1 + S/N) \quad , \quad (18)$$

where C is the maximum bit rate over the optical network channels (ONCs), $B.W_{sig.}$ is the bandwidth of the optical signal, and (S/N) is the signal to noise ratio.

4. Results and General Discussions

The following numerical data (set of controlling parameters) of our system model are employed to obtain the performance of multi-pumped Raman amplifiers in DWDM optical access networks as:
1.45 μm ≤ λ_{si}, optical signal wavelength≤ 1.65 μm, α_p = 0.4 dB/km, 1.4 μm ≤ λ_p, pumping wavelength≤ 1.55 μm, A_{eff} = 85 μm^2, α_{si} = 0.25 dB/km, power signal: P_{si}= 0.2 mWatt, pumping pump: P_P= 0.2 Watt/pump, N_R: number of pumps {2, 3, 4},N_t: total number of channels up to 480 channels, N_L: total number of links up to 12 links, 0.005 ≤ Δn, relative refractive index difference≤ 0.01. As shown in Figs. (3-14), the following facts are assured:

1- Figure 3 shows the Raman gain spectrum is evaluated utilizing four pump lasers at wavelengths of 1.46 μm, 1.48 μm, 1.5 μm, 1.52 μm, respectively, are employed to make gain uniform. It is evident from Fig. 3, that a reasonable uniform gain is achievable for the signal wavelength range of about 1.5 μm to 1.6 μm.
2- Figure 4 shows the power variation of the four pump lasers with the fiber length, where the input powers for the pumps are assumed to be 0.25 watt, 0.2 watt, 0.017 watt, and 0.015 watt, respectively. It is observed from the figure that the pump-1 is attenuated the most as it has the highest frequency. Also the pump-4 has the lowest frequency and hence gets amplified at the expense of other pump powers.
3- As shown in Figs. (5, 6), Raman gain increases as link number, N_L, increases or N_{ch} decreases at the same pump number, N_R. Also, Raman gain increases as number of pumps increase at the same link number in the fiber cable core.
4- As shown in Figs. (7, 8), signal to noise ratio (SNR) increases as link number, N_L, increases or N_{ch} decreases at the same pump number, N_R. Also, signal to noise ratio (SNR) increases as number of pumps increase at the same link number in the fiber cable core.
5- As shown in Figs. (9–12), signal to noise ratio (SNR) increases as link number, N_L, increases or N_{ch} decreases, or Δn increases, or both. Also, as pumping number increases, signal to noise ratio (SNR) increases for all number of links in the fiber cable core.
6- As shown in Figs. (13, 14), optical network channels bit rate increases as the bandwidth of the optical signal increases, or signal to noise ratio (SNR) increases, or both. Also, the pumping number (at N_R=4) indicates higher bit rates for optical network channels (ONCs) than the pumping number (at N_R=2).

5. Conclusions

In a summary, the net effective gain of multi-pumped Raman amplifiers in dense wavelength division multiplexing (DWDM) optical access networks has been modeled and parametrically investigated over wide range of the affecting parameters, taking into account the polarization effect. The two major criteria for designing the pump for Raman amplification, namely, selection of wavelength and power. It is observed that multiple pumps fed at suitable wavelengths can offer the desired broadband and uniform gain spectrum. Also, it is observed that the increased pumping number, and relative refractive index difference, this results in the improvement of the Raman gain and signal to noise ratio (SNR) which employed for optical network channels (ONCs). Moreover, the maximum bit rate or capacity over optical network channels (ONCs) is achieved within increasing pumping number, and decreasing pumping wavelength respectively.

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