# Improvement the Flatness, Gain and Bandwidth of Cascaded Raman Amplifiers for Long- Haul UW-WDM Optical Communications Systems

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## Abstract

In the present paper, the problem of multi-pumping all Raman amplifier has been investigated to obtain a maximum flatness gain and increases the bandwidth of the cascaded Raman amplifiers over a wide range of optical signal wavelengths for long-haul ultra-wide wavelength division multiplexing (UW-WDM) transmission systems due to multi-pumping wavelengths and pumping power . Three cases are analyzed where, five, eight and ten Raman pumping of special pumping powers are launched in the forward direction. We obtained a different bandwidth and different gain with flatness [1] but in the present paper we modified the flatness of the gain. The model equations are numerically handled and processed via specially cast software (Matlab). The gain is computed over the spectral optical wavelengths ($1.45\mu m \leq \lambda_{signal} \leq 1.65\mu m$).

*Keywords: Raman amplifier, Distributed multi-pumping Raman amplifier (DMRA), Raman gain, pumping power and wavelength, ultra wide-wavelength division multiplexing (UW-WDM).*

## 1. 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 [2]. Two approaches to Raman amplification have received the most attention. These are designated as single-order and dual- order Raman amplification, where the pump and signal laser are separated by a single Raman-Stokes shift [3].

In the mid-1990s, the development of suitable high power pumps sparked a renewed interest. Researchers were quick to demonstrate some of the advantages that Raman amplifiers have over erbium doped fiber amplifiers (EDFAs), particularly when the transmission fiber itself is turned into a Raman amplifier. This, in turn, shows the exponential increase since 1994 in the capacity-distance product of transmission experiments reported in literature [4].

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 [5].

The term distributed amplification refers to the method of cancellation of the intrinsic fiber loss. The loss in distributed amplifiers is counterbalanced at every point along the transmission fiber in an ideal distributed amplifier [5].

In the late eighties, Raman amplification was perceived as the way to overcome attenuation in optical fibers and research on long haul transmission was carried out demonstrating transmission over several thousand kilometers using distributed Raman amplification. However, with the development and commercialization of erbium-doped fiber amplifiers through the early nineties, work on distributed Raman amplifiers was abandoned because of its poor pump power efficiency when compared to erbium-doped fiber amplifiers (EDFAs). 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 [5].

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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 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 [5].

The use of distributed Raman amplification has already been demonstrated in ultra-high-capacity optical communication systems as the enabling method to transmit 40Gbit/s per channel in a wavelength-division-multiplexed transmission system [5].

The most important feature of Raman-gain spectrum is that the peak-gain wavelength only depends on the pump wavelength. The peak-gain wavelength for each pump still exists although the total gain spectrum of a multi-pumped fiber Raman amplifier (FRA) is the comprehensive result of all pumps [6].

Two critical merits of distributed Raman amplifier (DRA) are the low noise and the arbitrary gain band. Experiments show that 2.5 Gb/s system could be up graded to 10Gb/s by only adding a Raman amplifier [7].

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 [8].

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 [9].

In this paper, Raman gain coefficient and Raman differential gain are processed through a numerical solution of the mathematical model.

## 2. Mathematical Model

In the present section, we cast the basic model and the governing equation to process N-Raman amplifiers in a cascaded form of special pumping powers $P_{r1}$, $P_{r2}$, $P_{r3}$, $P_{r4}$, ......., $P_{rN}$ and corresponding pumping wavelengths $\lambda_{r1}$, $\lambda_{r2}$, $\lambda_{r3}$, $\lambda_{r4}$, ......., $\lambda_{rN}$. The map of δ-g is as shown in Fig. 1, where δ is the Raman shift and g is the Raman differential gain coefficient; both were cast based on [10-14] as:

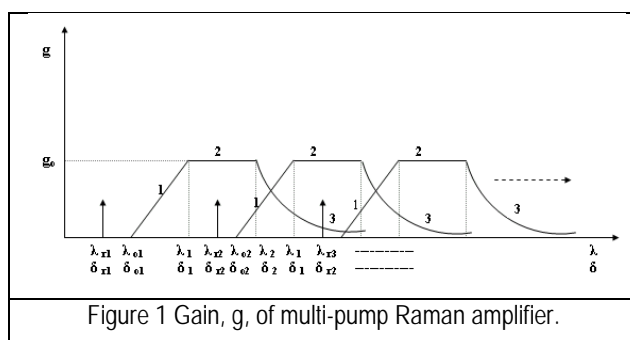$$\delta = \frac{\lambda_s - \lambda_r}{\lambda_s \lambda_r} \times 10^4 \, , cm^{-1} \qquad (1)$$



Figure 1 Gain, g, of multi-pump Raman amplifier.

The map of δ–g shown in Fig. 1 describes the basic model. This section depends on the position of the gain of each amplifier with wavelength, where the gain of each amplifier consists of three parts (three equations). A special software program is used to indicate the position of $\delta_{o,i}$ or $\lambda_{o,i}$ and studying the total gain of the amplifiers. In this case, the basic model depends on using more than one amplifier which is put in a cascaded form to increase the bandwidth of the amplifier to multiplexing more signals in the transmission system. The overall amplifier bandwidth increases and the gain flatness improved depend on the position of each amplifier corresponding to other amplifiers. This is achieved by more trials of changing of $\delta_{o,i}$ or $\lambda_{o,i}$ for each amplifier.

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The general equations representing the Raman gain in the three regions are respectively [14].

$$g_{1,i} = g_o \frac{\delta}{440} \quad , \quad 0 \leq \delta \leq 440 \tag{2}$$

Where

$$\delta = \frac{\lambda_s - \lambda_r}{\lambda_s \lambda_r} \times 10^4 \, , cm^{-1} \tag{3}$$

$$g_{2,i} = g_o \, , \quad \delta_{1,i} \leq \delta \leq \delta_{2,i} \; and \; \lambda_1 \leq \lambda \leq \lambda_2 \tag{4}$$

Where $g_o = 7.4 \times 10^{-14} \, m/W$ and

$$\delta_{1.i} = \frac{\lambda_{1,i} - \lambda_{r.i}}{\lambda_{1,i}\lambda_{r,i}} \times 10^4 \, , cm^{-1} \tag{5}$$

$$\delta_{2.i} = \frac{\lambda_{2,i} - \lambda_{r.i}}{\lambda_{2,i}\lambda_{r,i}} \times 10^4 \, , cm^{-1} \tag{6}$$

And

$$g_{3,i} = g_o e^{-0.005(\delta - 440)} \, , \quad \delta \geq 440 \tag{7}$$

Δλ = λ$_2$ – λ$_1$ = 15 nm = (fixed value)

$$\lambda_1 = \frac{\lambda_{r1}}{1 - 0.044\lambda_{r1}} \times 10^4 \, , \mu m \tag{8}$$

$$g_{1,i} = g_o \frac{\delta - \delta_{o,i}}{440} \tag{9}$$

Where

$$\delta_{o,i} \leq \delta \geq \delta_{1.i} \, , \quad 0 \leq \delta - \delta_{o,i} \leq 440 \tag{10}$$

With

$$\delta_{o.i} = \frac{\lambda_{o,i} - \lambda_{r.i}}{\lambda_{o,i}\lambda_{r,i}} \times 10^4 \, , cm^{-1} \tag{11}$$

With 1 cm$^{-1}$ = 30 GHz [15], 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.

$$g_{2,i} = g_o \, , \quad \delta_{1,i} \leq \delta \leq \delta_{2,i} \tag{12}$$

Where, $g_o = 7.4 \times 10^{-14} \, m/W$ is the differential Raman gain constant (of pure SiO$_2$ at λ = 1.34 μm), and

$$\delta_{1.i} = \frac{\lambda_{1,i} - \lambda_{r.i}}{\lambda_{1,i}\lambda_{r,i}} \times 10^4 \, , cm^{-1} \tag{13}$$

$$\delta_{2.i} = \frac{\lambda_{2,i} - \lambda_{r.i}}{\lambda_{2,i}\lambda_{r,i}} \times 10^4 \, , cm^{-1} \tag{14}$$

And

$$g_{3,i} = g_o e^{-0.025(\delta - \delta_{2,i})} \, , \quad \delta \geq \delta_{2,i} \tag{15}$$

Δλ = λ$_2$ – λ$_1$ = 16 nm = (fixed value)

$$\lambda_1 = \frac{\lambda_{o1}}{1 - 0.044\lambda_{o1}} \times 10^4 \, , \mu m \tag{16}$$

Where, $\lambda_r$ is Raman pump wavelength and $\lambda_o \geq$ 1.35um.

The shift δ$_{o,i}$ is the Raman shift that indicates the position of each amplifier. By changing this position, the total bandwidth and the flatness of the amplifier are changed. We are interested in obtaining a large bandwidth with flatness by more trials of changing δ$_{o,i}$ or λ$_{o,i}$. In this case, one uses δ > δ$_r$ or λ > λ$_r$ and δ$_o$ ≥ δ$_r$ or λ$_o$ ≥ λ$_r$, where λ$_r$ is Raman pump wavelength. Raman differential gain constant, g, and the effective core area, A, are defined as [11]:

$$g = 1.34 \times 10^{-6} \times g_o \frac{1 + 80\Delta}{\lambda_r} \tag{17}$$

$$A = \frac{\pi}{2}(W_s^2 + W_r^2), \tag{18}$$

Where

$$W = \frac{0.21\lambda}{\sqrt{\Delta}} \, , \tag{19}$$

Where, λ$_r$ is the pump wavelength, W$_s$ and W$_r$ are the mode field radii of two light waves coupled with each other with W=W$_s$ at λ= λ$_s$ and W=W$_r$ at λ= λ$_r$ and Δ is the relative refractive index difference.

Neglecting the cross coupling among the signal channels, one has the differential equation governing the signal propagation for N-channels Raman pumping [12]:

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$$\frac{ds_i}{dz} + \sigma_{si}s_i = \left(\sum_{i=1}^{i=N}\sum_{j=1}^{j=M}\frac{g_{ij}}{A_{ij}}P_{Rj}\right)s_i , \qquad (20)$$

Where, $i = 1,2,3,\ldots\ldots N$, M is the number of pumps, $S_i$ is signal power and $P_{Rj}$ is the pump power. Assume the R.H.S of equation (20) equals $g_{ti}$, as:

$$g_{ti} = \left(\sum_{i=1}^{i=N}\sum_{j=1}^{j=M}\frac{g_{ij}}{A_{ij}}P_{Rj}\right) , \qquad (21)$$

The total gain coefficient in $m^{-1}$ which represents the total gain coefficient of the $i^{th}$ signal due to the N-pumping. It is clear that $g_{ti}$ is a function of the set of variables {signal wavelength, fiber radius, Raman wavelength, relative refractive index difference, Raman power}. This term can be written in the form:

$$g_{ti} = \left(\sum_{i=1}^{i=N}\sum_{j=1}^{j=M}g_{di}P_{Rj}\right) , \qquad (22)$$

Define $g_{ci}$, the total gain coefficient per watt, as

$$g_{ci} = \left(\sum_{i=1}^{i=N}\sum_{j=1}^{j=M}\frac{g_{dij}}{A_{ij}}\right), m^{-1}W^{-1} \qquad (23)$$

Then, the total differential gain, $g_{di}$, is:

$$g_{di} = \left(\sum_{i=1}^{i=N}\sum_{j=1}^{j=M}g_{ij}\right), mW^{-1} \qquad (24)$$

The three gain coefficients $g_{di}$, $g_{ci}$ and $g_{ti}$ are also functions of the propagation distance.

## 3. Simulation Results and Discussions

The bandwidth for cascaded multi-pumping Raman amplifier is optimized. Optimal results show that the amplifier bandwidth, $\Delta\lambda_r$, can be evidently broadened by means of increasing the number of pumps and according to the position of each amplifier. It is found that $\Delta\lambda r$ decreases with the increase of Raman gain and with the improvement of flatness. The hybrid EDFA and DMRA can availably overcome the weakness of pure DMRA. In this paper,

we discus three different models; namely, five, eight and the ten Raman pumping optical wavelengths and pumping powers are shown in the tables I, II, and III, respectively, where the sum of pumping powers is one watt. The three gain coefficients $g_{di}$, $g_{ci}$, and $g_{ti}$ are displayed for each case.

## Case I

Table I    Number of amplifiers = 5

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

$\lambda_1 - \lambda_o$ =fixed value (0.096294798) and $\lambda_2 - \lambda_1$ =16 nm

| $\lambda_r$ | $\lambda_o$ | $\lambda_1$ | $\lambda_2$ | $P_p(W)$ |
|---|---|---|---|---|
| 1.4 | 1.432 | 1.528294799 | 1.544294799 | 0.17 |
| 1.44 | 1.477 | 1.573294799 | 1.589294799 | 0.25 |
| 1.46 | 1.500 | 1.596294799 | 1.612294799 | 0.18 |
| 1.48 | 1.523 | 1.619294799 | 1.635294799 | 0.24 |
| 1.5 | 1.532 | 1.628294799 | 1.644294799 | 0.16 |

## Differential gain

Figure 2 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.

We note that Raman gain is starts to increase from the first pumping wavelength to reach to peak value at 1.59 µm, then the gain is start to decrease exponentially tended to zero at 1.65 µm. Because of optical amplifiers and optical signals are operated in range 1.45 µm to 1.65 µm.

In this case we obtained, total bandwidth =110nm, where $\lambda_{1t}$ = 1.51 µm (for all amplifiers) and $\lambda_{2t}$ = 1.62 µm (for all amplifiers).
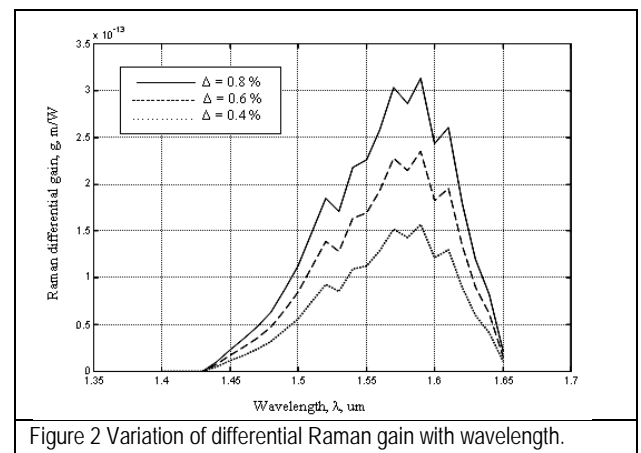


Figure 2 Variation of differential Raman gain with wavelength.

Fig.3 depicts the relation between Raman gain, g m/w and pumping wavelength. This figure is plotted

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at different values of relative index difference, where pumping wavelengths for optical signals in range from 1.4 to 1.55 µm, this range is suitable for Raman amplifier to avoid noise and losses.

Then any source has pumping wavelength and pumping power must be suitable for choice design to obtained suitable gain and bandwidth
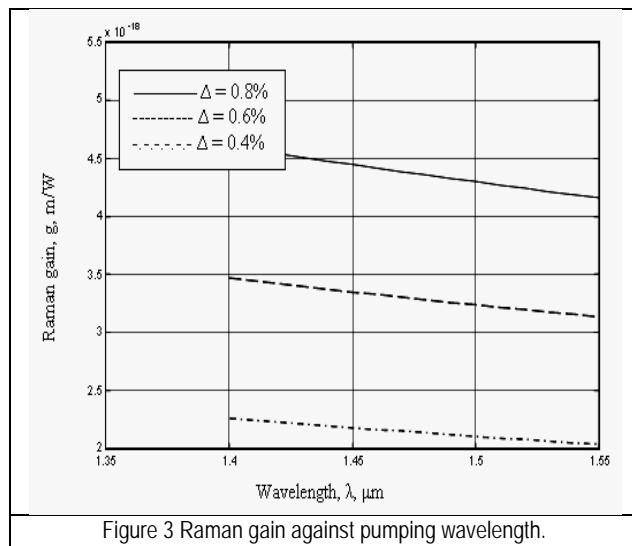

Figure 3 Raman gain against pumping wavelength.

Figure 4 displays Raman gain, g, against the relative refractive index difference. This figure is plotted for special pumping wavelengths.

So relative index difference of the materials must be take in account in design for optical amplifiers.
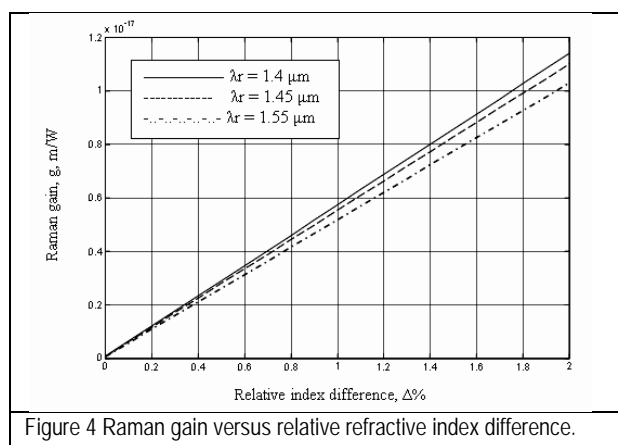

Figure 4 Raman gain versus relative refractive index difference.

## Gain coefficient per unit watt

The gain coefficient/unit watt, $\sum g_i / A_i$, $m^{-1} W^{-1}$ against wavelength is shown in Fig. 5 at different values of relative refractive index difference.
We note that gain coefficient/unit watt is starts to increase from the first pumping wavelength to reach to peak value at 1.59 µm, then the gain is start to

decrease exponentially tended to zero at 1.65 µm. In this case more than one parameter can be control in gain coefficient per unit watt such that effective core area, relative refractive index difference, pumping wavelengths and pumping powers. So these parameters take in account for any design. Where each parameter can effected in design.

In this case we obtained, total bandwidth =110nm, where $\lambda_{1t}$ = 1.51 µm (for all amplifiers) and $\lambda_{2t}$ = 1.62 µm (for all amplifiers).
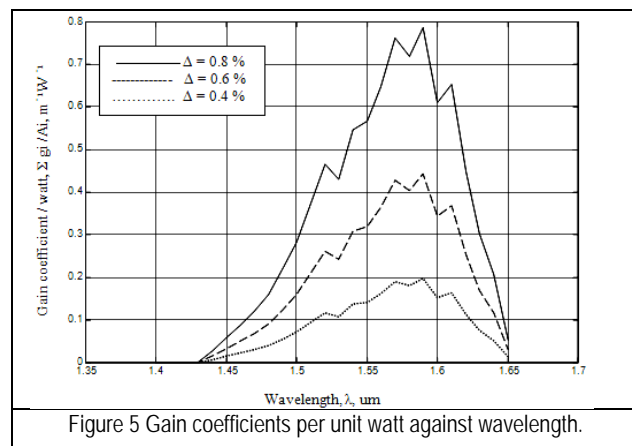

Figure 5 Gain coefficients per unit watt against wavelength.

## Total gain coefficient

Figure 6 displays the variation of the total gain coefficient with wavelength. In this case, a bandwidth of 110 nm 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 1.59 µm, 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.

Where pumping powers increase the total gain is increase so Raman amplifiers is used to sources with high pumping powers.
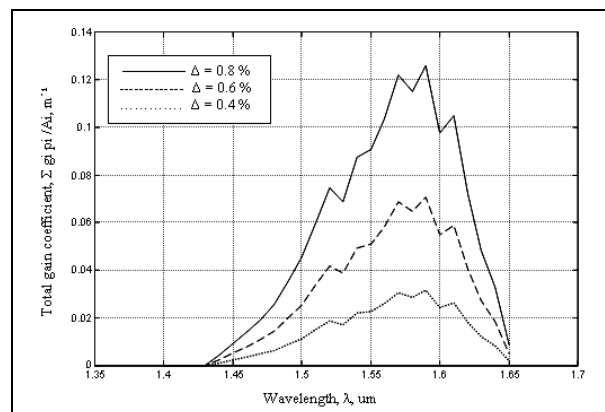
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Figure 6 Variation of total gain coefficient with wavelength.

## Case II

Table II   Number of amplifiers = 8
$\lambda_1 - \lambda_0$ =fixed value (0.093262399) and $\lambda_2 - \lambda_1$ =16 nm

| $\lambda_r$ | $\lambda_0$ | $\lambda_1$ | $\lambda_2$ | $P_p$(W) |
|------|-------|-------------|-------------|------|
| 1.41 | 1.41 | 1.503262399 | 1.519262399 | 0.14 |
| 1.44 | 1.444 | 1.537262399 | 1.553262399 | 0.12 |
| 1.45 | 1.455 | 1.548262399 | 1.564262399 | 0.14 |
| 1.46 | 1.466 | 1.559262399 | 1.575262399 | 0.10 |
| 1.47 | 1.478 | 1.571262399 | 1.587262399 | 0.14 |
| 1.48 | 1.489 | 1.582262399 | 1.598262399 | 0.12 |
| 1.49 | 1.501 | 1.594262399 | 1.610262399 | 0.11 |
| 1.5 | 1.512 | 1.605262399 | 1.621262399 | 0.13 |

The differential Raman gain and the gain coefficient per unit watt are displayed, respectively, in Figs. 7 and 8, while the total gain is displayed in Fig. 9. In this case, a 110 nm bandwidth is obtained. Peak value in this case at 1.55 µm for the different gain.
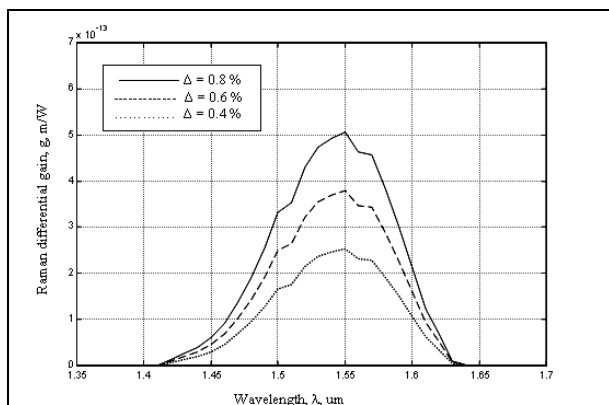


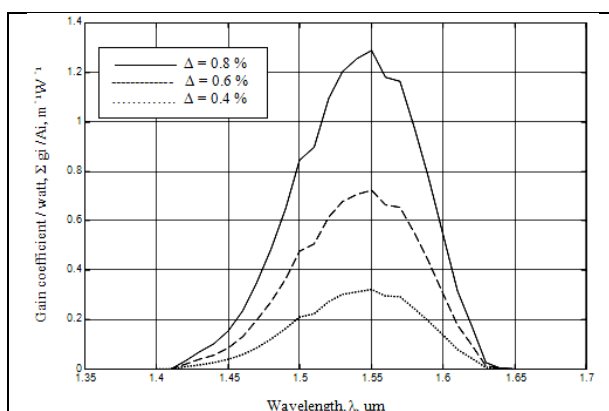Figure 7 Variation of differential Raman gain with wavelength.



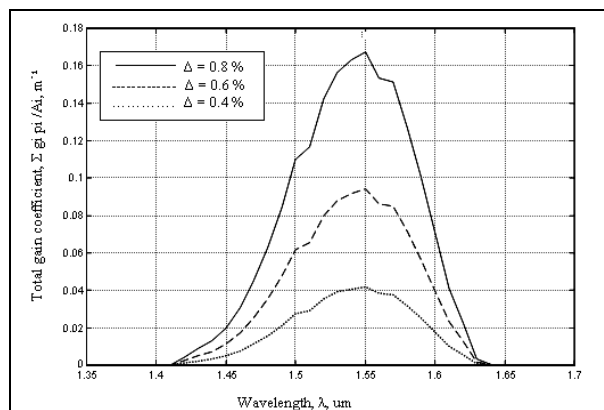Figure 8 Gain coefficients per unit watt against wavelength.



Figure 9 Variation of total gain coefficient with wavelength.

## Case III

Table III   Number of amplifiers = 10
$\lambda_1 - \lambda_0$ =fixed value (0.093262399) and $\lambda_2 - \lambda_1$ =16 nm

| $\lambda_r$ | $\lambda_0$ | $\lambda_1$ | $\lambda_2$ | $P_p$(W) |
|------|-------|-------------|-------------|------|
| 1.41 | 1.41 | 1.503262399 | 1.519262399 | 0.08 |
| 1.42 | 1.421 | 1.514262399 | 1.530262399 | 0.08 |
| 1.43 | 1.432 | 1.525262399 | 1.541262399 | 0.12 |
| 1.44 | 1.444 | 1.537262399 | 1.553262399 | 0.13 |
| 1.45 | 1.455 | 1.548262399 | 1.564262399 | 0.10 |
| 1.46 | 1.466 | 1.559262399 | 1.575262399 | 0.10 |
| 1.47 | 1.478 | 1.571262399 | 1.587262399 | 0.12 |
| 1.48 | 1.489 | 1.582262399 | 1.598262399 | 0.11 |
| 1.49 | 1.501 | 1.594262399 | 1.610262399 | 0.08 |
| 1.5 | 1.512 | 1.605262399 | 1.621262399 | 0.08 |

The differential Raman gain and the gain coefficient per unit watt are displayed, respectively, in Figs. 10 and 11, while the total gain is displayed in Fig. 12. In this case, a 110 nm bandwidth is obtained. Peak value in this case at 1.52 µm for the different gain.
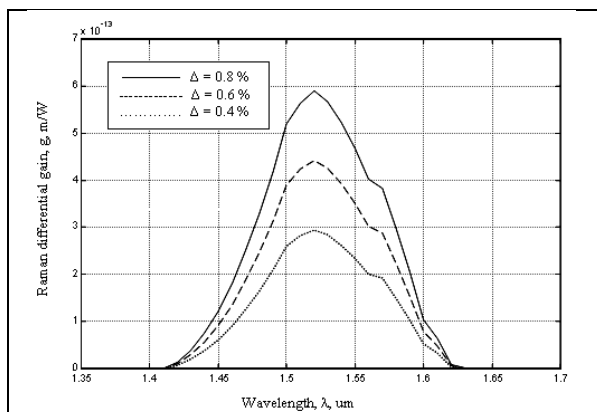
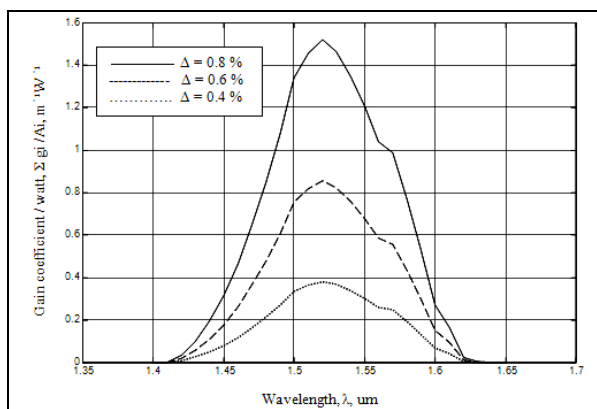Figure 10 Variation of differential Raman gain with wavelength.



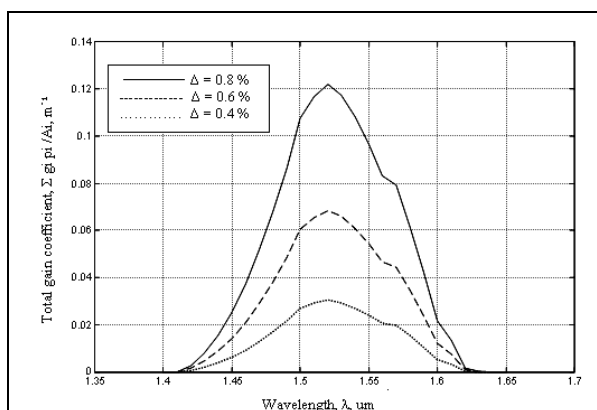Figure 11 Gain coefficients per unit watt against wavelength.



Figure 12 Variation of total gain coefficient with wavelength.

A summary of the obtained results, in different cases, is found in the following comparison table, where one can note that the maximum gain increases with the relative refractive index difference increase. And bandwidth is change according to the change of the position of optical amplifiers.

From table IV we conclude that:

1- If number of optical amplifiers increases, Raman gains increase.
2- If relative index difference increase then we gets Raman gain is increase.
3- Also, for each case only if relative index difference increases, Raman gain is increase.
4- Bandwidth and flatness of the gain depends on the position of amplifiers corresponding to each other's and number of amplifiers, where in case 1 the flatness of the gain is better than in case 2 of [1], then for case 1 BW = 110 nm for different number of optical amplifiers but the flatness of the gain for N = 8 is better than in case of N= 5, also for case 2 [1] the bandwidth is change according to the number of optical amplifiers and the position of each amplifier corresponding to each others, for N = 4 , BW = 100 nm and for N = 6, BW = 110 nm and 130 nm.

The we get case 1 is better than case 2 [1], where the flatness of the gain is improved.

Table IV Maximum gain and bandwidth for different number of amplifiers.

| Case 1 | | | |
|---|---|---|---|
| No of optical amplifiers | $g_{max}$ (m/W) | $\Delta$ % | BW(nm) |
| 5 | $3.1308 \times 10^{-13}$ | 0.8 | 110 |
| | $2.3481 \times 10^{-13}$ | 0.6 | |
| | $1.5654 \times 10^{-13}$ | 0.4 | |
| 8 | $5.0577 \times 10^{-13}$ | 0.8 | 110 |
| | $3.7933 \times 10^{-13}$ | 0.6 | |
| | $2.5289 \times 10^{-13}$ | 0.4 | |
| 10 | $5.8978 \times 10^{-13}$ | 0.8 | 110 |
| | $4.4234 \times 10^{-13}$ | 0.6 | |
| | $2.9489 \times 10^{-13}$ | 0.4 | |
| Case 2 [1] | | | |
| No of optical amplifiers | $g_{max}$ (m/W) | $\Delta$ % | BW(nm) |
| 4 | $2.4326 \times 10^{-13}$ | 0.8 | 100 |
| | $1.8245 \times 10^{-13}$ | 0.6 | |
| | $1.2163 \times 10^{-13}$ | 0.4 | |
| 6 | $3.6239 \times 10^{-13}$ | 0.8 | 110 |
| | $2.7179 \times 10^{-13}$ | 0.6 | |
| | $1.8119 \times 10^{-13}$ | 0.4 | |
| 6 | $3.2401 \times 10^{-13}$ | 0.8 | 130 |
| | $2.4301 \times 10^{-13}$ | 0.6 | |
| | $1.6201 \times 10^{-13}$ | 0.4 | |

## 4. Conclusions

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The bandwidth of cascaded multi-pumping Raman amplifier is investigated, where N Raman pumping signals are injected in a parallel processing at different pumping powers wavelengths. The differential gain of each pumping is according to the straight line-exponential model of a small maximum constant gain of $7.4 \times 10^{-14}$ m/W over an optical wavelength interval of 16 nm. The processed gains are functions of the set of variables {$\lambda_s$, $\lambda_r$, $\Delta$ and the locations of the maximum constant gain interval}. We have obtained bandwidth of about, 110 nm at different value of $\Delta$ % for use 5, 8 and 10 optical Raman amplifiers, respectively.

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