Effect of Distributed Multi-Raman Amplifiers on Bandwidth, Gain and the Flatness of the Gain

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Abstract: In the present paper, the problem of multi-pumping Raman amplifiers has been investigated to study the relation between the number of optical amplifiers, gain and the flatness of the gain and also we discuss the relation between the cascaded optical amplifiers and the bandwidth 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. Four cases are analyzed where, five, six, six and eight Raman pumping of special pumping powers are launched in the forward direction. The model equations are numerically handled and processed via specially cast software (Matlab). The gain is computed over the spectral optical wavelengths ($1.45\mu m \leq \lambda_{signal} \leq 1.65\mu m$).

[Fathy M. Mustafa, Ashraf A. Khalaf and F. A. El-Geldawy. **Effect of Distributed Multi-Raman Amplifiers on Bandwidth, Gain and the Flatness of the Gain**. *J Am Sci* 2012;8(10):267-274]. (ISSN: 1545-1003). http://www.jofamericanscience.org. 39

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

1. Introduction

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 [1].

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 [1].

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 [1].

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 [1].

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 [1].

Ultra long-haul (ULH) and ultrahigh-capacity (UHC) dense wavelength-division-multiplexed (DWDM) optical communication systems have recently attracted considerable attention due to their potential to greatly reduce bit-transport costs while addressing the ever-increasing demand for voice and data traffic. A flexible all-Raman pumping scheme, including forward-and backward-pumping of the fiber span and backward pumping of the dispersion compensation modules (DCMs), can be used as a common platform yielding excellent system performance for 10 Gb/s ULH and 40Gb/s signals and ULH transmission over 2500 km in a hybrid configuration [2]. It was shown how that amplification scheme provides enough gain to handle discrete losses from optical add/drop multiplexers (OADMs) inserted along the transmission. A comprehensive experimental investigation of an all-Raman ultra wide signal-band transmission system for both 10 and 40 Gb/s line rates was done [2].

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 [3].

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 [4].

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 [5].

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 [6].

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 λ_{r1}, λ_{r2}, λ_{r3}, λ_{r4}, ……., λ_{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 [7-11] as:

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

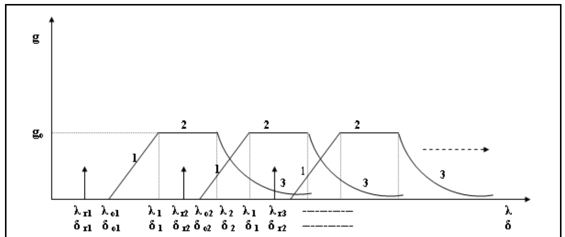

Figure 1 Gain, g, of multi-pump Raman amplifier.

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.

The general equations representing the Raman gain in the three regions are respectively [11].

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

Where

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

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

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

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

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

And

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

$\Delta\lambda = \lambda_2 - \lambda_1 = 15$ nm = (fixed value)

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

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

Where

$$\delta_{o,i} \leq \delta \geq \delta_{1,i} \quad , \qquad 0 \leq \delta - \delta_{o,i} \leq 440 \quad (10)$$

With

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

With 1 cm^{-1} = 30 GHz [12], 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.

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

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

$$\delta_{1,i} = \frac{\lambda_{1,i} - \lambda_{r,i}}{\lambda_{1,i}\lambda_{r,i}} \times 10^4 \, , cm^{-1} \qquad (13)$$

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

And

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

$\Delta\lambda = \lambda_2 - \lambda_1 = 16$ nm = (fixed value)

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

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

The shift $\delta_{o,i}$ 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 $\delta_{o.i}$ or $\lambda_{o,i}$. In this case, one uses $\delta > \delta_r$ or $\lambda > \lambda_r$ and $\delta_o \geq \delta_r$ or $\lambda_o \geq \lambda_r$, where λ_r is Raman pump wavelength.

Raman differential gain constant, g, and the effective core area, A, are defined as [8]:

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

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

Where

$$W = \frac{0.21\lambda}{\sqrt{\Delta}} = \frac{0.3\lambda n_1}{N_A} \, , \qquad (19)$$

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 $\lambda = \lambda_s$ and $W=W_r$ at $\lambda = \lambda_r$ and Δ is the relative refractive index difference, n_1 is refractive index of the core and N_A is the numerical aperture.

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

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

Where, i = 1,2,3,……..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 distributed multi-pump Raman amplifier (DMRA) 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 two different case with four different models; namely, five, six, six and the eight Raman pumping optical wavelengths and pumping powers are shown in the Tables I ,II, III and IV, 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.

3.1. Effect of Number of pumping (number of optical amplifier) on the Gain and the Flatness of the Gain

In this case we discuss two different models namely five and eight Raman pumping optical wavelengths and pumping powers in this case we get the gain of the amplifiers increased and the flatness of the gain is improved with increasing the number of pumping.

3.1.1 Number of optical amplifier = 5

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

λ_r	λ_o	λ_1	λ_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 λ_{1t} = 1.51 µm (for all amplifiers) and λ_{2t} = 1.62 µm (for all amplifiers).

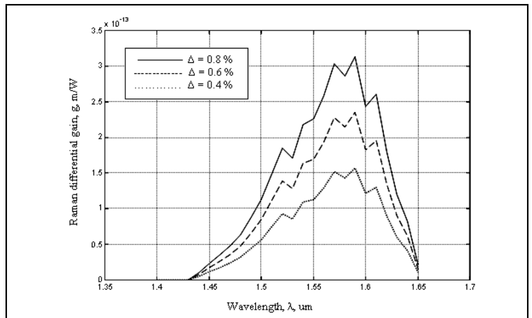

Figure 2 Variation of differential Raman gain with wavelength.

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

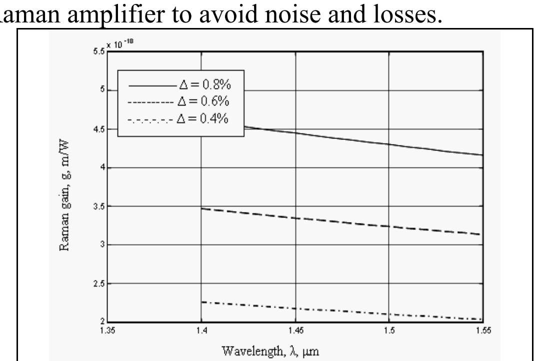

Figure 3, Variation of Raman gain, g, with pumping wavelength, λ_r, um

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

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.

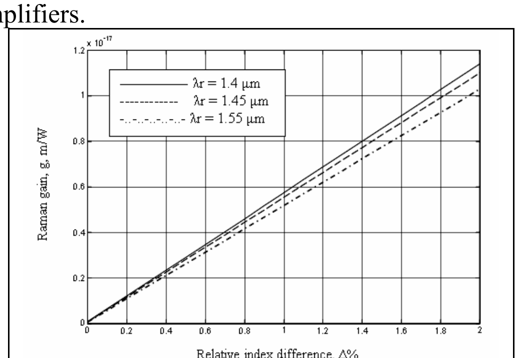

Figure 4 Raman gain versus relative refractive index difference.

Gain coefficient per unit watt

The gain coefficient/unit watt, $\sum gi / Ai$, $m^{-1} W^{-1}$ 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.

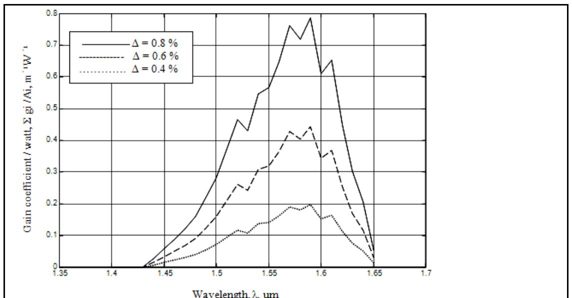

Figure 5 Gain coefficients per unit watt against wavelength.

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

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.

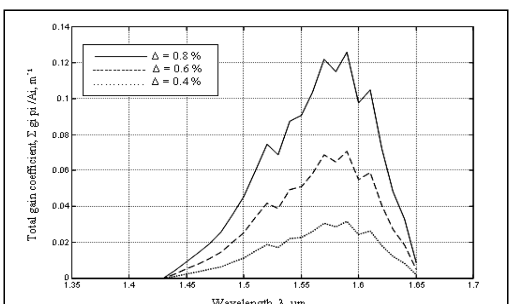

Figure 6 Variation of total gain coefficient with wavelength.

Where pumping powers increase the total gain is increase so Raman amplifiers is used to sources with high pumping powers.

3.1.2 Number of optical amplifier = 8

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

λ_r	λ_o	λ_1	λ_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.

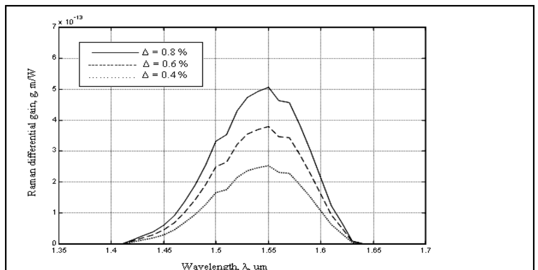

Figure 7. Variation of differential Raman gain with wavelength.

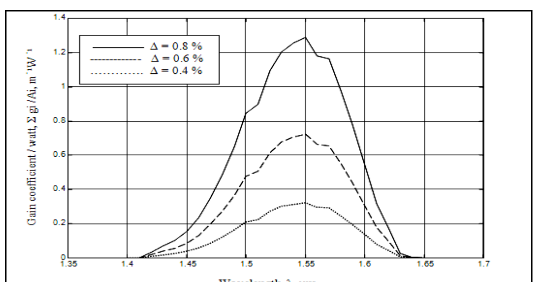

Figure 8. Gain coefficients per unit watt against wavelength.

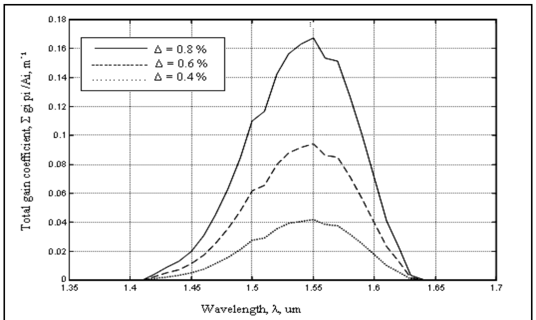

Figure 9. Variation of total gain coefficient with wavelength.

3.2 Effect of Distributed optical amplifier on Bandwidth

In this case we discuss two different models with the same number of optical amplifiers but the position of the amplifiers is change, then we get the bandwidth is also change according to the position of each amplifier corresponding to each others.

3.2.1 Number of Optical Amplifier = 6

Table III Number of amplifiers = 6

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

λ_r	λ_o	λ_1	λ_2	P_p(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

The differential Raman gain is displayed in Fig. 10 against wavelength at different values of the relative refractive index difference while the gain coefficient per unit watt is displayed in Fig. 11. The total gain coefficient is drawn with wavelength in Fig. 12, where a bandwidth of 110 nm is obtained. Peak value in this case at 1.54µm for the different gain.

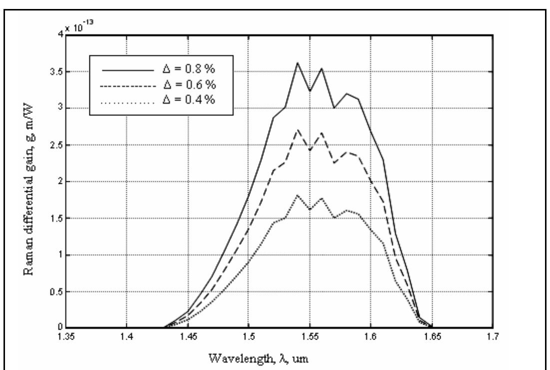

Figure 10 Variation of differential Raman gain with wavelength.

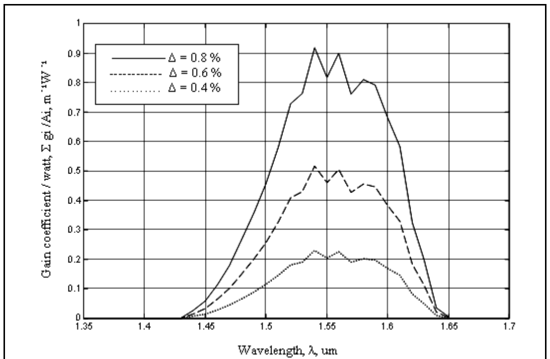

Figure 11 Gain coefficients per unit watt against wavelength.

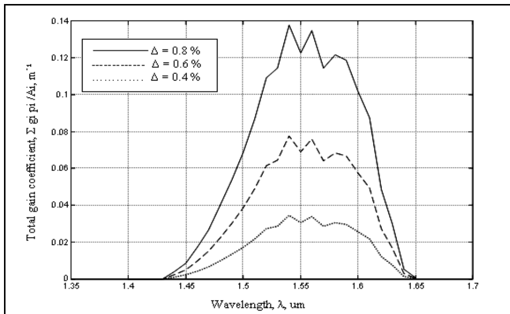

Figure 12 Variation of total gain coefficient with wavelength.

3.2.2 Number of Optical Amplifier = 6

Table IV Number of amplifiers = 6

$\lambda_1 - \lambda_o$ = fixed value (0.096294799) and $\lambda_2 - \lambda_1$ = 16 nm

λ_r	λ_o	λ_1	λ_2	P_p(W)
1.4	1.432	1.528294799	1.544294799	0.20
1.42	1.454	1.550294799	1.566294799	0.15
1.44	1.477	1.573294799	1.589294799	0.15
1.467	1.514	1.610294799	1.626294799	0.20
1.48	1.523	1.619294799	1.635294799	0.15
1.5	1.532	1.628294799	1.644294799	0.15

The results in this case are shown in Figs. 13-15, where they obtained bandwidth is 130 nm. Peak value at 1.55µm for the different gain.

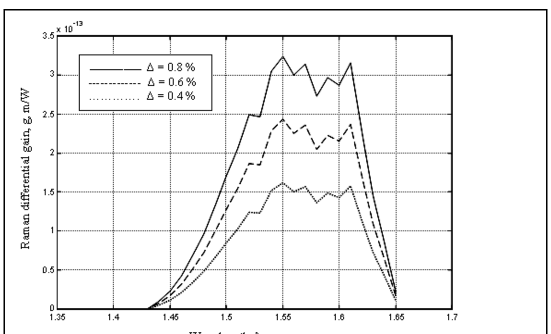

Figure 13 Variation of differential Raman gain with wavelength.

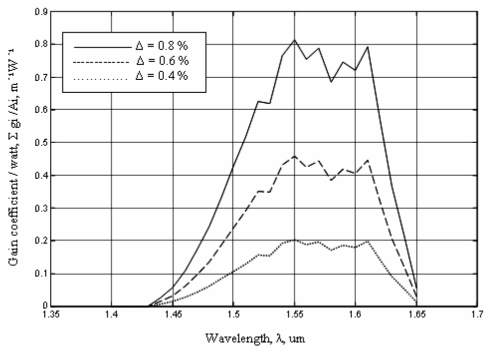

Figure 14 Gain coefficients per unit watt against wavelength.

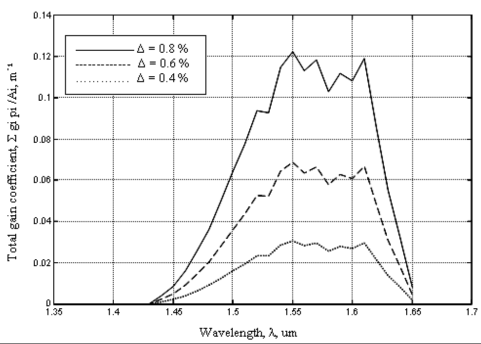

Figure 15 Variation of total gain coefficient with wavelength.

4. Conclusions

The bandwidth of multi-distributed Raman amplifier (MDRA) 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 7.4×10^{-14} m/W over an optical wavelength interval of 16 nm. The processed gains are functions of the set of variables {λ_s, λ_r, Δ and the locations of the maximum constant gain interval}. We have obtained bandwidth of about, 110, 130, 110, and 110 nm at different value of Δ % for use 5, 6, 6 and 8 optical Raman amplifiers, respectively. A summary of the obtained results, in different cases, is found in the following comparison table V, 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, also the gain is increased and the flatness of the gain is improved with increasing the number of optical amplifiers.

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

Case 1			
No of optical amplifiers	g_{max}	Δ %	BW(nm)
5	3.1308×10^{-13} 2.3481×10^{-13} 1.5654×10^{-13}	0.8 0.6 0.4	110
8	5.0577×10^{-13} 3.7933×10^{-13} 2.5289×10^{-13}	0.8 0.6 0.4	110
Case 2			
No of optical amplifiers	g_{max}	Δ %	BW(nm)
6	3.6239×10^{-13} 2.7179×10^{-13} 1.8119×10^{-13}	0.8 0.6 0.4	110
6	3.2401×10^{-13} 2.4301×10^{-13} 1.6201×10^{-13}	0.8 0.6 0.4	130

From table v 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 case1 for number of optical amplifiers equal five and eight (N = 5 and N = 8) the bandwidth equal to 110 nm, means equal bandwidth for the different number of optical amplifiers but the flatness of the gain for N = 8 is better than for N = 5 and also the gain is large, then we find the value of the gain and the flatness of the gain depends on number of optical amplifiers.

   But in case 2 for number of optical amplifiers equal to six (N = 6) we get the bandwidth equal to 130 nm and 110 nm, and then we concluded that the bandwidth depends on the position of the amplifiers corresponding to each other.

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9/10/2012