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Demonstration of Multi Pump Wide Gain Raman Amplifiers for Maximization of Repeaters Distance in Optical Communication Systems

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ABSTRACT

Fiber Raman amplifiers in ultra wide wavelength division multiplexing (UW-WDM) systems have recently received much more attention because of their greatly extended bandwidth and distributed amplification with the installed fiber as gain medium. It has been shown that the bandwidth of the amplifier can be further increased and gain spectrum can be tailored by using pumping with multiple wavelengths. Wide gain of the amplifier is considered where two sets of pumps N_R {5,10} are investigated. The gain coefficient is cast under polynomial forms. The pumping wavelength λ_R is over the range $1.40 \leq \lambda_R$, μm ≤ 1.44 and the channel wavelength λ_s is over the range $1.45 \leq \lambda_s$, μm ≤ 1.65. Two multiplexing techniques are processed in long-haul transmission cables where number of channels is up to 10000 in ultra-wide wavelength division multiplexing (UW-WDM) with number of links up to 480. The problem is investigated over wide ranges of affecting sets of parameters.

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1. INTRODUCTION

Multi-wavelength pumped Raman amplifiers (RAs) have attracted more and more attention in recent years [1]. 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 [2]. 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) [3]. In addition, it can be used for increasing the bandwidth of Erbium doped fiber amplifiers (EDFAs) in hybrid systems [4]. 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 [5], because this scheme can suppress the related signal power fluctuation. Of course, the reported results in the literatures show the OSNR of this excitation is tilted, and channels with longer wavelength have longer OSNR respect to the shorter wavelength channels [6]. These amplifiers also have the unique characteristic of being tunable at any wavelength, simply by changing the pump frequency, since gain depends only on the signal-pump frequency shift [7]. The saturation power of fiber Raman amplifiers is by far larger than that of the equivalent EDFAs, thus, limit the effects of cross-gain modulation in reconfigurable DWDM systems. Due to these reasons, Raman amplifiers are widely used in the fiber optical communication systems. Indeed, attention has been focused on RAs because of the availability of high-power compact pump lasers [8], their superior performance, such as ultra-wide bandwidth, low noise and suppressed nonlinearity performances in transmission systems, and lower noise figure. The performance of a RA depends on the characteristics of fiber gain. So, to design appropriate fibers, it is useful to predict the fiber properties. In silica-optical fibers, Raman amplification band extends over a few terahertz, and it can be further broadened by multiple pumping schemes [5] and [7]. There are many methods to design a multistage gain flattened fiber RAs using multi-wavelength pumping scheme (for example in [9, 10]).

In the present study, the repeater spacing using multi-pumping Raman amplifier will be investigated for N_R pumps in optical pumping wavelength $1.42 \leq \lambda_{RM} \leq 1.44$ to amplify N_t optical channels where the optical wavelength range satisfies $1.45 \leq \lambda_s$, μm≤ 1.65. The present investigation has clarified vital causes that affect both Raman gain and the repeater spacing up to 360 km. The investigation of the flatness of the gain constant has indicated that the Raman pumps should be distributed over wide range of pumping wavelength before the starting of the channels wavelength range.

2. MODELING DESCRIPTION AND ANALYSIS

The two major rate equations of multi-pumping [11,12] Raman amplifier case of UW-WDM are that of signal power P_{si}, and pump power P_{Rj} where "i" refer to the $i^{\underline{th}}$ channel, and "j" refer to the pump, where

$$\frac{dP_{si}}{dz} + \sigma_{si}P_{si} = (\alpha_1 P_{Rj} + \alpha_2 P_{si} - \alpha_3 P_{Sm})P_{si} \tag{1}$$

$$\frac{dP_{Rj}}{dz} + \sigma_{Rj}P_{Rj} = (\beta_1 P_{Si} + \beta_2 P_R - \beta_3 P_{Rm})P_{Si} \tag{2}$$

Where:

$$\alpha_1 = G_{c0} N_R, \tag{3}$$

$$\alpha_2 = G_{c1}(i_s - 1), \tag{4}$$

$$\alpha_3 = -G_{c2}\frac{\lambda_{sa1}}{\lambda_{si}}(N_{ch} - i_s) \tag{5}$$

$$\beta_1 = -G_{R0}N_{ch}\frac{\lambda_{sa2}}{\lambda_{si}}, \tag{6}$$

$$\beta_2 = G_{R1}(j_R - 1), \tag{7}$$

$$\beta_3 = -G_{R2}\frac{\lambda_{Ra}}{\lambda_{Rj}}(N_R - j_R), \tag{8}$$

$$G_{os} = \frac{g_R}{A_{es}\Gamma}, \text{ and } G_{oR} = \frac{g_R}{A_{er}\Gamma} \tag{9}$$

where: N_R = number of Raman Pumps, N_{ch} = number of channels/link,

$$g_R = g_o(1+80\Delta n)\lambda_{Rj}/1.34, \tag{10}$$

$$\lambda_{sa1} = 0.5(\lambda_{sch} + \lambda_{s(i-1)}), \text{ and} \tag{11}$$

$$\lambda_{sa2} = 0.5(\lambda_{sch} + \lambda_{si}). \tag{12}$$

Where g_R is the differential gain, A_e is the effective area, $\frac{g_R}{A_e\Gamma}$ is the gain constant, $\sigma_{s,R}$ is the spectral loss, the suffix "S" refers to the signal, suffix :R" refers to the pump and Γ is a polarization factor, = 2.

In the present paper, we cast the gain constant $\frac{g_R}{A_e\Gamma}$ under the form:

$$G_c = \left\langle \frac{g_R}{A_e\Gamma} \right\rangle = \sum_{m=1} a_m \lambda_{si}^m \tag{13}$$

a_m is a function of N_R and Δn where N_R is over the range {5,10} and Δn is over the range {0.005, 0.012}. where a_m is given by:

$$a_m = \sum_{j=0} b_j \Delta n^j \text{ , and} \tag{14-a}$$

$$b_k = \sum_{k=1} C_k N_R^k . \tag{14-b}$$

where λ_{Si} is the optical channel wavelength and is given by:

$$\lambda_{Si} = \lambda_o + \left(\frac{\lambda_f - \lambda_o}{N_t - 1}\right)(i-1) = \lambda_o + \Delta\lambda(i-1) \tag{15}$$

λ_o is the initial channel of interest, =1.45 μm, λ_f is the final channel of interest, =1.65 μm, and N_t is the total number of channels (up to 10000). In Eq.(13), averaging is done over pumping wavelength in the range $1.40 \le \lambda_R$, $\mu m \le 1.44$, and the coefficients α_m are functions of Δn (the relative refractive index difference), and the number of Raman pumps. Now, N_t (total channels) is distributed in N_L links (space-division multiplexing) where each link carries $N_{Ch/L}=N_t/N_L$ channels and its center is λ_{CL} where:

$$\lambda_{CL} = \lambda_{iL} + N_{ch}\Delta\lambda(N_{O.L} - 0.5) \tag{16}$$

$$\lambda_{iL} = \lambda_i + N_{ch}\Delta\lambda(N_{O.L} - 0.5) \tag{17}$$

With $N_{O.L}$ is the order of link and $\Delta\lambda$ is the channel spacing and is given by: $\Delta\lambda = (\lambda_f - \lambda_i)/(N_t - 1)$.

In the present paper, we suggested a new approach to investigate the flatness of the gain constant G_c(Eqn.(13)) through the following bandwidth BW_c. It is the bandwidth which satisfies $\lambda_{2,1}$ at which $G_c(\lambda_{si})/G_{c,\max} = 3/4$, i.e., $10 Log\left|G_c(\lambda_{si})/G_{c,\max}\right| = 1.25 dB$ (18-a)

Where $G_{c,max}$ is the maximum gain constant. Thus:

$$BW_c = \lambda_2 - \lambda_1 \tag{18-b}$$

3. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

Employing the above model, we have investigated the multiplexing of N_t optical channels in the range $1.45 \le \lambda_s$, $\mu m \le 1.65$ through N_L of fibers $80 \le N_L \le 480$, using N_R pumps (5 or 10) of equal spacing pumping wavelength λ_R in the range $1.40 \le \lambda_{RM} \le 1.44$.

At entrance of a link z=0.0, each channel possesses a power $P_{si}(0.0)=P_s$ Watt and each pump possesses a power $P_{Rj}(0.0)=P_R$ where P_s=0.2 mWatt and P_R=0.5 Watt. Thus, at z=0.0, we have:

$$\left.\frac{dP_{si}}{dz}\right|_{z=0.0} = -\sigma_s P_s + \left[\alpha_1 P_R + \alpha_2 P_s - \alpha_3 P_s\right] P_s \tag{19}$$

$$\left.\frac{dP_{Rj}}{dz}\right|_{z=0.0} = -\sigma_R P_R + \left[-\beta_1 P_s + \beta_2 P_R - \beta_3 P_R\right] P_R \tag{20}$$

Equations (1) and (2) will be numerically handled with more rigorous analysis than that had been done in [12] employing Runge-Kutta of fourth order [13] with the initial conditions given by Eqs. (19) and (20) where we have at $\Delta z=h$, h=0.1 km

$$P_{n1} = P_{no} + \frac{1}{6}\left[K_{n1} + 2K_{n2} + 2K_{n3} + K_{n4}\right] \tag{21}$$

where: $K_{1n}=h\ K_n(P_{no})$, $K_{2n}=h\ K_n(P_{no}+0.5\ K_{1n})$, $K_{3n}=h\ K_n(P_{no}+0.5\ K_{2n})$, and $K_{4n}=h\ K_n(P_{no}+K_{3n})$. The suffix "n" in the above equations stands for either "S" in Eq. (1) or "R" in Eq. (2). A specially designed software is cast to handle the set of equations {(1)-(2)} for either P_{si} or P_{Rj} along the propagation distance z=nh, n=1,2,3,…., N_f, where at $z=N_f h$ we get the desired repeater spacing R_R due to Raman amplifier only.

$$P_{si}(R_R)=ASE\ \text{,Watt} \tag{22}$$

where ASE is the amplified spontaneous emission noise power and is given by [11]:

$$ASE = 1.9876x10^{-19} BW_e / \lambda_{Ra}\ \text{, Watt} \tag{23}$$

where BW_e is the effective bandwidth and λ_{Ra} is the average Raman wavelength, = 1.43 μm. All-wave fibers are employed [14] where the spectral losses $\sigma(\lambda_s)$ is cast under the form:

$$\begin{aligned}\sigma(\lambda_s) &= 0.19 + 7.04(\lambda_s - 1.55)^2 + 34.06(\lambda_s - 1.55)^3 \\ &\quad + 72.11(\lambda_s - 1.55)^4 + 36.7(\lambda_s - 1.55)^5\ , dB/km\end{aligned} \tag{24}$$

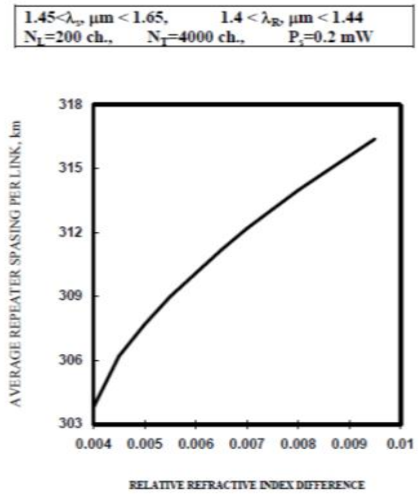

Fig. 1. Variation of average repeater spacing per link, R_R , km against relative refractive index difference, Δn, at the assumed set of parameters.

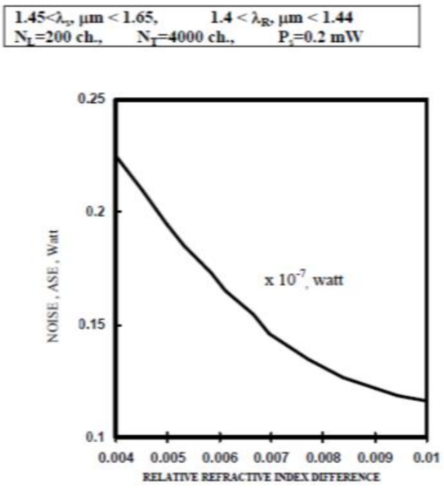

Fig. 2. Variation of noise, ASE, Watt against relative refractive index difference, Δn, at the assumed set of parameters

Based on the basic equations analysis, and the series of the operating parameters, the following features are assured as shown in the series of the Figure 1-12:

1. Figure. (1-4) have assured that as relative refractive index difference Δn increases, resulting in increasing of both average repeater spacing per link and gain, and decreasing of both amplified spontaneous emission power and effective core area.
2. As the number of pumps increases, resulting in average repeater spacing per link as shown in Fig. 5.
3. Figure (6-8) have demonstrated that as in the spectral domain around the optical wavelength $\lambda_C \approx 1.55$ μm, lead to average repeater spacing per link possesses its maximum value.
4. As shown in the series of Figs. (9-11) has proved that as the number of transmitted channels N_T increases, resulting in deceasing of average repeater spacing per link.

5. As initial Raman pumping wavelength, λ_{Ri} decreases, effective bandwidth, BW_c increases inside the operating channels range ($1.45 \le \lambda_{si}, \mu m \le 1.65$ as shown in Fig.12, where good flatness has been obtained up to 90% of the above range.

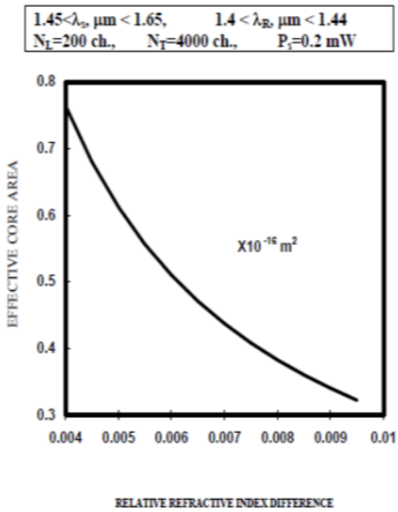

Fig. 3. Variation of effective core area, A_e against relative refractive index difference, Δn, at the assumed set of parameters.

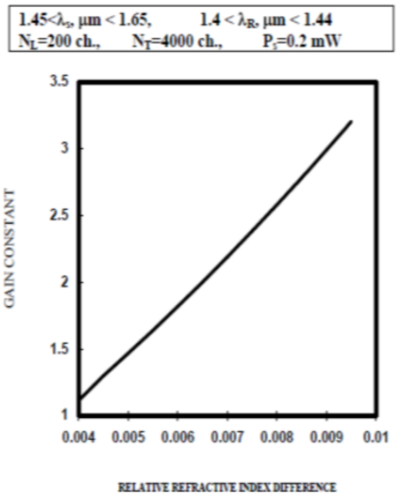

Fig.4. Variation of gain constant , G_c, $(km.Watt)^{-1}$ against relative refractive index difference, Δn, at the assumed set of parameters.

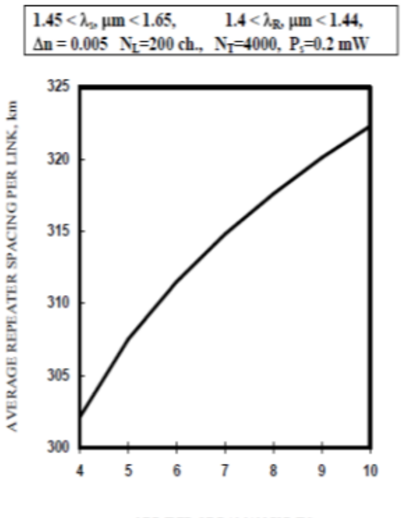

Fig. 5. Variation of average repeater spacing per link, R_R , km against number of Raman pumps, N_R at the assumed set of parameters

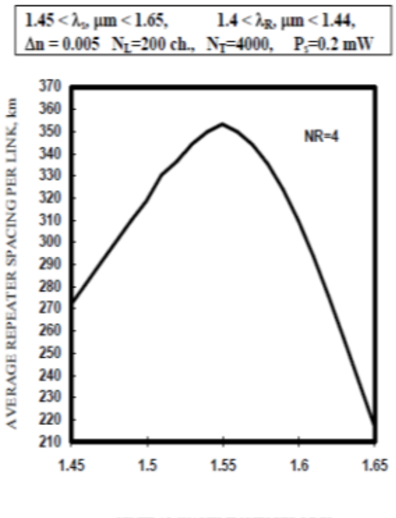

Fig. 6. Variation of average repeater spacing per link, R_R , km against central wavelength per link, λ_c, μm at the assumed set of parameters

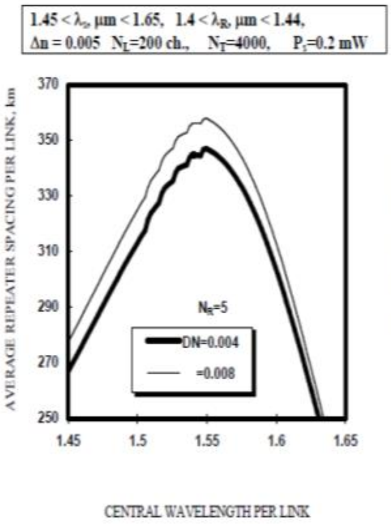

Fig.7.Variation of average repeater spacing per link, R_R , km against central wavelength per link, λ_c, μm at the assumed set of parameters

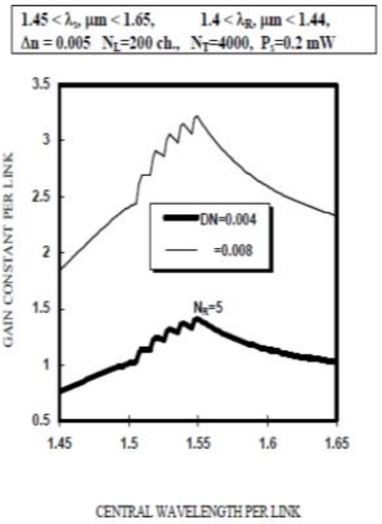

Fig. 8. Variation of average repeater spacing per link, R_R , km against number of links, N_L at the assumed set of parameters

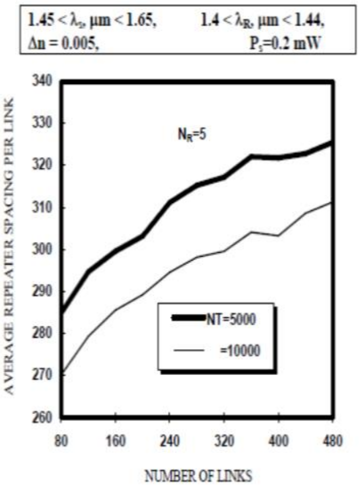

Fig. 9. Variation of average repeater spacing per link, R_R , km against number of links, N_L at the assumed set of parameters

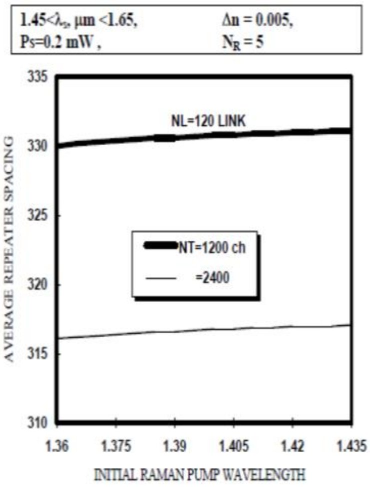

Fig. 10. Variation of average repeater spacing, R_R , km against initial Raman pump wavelength, λ_{Ri} , μm at the assumed set of parameters

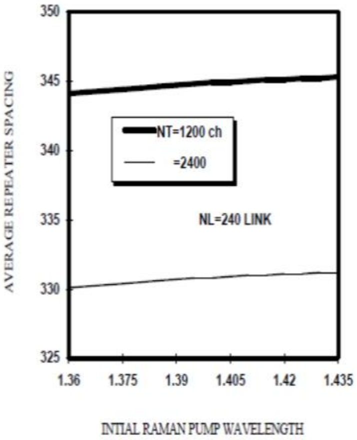

Fig. 11 Variation of average repeater spacing, R_R , km against initial Raman pump wavelength, λ_{Ri} , μm at the assumed set of parameters.

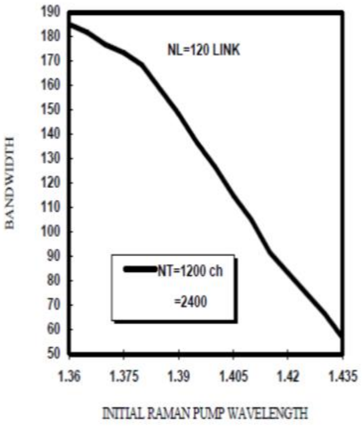

Fig. 12. Variation of bandwidth, BW_c , nm against initial Raman pump wavelength, λ_{Ri} , μm at the assumed set of parameters.

4. CONCLUSIONS

The advantages of fiber Raman amplifiers over the optical amplifiers include the possibility to operate in any wavelength region and superior noise performance of distributed amplification, as well as permits, with the appropriate choice of pump wavelengths and powers, flattening of the gain profile over the whole bandwidth. Employing special numerical technique, we have succeeded to maximize the repeater spacing employing multi-pumping Raman amplifier of wide flat gain. We have processed two coupled nonlinear differential equations to account the signal behavior. Raman pumps are of equal spectral spacing and equal pumping power. Two sets of pumps are processed over the spectral width $1.40 \leq \lambda_R$, $\mu m \leq 1.44$ and channel width $1.45 \leq \lambda_s$, $\mu m \leq 1.65$. Two ultra-wide transmission multiplexing techniques are applied, where 10,000 optical channels are multiplexed (WDM) through 480 fiber links (SDM). In general, positive linear or weak nonlinear correlations are depicted among the average repeater spacing and the controlling sets of parameters. The gain coefficient undergoes good flatness at higher Δn and possesses , in general, positive correlation with the relative refractive index difference. A maximum repeater spacing of 360 km can be achieved. A maximum flatness over 90% of the channel operating range has been obtained by decreasing the initial Raman pumping wavelength.

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