Gain and Bandwidth Improvements for Distributed Raman Amplifier in UW-WDM Communication Systems

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***Abstract*—Fiber Raman amplifiers in ultra wideband 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. In this paper, the distributed multi-pumping Raman amplifier has been studied and analyzed by testing two designed model of amplifier to obtain the gain of maximum flatness and bandwidth. Also we have investigated the effects of many parameters on the gain and bandwidth of Raman amplifier such as: pumping wavelength, offset wavelength, the relative refractive index difference and the number and location of the cascaded units used in the amplifier model design. The models is analyzed where six and eight Raman pumping of special pumping power and pumping wavelengths are lunched in the forward direction where each model is analyzed by two different way. The gain is computed over the spectral optical wavelengths (1.45μm ≤ λ signal ≤ 1.65μm). The differential gain of each unit of the amplifier is obtained according to the straight line-exponential model of a small maximum constant gain of 7.4×10^{-14} m/W over an optical wavelength interval of 16 nm**

***Keyword*—**Distributed Raman amplifier, Raman gain, Raman Bandwidth, Ultra wideband-wavelength division multiplexing (UW-WDM).

I. INTRODUCTION

OPTICAL amplifiers have played a critical role in the telecommunication revolution that has begun two decades ago. Raman amplification has enabled a dramatic increase in the distance and capacity of light wave systems [1]-[3].

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There are mainly three reasons for the interest in Raman amplifier. First its capability to provide distributed amplification second is the possibility to provide gain at any wavelength by selecting appropriate pump wavelengths, and the third is the fact that the amplification bandwidth may be broadened simply by adding more pump wavelengths. An important feature of the Raman amplification process is that amplification is achievable at any wavelength by choosing the pump wavelength in accordance with the signal wavelength [4].

The term distributed amplification refers to the method of cancellation of the intrinsic fiber loss. The loss in distributed amplifiers is counter balanced at every point along the transmission fiber in an ideal distributed amplifier [4].

In the mid-nineties, high-power pump lasers became available and in the years following, several system experiments demonstrated the benefits of distributed Raman amplification including repeater-less undersea experiments, high-capacity terrestrial as well as submarine systems transmission experiments, shorter span single-channel systems including 320 Gbit/s pseudo linear transmissions, and in soliton systems [4].

distributed Raman amplifiers improved noise performance because of amplification at any wavelength controlled simply by selecting the appropriate pump wavelength, extended bandwidth achieved by using multiple pumps when compared to amplification using erbium-doped fiber amplifiers (EDFAs), and finally control of the spectral shape of the gain and the noise figure, which may be adjusted by combining and controlling the wavelength and power among multiple pumps [4], [6].

Raman amplifiers pumped at multiple wavelengths draw significant attention in high-speed long-haul WDM transmission, for example, because of their wideband flat-gain profile (100nm with 12 channel-WDM pumping) and superior signal-to-noise ratio (SNR) performance. However, they require numbers of high power pump lasers to achieve high-gain and high bandwidth which makes it very expensive at the initial deployment stage where the WDM bandwidth is not in full use. While modular band-by-band and high upgrade like EDFA-based WDM systems reduces system introduction cost very much, in which either C or L-band EDFAs can be added later when a new bandwidth becomes needed. However, such modular addition of amplifiers is not possible for a DRA in which a transmission fiber is shared as common-gain medium. Neglecting nonlinear pump interaction or saturation WDM-pumped Raman amplifier gain can be approximated as the linear superposition of Raman gains induced by each pump laser [7].

Currently, RFAs are the only silica-fiber based technology that can extend the amplification bandwidth to the S band while providing performance and reliability comparable with those of EDFAs. However, the noise figure remains high compared to that of the C and L bands [8].

In this paper, the distributed multi-pumping Raman amplifier has been studied and analysed by using N cascaded Raman amplifier units, N pumping signals are injected in a parallel processing at different pumping powers and wavelengths. The designed model of amplifier are considered to obtain the gain of maximum flatness and wider bandwidth. Also we have investigated the effects of many parameters on the gain and bandwidth of Raman amplifier such as: pumping wavelength, offset wavelength, the relative refractive index difference and the number and location of the cascaded units used in the amplifier model design. The gain is computed over the spectral optical wavelengths (1.45μm ≤ λ signal ≤ 1.65μm). The differential gain of each unit of the amplifier is obtained according to the straight line-exponential model of a maximum gain constant of 7.4×10^{-14} m/W over an optical wavelength interval of 16 nm. Computer simulations are carried out using the Matlab software package.

II. Mathematical Model

Figure 1 shows an N-Raman amplifier in a cascade form of special pumping powers Pr1, Pr2, Pr3, Pr4,…, PrN and corresponding pumping wavelengths λr1, λr2, λr3, λr4, ……., λrN.

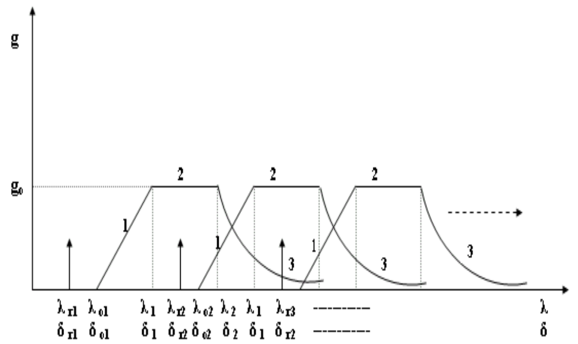

Figure 1. The gain, g, of multi-pump Raman amplifier versus wavelength, λ

The map of δ-g or λ –g is as shown in Figure 1, where δ is the Raman shift and g is the Raman differential gain coefficient; both were cast based on [9-13] as:

$$\delta = \frac{\lambda_s - \lambda_r}{\lambda_s \lambda_r} \times 10^4 \, , \mathrm{cm}^{-1} \tag{1}$$

The general equations representing the Raman gain in the three regions are $g_{1,i}$, $g_{2,i}$ *and* $g_{3,i}$ respectively [13]. Where, *i* denotes the order of amplifier unit in cascade.

$$g_{1,i} = g_o \frac{\delta - \delta_{o,i}}{440} \tag{2}$$

Where, "i" is the number of cascaded units, λr is Raman pumping wavelength and $\lambda_o \geq 1.35$um. The symbol $\delta_{o,i}$ is the Raman shift that indicates the position of each i[th] amplifier unit.

$$\delta_{o,i} \leq \delta \geq \delta_{1.i}, \qquad 0 \leq \delta - \delta_{o,i} \leq 440 \tag{3}$$

With

$$\delta_{o.i} = \frac{\lambda_{o,i} - \lambda_{r.i}}{\lambda_{o,i}\lambda_{r,i}} \times 10^4 \, , cm^{-1} \tag{4}$$

With 1 cm^{-1} = 30 GHz [11], where $\lambda_{o,i}$ indicates the offset wavelength and $\lambda_{r,i}$ indicates the pumping wavelength of each amplifier. These wavelengths are then used to indicate $\delta_{o,i}$ for each amplifier.

$$g_{2,i} = g_o \quad , \qquad \delta_{1,i} \leq \delta \leq \delta_{2,i} \tag{5}$$

Where, $g_o = 7.4 \times 10^{-14} \, m/W$ is the differential Raman gain constant (of pure SiO2 at λ = 1.34 μm), and

$$\delta_{1.i} = \frac{\lambda_{1,i} - \lambda_{r.i}}{\lambda_{1,i}\lambda_{r,i}} \times 10^4 \, , cm^{-1} \tag{6}$$

$$\delta_{2.i} = \frac{\lambda_{2,i} - \lambda_{r.i}}{\lambda_{2,i}\lambda_{r,i}} \times 10^4 \, , cm^{-1} \tag{7}$$

And

$$g_{3,i} = g_o e^{-0.025(\delta - \delta_{2,i})} \; , \qquad \delta \geq \delta_{2,i} \tag{8}$$

Δλ = λ2 – λ1=16 nm (fixed value for all units)

$$\lambda_1 = \frac{\lambda_{o1}}{1 - 0.044\lambda_{o1}} \times 10^4 \, , \mu m \tag{9}$$

By changing the position $\delta_{o,i}$, the total bandwidth and the flatness of the amplifier are changed.

We are interested in obtaining a large bandwidth with a wider flat gain by changing $\delta_{o,i}$ or $\lambda_{o,i}$. In this case, we can use either of two cases: $\delta_o = \delta_r$ (i.e. $\lambda_o = \lambda_r$) or $\delta_o > \delta_r$ (i.e. $\lambda_o > \lambda_r$), where λ_r is Raman pump wavelength and λ_o is the offset wavelength.

Raman differential gain constant, g, and the effective core area, A, are defined as [9]:

$$g = 1.34 \times 10^{-6} \times g_o \frac{1 + 80\Delta}{\lambda_r}, \qquad and$$
$$\Delta = \frac{n_1 - n_2}{n_1} \tag{10}$$

Where Δ is the refractive index difference, n_1 is the refractive index of the core, and n_2 is the refractive index of the clad.

$$A = \frac{\pi}{2}(W_s^2 + W_r^2), \tag{11}$$

And

$$W = \frac{0.21\lambda}{\sqrt{\Delta}} \quad (12)$$

Where, W_s and W_r are the mode field radii of two light waves coupled with each other with $W=W_s$ at $\lambda = \lambda_s$ and $W=W_r$ at $\lambda = \lambda_r$.

Neglecting the cross coupling among the signal channels, one has the differential equation governing the signal propagation for N-channels Raman pumping [9]:

$$\frac{ds_i}{dz} + \sigma_{si} s_i = \left(\sum_{i=1}^{i=N} \sum_{j=1}^{j=M} \frac{\boldsymbol{g_{ij}}}{\boldsymbol{A_{ij}}} \boldsymbol{P_{Rj}} \right) \boldsymbol{s_i} \, , \quad (13)$$

Where, i = 1,2,3,……..N, M is the number of pumps, S_i is signal power and P_{Rj} is the j^{th} unit pumping power.
Assume the R.H.S of equation (13) equals g_{ti} , as:

$$\boldsymbol{g_{ti}} = \left(\sum_{i=1}^{i=N} \sum_{j=1}^{j=M} \frac{\boldsymbol{g_{ij}}}{\boldsymbol{A_{ij}}} \boldsymbol{P_{Rj}} \right), \quad (14)$$

The total (overall) gain coefficient, $\boldsymbol{g_{ti}}$ in m^{-1} represents the total gain coefficient of the i^{th} signal due to the N-pumping cascaded units. It is clear that $\boldsymbol{g_{ti}}$ is a function of a set of variables such as: signal wavelength; fiber core radius; Raman wavelength; relative refractive index difference; and Raman pumping power. The overall gain, $\boldsymbol{g_{ti}}$ can be written in the form:

$$\boldsymbol{g_{ti}} = \left(\sum_{i=1}^{i=N} \sum_{j=1}^{j=M} \boldsymbol{g_{di}} \boldsymbol{P_{Rj}} \right), \quad (15)$$

Where, the total differential gain, $\boldsymbol{g_{di}}$, is:

$$g_{di} = \left(\sum_{i=1}^{i=N} \sum_{j=1}^{j=M} g_{ij} \right), mW^{-1} \quad (16)$$

And by Defining a total gain coefficient per watt (m/w) , g_{ci} , as:

$$g_{ci} = \left(\sum_{i=1}^{i=N} \sum_{j=1}^{j=M} \frac{g_{dij}}{A_{ij}} \right), m^{-1}W^{-1} \quad (17)$$

Then, we have three gain coefficients: $\boldsymbol{g_{di}}$, $\boldsymbol{g_{ci}}$ and $\boldsymbol{g_{ti}}$, are functions of the propagation distance.

III. MODEL EXAMPLES AND CASES

In this paper, we investigated two model examples of cascaded Raman amplifier, these examples are the 6^{th} order and 8^{th} order Raman amplifier, respectively. Both of these examples design are obtained by using the following equation:

$$\lambda_1 = \frac{\lambda_o}{1 - 0.044\lambda_o} \times 10^4 \, , \mu m \quad (18)$$

TABLE 1.MODEL 1: NUMBER OF AMPLIFIERS = 6

Λr	λo	λ1	λ2	Pr(W)
1.4	1.432	1.528294799	1.544294799	0.20
1.42	1.452	1.548294799	1.564294799	0.15
1.44	1.472	1.568294799	1.584294799	0.15
1.467	1.499	1.595294799	1.611294799	0.20
1.48	1.512	1.608294799	1.624294799	0.15
1.5	1.52	1.616294799	1.632294799	0.15

TABLE 2.MODEL 2: NUMBER OF AMPLIFIERS = 8

λ_r	λ_o	λ_1	λ_2	P_p(W)
1.4	1.4443	1.540830404	1.556830404	0.14
1.405	1.448	1.545830404	1.561830404	0.12
1.425	1.471	1.568830404	1.584830404	0.14
1.43	1.477	1.574830404	1.590830404	0.10
1.45	1.499	1.596830404	1.612830404	0.14
1.455	1.505	1.602830404	1.618830404	0.12
1.475	1.528	1.625830404	1.641830404	0.11
1.48	1.534	1.631830404	1.647830404	0.13

Firstly, we choose the offset wavelength of the first unit of the cascaded units consisting the overall Raman amplifier; we choose $\boldsymbol{\lambda_o}$ from the wave length range (from 1.45µm – to- 1.65µm). Then, we calculate $\boldsymbol{\lambda_1}$ using Eq.(18). After that, we assume the identical Raman units of individual bandwidth of $\lambda_2 - \lambda_1$=16 nm. This is done for each amplifier unit.
Finally, we obtain the two design examples , which are the 6^{th} order and 8^{th} order Raman amplifier as shown in TABLE 1 and TABLE 2, respectively. Note that $\lambda_1 - \lambda_o$ =0.096294798, and $\lambda_2 - \lambda_1$=16 nm.
We consider two cases for the pumping wavelength $\boldsymbol{\lambda_r}$, these two cases are considered for each model example.

A. Case A : $\lambda_r \neq \lambda_o$

B. Case B **:** $\lambda_r = \lambda_o$

For each case we execute a simulation program to find and demonstrate the figures of the three gain coefficients of the Raman amplifier: $\boldsymbol{g_{di}}$, $\boldsymbol{g_{ci}}$ and $\boldsymbol{g_{ti}}$.
There are many parameters affecting the gain coefficients such as: effective core area, relative refractive index difference, pumping wavelengths and pumping powers. So these parameters must be taken into account for any design.

IV. SIMULATION RESULTS AND DISCUSSIONS

The bandwidth for distributed multi-pumping Raman amplifier is investigated with aim of obtaining maximum flat-gain amplifier with as wider bandwidth as possible. Bandwidth; $\Delta\lambda_r$, can be evidently broadened by means of increasing the number of pumps (amplifier units) and by adjusting the position of these cascaded units.

As we said in Sec. III, we have investigated the distributed multi-pumping Raman amplifier by two model examples that are 6th order and 8th order amplifier. Each model example have been tested under two cases. That are : $\lambda_r \neq \lambda_o$ case and $\lambda_r = \lambda_o$.

A. *Results of Model 1:*

For The 6th order Raman, the three gain coefficients g_{di}, g_{ci} and g_{ti}, are obtained through simulation results and depicted in the corresponding figures.

A. *Model 1: Case A : $\lambda_r \neq \lambda_o$*

In this case we put the pumping wavelengths of the amplifier units not equal to the offset wavelengths.
The design structure of the 6th order Raman amplifier is obtained as shown in TABLE 1.
The following results will be demonstrated as:

1) Differential gain:

Figure 2 displays the differential Raman gain versus wavelength, *λ*, at different values of the relative refractive index difference (Δ). If the relative index difference increases, Raman gain will increase.

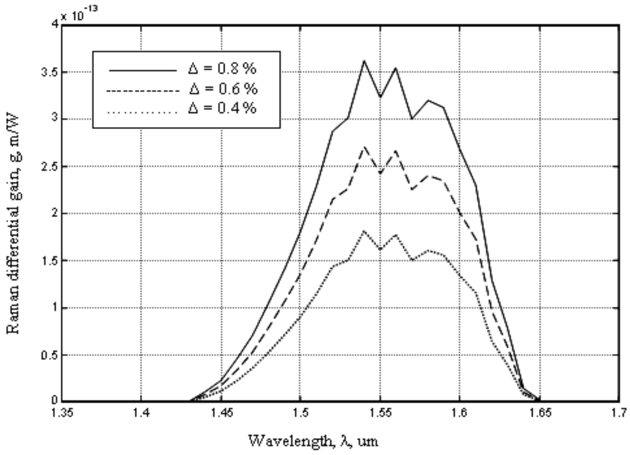

Figure 2. Differential gain versus the wavelength *λ* at different and $\lambda_r \neq \lambda_o$

We note that Raman gain starts to increase from the first pumping wavelength to reach its peak value at 1.54μm, then it decreases exponentially tending to zero at 1.65μm. Since the optical amplifiers and optical signals are operated in the range of 1.45μm to 1.65μm. In this case we obtained, the overall bandwidth of the cascaded amplifier =110nm, (from λ_{1t} =1.5μm to λ_{2t} =1.61μm).

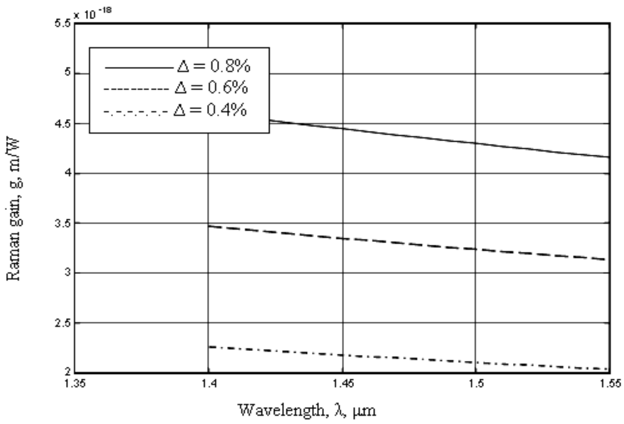

Figure 3. Raman gain variation with different values of .

Figure 3 depicts the relation between Raman gain and pumping wavelength. This figure is plotted at different values of relative index difference, where pumping wavelengths for optical signals in the range from 1.4 to 1.55 μm, this range is suitable for Raman amplifier to avoid noise and losses.

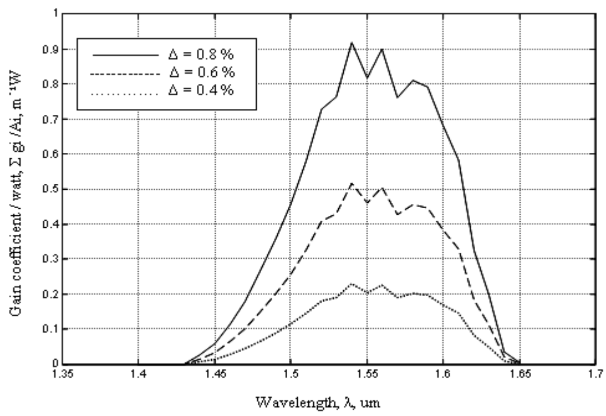

Figure 4. The gain per unit watt at different values of wavelength λ

Figure 4 shows the gain coefficient per unit watt, at different values of relative refractive index difference.
We note that gain coefficient/unit watt starts to increase from the first pumping wavelength to reach its peak value at 1.56μm, then it decreases exponentially tended to zero at 1.65μm. In this case we obtained, a total bandwidth (overall bandwidth) =110nm, (from λ1t =1.5μm to λ2t =1.61μm).
Depending on these results, we noticed that there are many parameters affecting the gain coefficient per unit watt such as: effective core area, relative refractive index difference, pumping wavelengths and pumping powers. So these parameters must be taken into account for any design.

2) The total gain coefficient:

Figure 5 displays the variation of the total gain coefficient with wavelength. In this case, a bandwidth of 110 nm is obtained. Similarly, we note the peak value of the gain is at 1.54μm, and the gain tended to zero at 1.65μm.
It is found that, when pumping powers increase the total gain increases, so Raman amplifier is preferred to be used with high pumping powers.

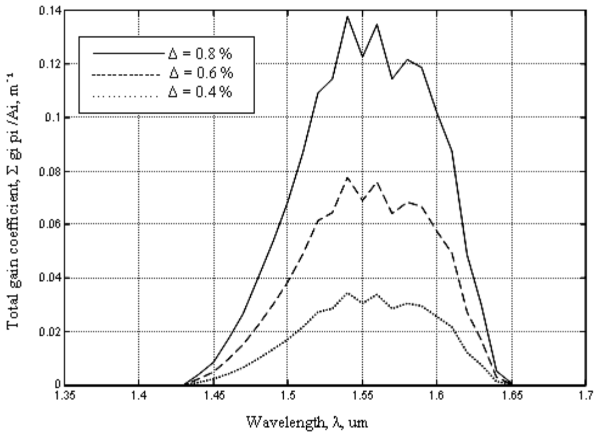

Figure 5. Variation of total gain coefficient with wavelength.

B. Model 1: Case B : $\lambda_r = \lambda_o$

In this case we put the pumping wavelengths equal to the offset wavelengths of the corresponding units.
The following results will be demonstrated as:

1) Differential gain:

Figure 6 displays the differential Raman gain, g, with wavelength, λ, at different values of the relative refractive index difference.

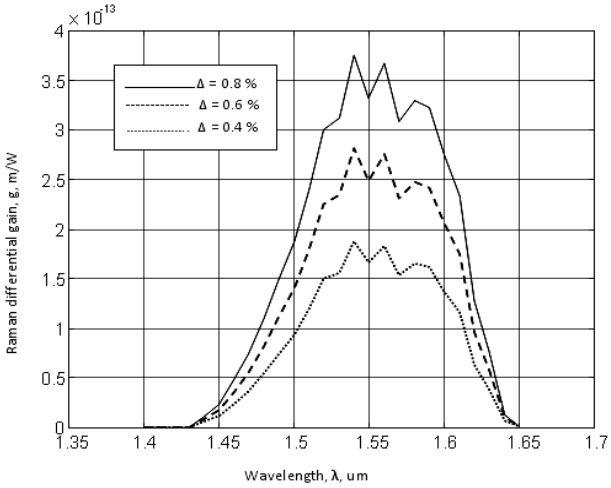

Figure 6. Differential gain versus the wavelength λ at different and $\lambda_r = \lambda_o$

If relative index difference increases, Raman gains increases.
We note that Raman gain starts to increase from the first pumping wavelength to reach to peak value at 1.54µm, then the gain decreases exponentially tended to zero at 1.65µm.
In this case we obtained, an overall bandwidth =120nm, (λ_{1t} =1.49µm and λ_{2t} =1.61µm).

2) The gain coefficient per unit watt:

The gain coefficient/unit watt, against wavelength is shown in Fig. 7 at different values of relative refractive index difference.
We note that the gain coefficient/unit watt starts to increase from the first pumping wavelength to reach its peak value at 1.56µm, then the gain decreases exponentially tended to zero at 1.65µm.

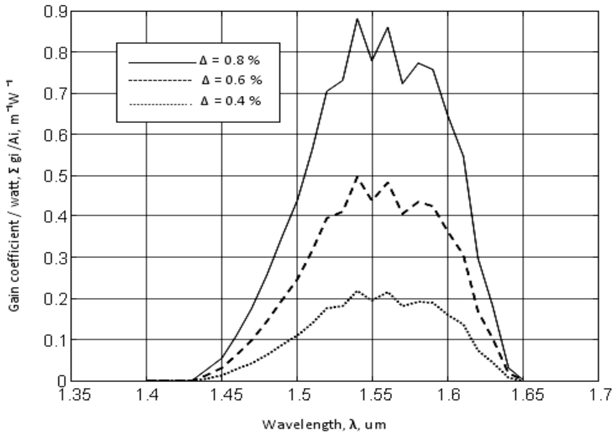

Figure 7. Gain coefficient per unit watt against wavelength.

3) The total gain coefficient:

Figure 8 displays the variation of the total gain coefficient with wavelength. In this case, a bandwidth of 120nm is obtained. Similarly, we note the total gain coefficient has its peak value at 1.54µm, and its zero value at 1.65µm.

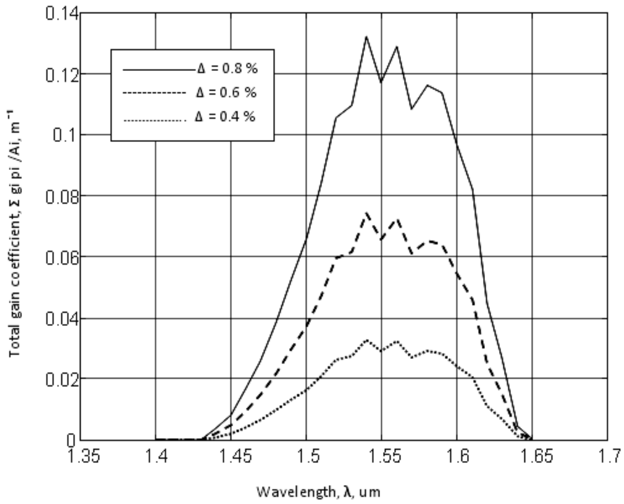

Figure 8. Variation of total gain coefficient with wavelength.

*B. **Results of Model 2:***

For The 8th order Raman, the three gain coefficients : g_{di}, g_{ci} and g_{ti}, are obtained through simulation results and depicted in the corresponding figures.

A. Results of Model 2: Case A : $\lambda_r \neq \lambda_o$

In this case we put the pumping wavelengths of the amplifier units not equal the offset wavelengths.
The design structure of the 8th order Raman amplifier is obtained as shown in TABLE 2.

1) Differential gain:

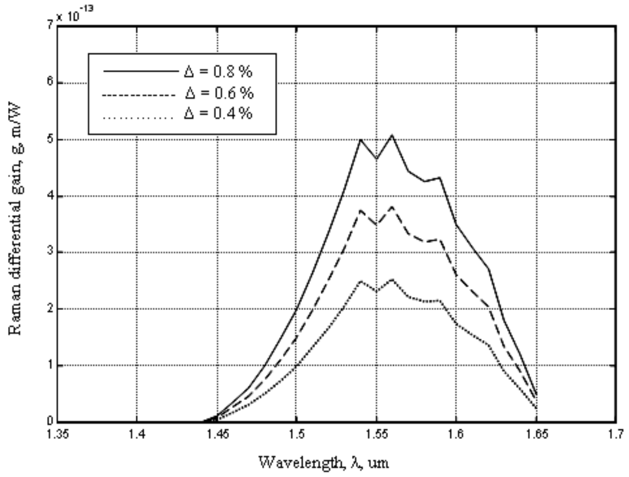

Figure 9. Differential gain versus the wavelength λ at different and $\lambda_r \neq \lambda_o$

Figure 9 displays the differential Raman gain, g m/w, with wavelength, λ, at different values of the relative refractive index difference (Δ). If the relative index difference increases, Raman gain will increase.

We note that Raman gain starts to increase from the first pumping wavelength to reach to peak value at 1.56μm, then the gain it starts to decrease exponentially tending to zero at 1.65μm. Because of optical amplifiers and optical signals are operated in range 1.45μm to 1.65μm. In this case we obtained, total bandwidth =120nm, where λ_{1t} =1.5μm , and λ_{2t} =1.62μm.

2) The gain coefficient per unit watt:

Figure 10 shows the gain coefficient/unit watt, $\sum$ gi / Ai, m^{-1} W^{-1} at different values of relative refractive index difference.

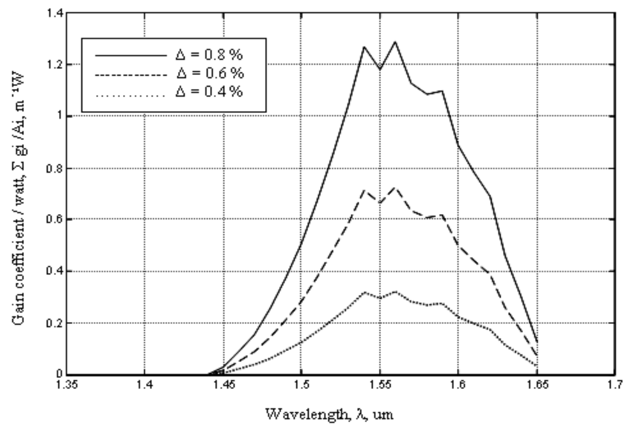

Figure 10. The gain per unit watt at different values of .

We note that gain coefficient/unit watt starts to increase from the first pumping wavelength to reach to peak value at 1.56μm, then the gain decreases exponentially tended to zero at 1.65μm. Depending on these results, we can say that there are many parameters affect the gain coefficient per unit watt such as: effective core area, relative refractive index difference, pumping wavelengths and pumping powers. So these parameters must be taken into account for any design.

In this case we obtained, total (overall) bandwidth =120nm, where λ_{1t} =1.5μm and λ_{2t} =1.62μm.

3) The total gain coefficient:

Figure 11 displays the variation of the total gain coefficient with wavelength. In this case, a bandwidth of 120 nm is obtained. Similarly, we note the total gain coefficient starts to increase from the first pumping wavelength to reach to peak value at 1.56 μm. The gain decreases exponentially until it reaches to zero at 1.65μm. Gain in this case is affected by pumping powers, effective core area and the relative index difference.

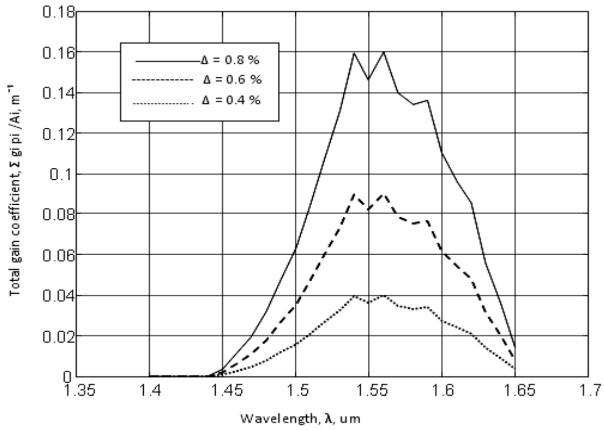

Figure 11. Variation of total gain coefficient with wavelength.

It is found that, when pumping powers increase the total gain increases, so Raman amplifiers is preferred to be used with high pumping powers.

B. Model 2 :Case B: $\lambda_r = \lambda_o$

In this case we put the pumping wavelengths equal to the offset wavelengths of the corresponding units.

1) Differential gain:

Figure 12 displays the differential Raman gain, g, with wavelength, λ, at different values of the relative refractive index difference. If relative index difference increases, Raman gains increases.

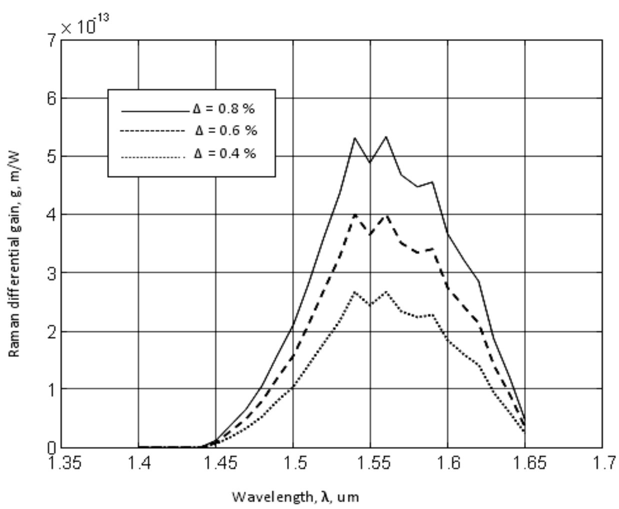

Figure 12. Differential gain versus the wavelength λ at different and $\lambda_r = \lambda_o$

We note that Raman gain starts to increase from the first pumping wavelength to reach the peak value at 1.56μm, then it decreases exponentially tended to zero at 1.65μm. Because of optical amplifiers and optical signals are operated in the range 1.45μm to 1.65μm.
In this case we obtained, total bandwidth =120nm, where λ_{1t} =1.5μm (for all amplifier units) and λ_{2t} =1.62μm (for all amplifier units).

2) The gain coefficient per unit watt:

The gain coefficient/unit watt, $\sum$ gi / Ai, m^{-1} W^{-1} against wavelength is shown in Fig. 13 at different values of relative refractive index difference.

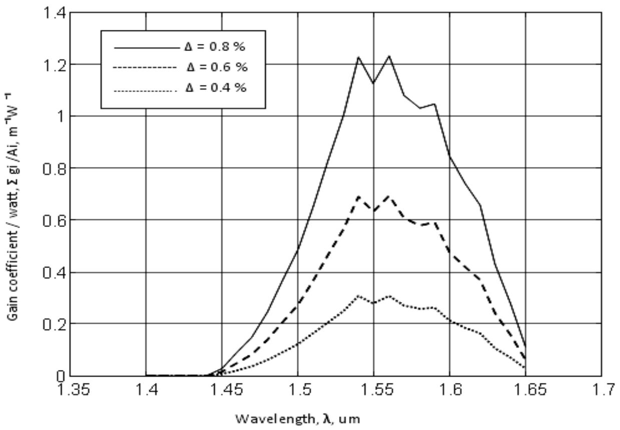

Figure 13. Gain coefficient per unit watt against wavelength.

We note that the peak value at 1.56μm, and the zero value at 1.65μm.
Depending on these results, we can say that there are many parameters affect the gain coefficient per unit watt such as: effective core area, relative refractive index difference, pumping wavelengths and pumping powers.

3) The total gain coefficient:

Figure 14 displays the variation of the total gain coefficient with wavelength. In this case, a bandwidth of 120nm is obtained. By similar we note the total gain coefficient is start to increase from the first pumping wavelength to reach to peak value at 1.56μm, the gain is start to decrease exponentially tended to zero at 1.65μm. Gain in this case is affected by pumping powers, effective core area and relative index difference. It is found that, when pumping powers increase the total gain increases, so Raman amplifiers is preferred to be used with high pumping powers.

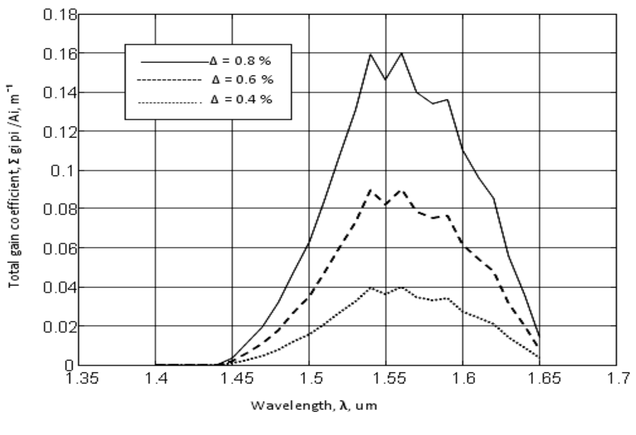

Figure 14. Variation of total gain coefficient with wavelength.

TABLE 3. COMPARISON BETWEEN TWO MODEL

Model 1 number of amplifier N=6			*Model 1 number of amplifier N=6*		
Case A			*Case B*		
g_{max}	Δ %	*BW nm*	g_{max}	Δ %	*BW nm*
3.6239×10^{-13} 2.7179×10^{-13} 1.8119×10^{-13}	0.8 0.6 0.4	110	3.7553×10^{-13} 2.8165×10^{-13} 1.8776×10^{-13}	0.8 0.6 0.4	120
Model 2 number of amplifier N=8			*Model 2 number of amplifier N=8*		
Case A			*Case B*		
g_{max}	Δ %	*BW nm*	g_{max}	Δ %	*BW nm*
5.0734×10^{-13} 3.8050×10^{-13} 2.5367×10^{-13}	0.8 0.6 0.4	120	5.3468×10^{-13} 4.0101×10^{-13} 2.6734×10^{-13}	0.8 0.6 0.4	120

From TABLE 3, we note that the gain of each unit of the amplifiers in case B is better than the gain in case A also, the bandwidth in case B is larger than in case A for model 1 but for model 2 the bandwidth in case A is the same as in case B but the gain increases in case B. The maximum gain increases with the relative refractive index difference increase. And bandwidth changes according to the change of the position of optical amplifiers. Also from table 3 the gain and bandwidth for model 2 is better than that of model 1, therefore by increasing the cascaded units we can improve the overall performance of the Raman amplifier.

V. CONCLUSIONS

By using N cascaded Raman amplifier units, N pumping signals are injected in a parallel processing at different pumping powers and wavelengths, we have obtained the following simulation results:

1- The overall gain of Raman amplifier is increased due to putting the pumping wavelengths equal to the offset wavelengths of the amplifier units.
2- We have obtained a bandwidth of about 110 nm and 120 nm at different value of the relative refractive index difference for 6 cascaded units of optical Raman amplifiers.
3- And also we have obtained a bandwidth of about 120 nm at different value of the relative refractive index difference for 8 cascaded units of optical Raman amplifiers.
4- The overall gain of the cascaded Raman amplifier increases if the number of optical amplifier units and/or the relative refractive index difference increases.
5- The bandwidth and/or the flatness of the gain depend on the position of the amplifier units (wavelength value of

the cascaded units) corresponding to each other's and on the number of amplifier units.

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