24th NATIONAL RADIO SCIENCE CONFERENCE (NRSC 2007)
March 13-15, 2007
Faculty of Engineering, Ain shams Univ., Egypt

All Optical Broad-Band Multi-Raman Amplifier for Long-Haul UW-WDM Optical Communication Systems

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Abstract

In the present paper, the problem of multi-pumping all Raman amplifier has been investigated to obtain a gain of maximum flatness over a wide range of optical signal wavelengths for long-haul ultra-wide wavelength division multiplexing (UW-WDM) transmission systems. Four cases are analyzed where, four, five, and seven Raman pumping of special pumping powers are launched in the forward direction. The model equations are numerically handled and processed. The gain is computed over the spectral optical wavelengths (1.45 μm $\leq \lambda_{signal} \leq$ 1.65 μm).

Keywords: Raman amplifier, 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 [1]. 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 [2]. 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 [3].

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 [4]. 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 [4].

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 [5]. 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 [6].

Raman amplifiers pumped at multiple wavelengths draw significant attention in high-speed long-haul WDM transmission 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 the present 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 [9-13] as:

$$\delta = \frac{\lambda_s - \lambda_r}{\lambda_s \lambda_r} \text{ . cm}^{-1} \tag{1}$$

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 with the number of amplifiers but the gain flatness depends 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

$$g_1 = g_o \frac{\delta - \delta_{o,i}}{440} \qquad \delta_{o,i} \le \delta \le \delta_{1,i} \tag{2}$$

with

$$\delta_{o,i} = \frac{\lambda_{o,i} - \lambda_{ri}}{\lambda_{o,i} \lambda_{ri}} \text{ . cm}^{-1} \tag{3}$$

with 1 cm^{-1} = 30 GHz [14], 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.

$$g_2 = g_o \qquad \delta_{1,i} \le \delta \le \delta_{2,i} \text{ .} \tag{4}$$

where $g_o = 7.4\times10^{-14}$ m/W and

$$\delta_{1,i} = \frac{\lambda_{1,i} - \lambda_{ri}}{\lambda_{1,i} \lambda_{ri}} \text{ , cm}^{-1} \tag{5}$$

$$\delta_{2,i} = \frac{\lambda_{2,i} - \lambda_{ri}}{\lambda_{2,i} \lambda_{ri}} \text{ , cm}^{-1} \tag{6}$$

and

$$g_3 = g_o e^{-0.025\left(\delta - \delta_{2,i}\right)} \quad , \delta \ge \delta_{2,i} \tag{7}$$

where λ_p is Raman pump wavelength and $\lambda_o \ge 1.35$um.

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 $\delta > \delta_p$ or $\lambda > \lambda_p$ and $\delta_o \ge \delta_p$ or $\lambda_o \ge \lambda_p$, where λ_p is Raman pump wavelength.

Raman differential gain constant, g, and the effective core area, A, are defined as [10]:

$$g = 1.34 * 10^{-6} g_o (1 + 80\Delta) / \lambda_P \tag{8}$$

$$A = \frac{\pi}{2}\left(W_s^2 + W_r^2\right), \tag{9}$$

where

$$W = 0.21\,\lambda / \sqrt{\Delta}. \tag{10}$$

where g_o (=7.4×10^{-14} m/W) is the differential Raman gain constant (of pure SiO_2 at λ = 1.34 μm), λ_p 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.

Neglecting the cross coupling among the signal channels, one has the differential equation governing the signal propagation for N-channels Raman pumping [11]:

$$\frac{dS_i}{dz} + \sigma_{si} S_i = \left(\sum_{i=1}^{i=N} \sum_{j=1}^{j=M} \frac{g_{ij}}{A_{ij}} P_{Rj} \right) S_i\,, \tag{11}$$

where i = 1,2,3,……..N, M is the number of pumps, S_i is signal power and P_{Rj} is the pump power.
Call the term in the R.H.S of g_{ti} , i.e.

$$g_{ti} = \left(\sum_{i=1}^{i=N} \sum_{j=1}^{j=M} \frac{g_{ij}}{A_{ij}} P_{Rj} \right). \tag{12}$$

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:

$$g_{ti} = \left(\sum_{i=1}^{i=N} \sum_{j=1}^{j=M} g_{di} P_{Rj} \right). \tag{13}$$

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

$$g_{ci} = \left(\sum_{i=1}^{i=N} \sum_{j=1}^{j=M} \frac{g_{dij}}{A_{ij}} \right), \ m^{-1}\,W^{-1} \tag{14}$$

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

$$g_{di} = \left(\sum_{i=1}^{i=N} \sum_{j=1}^{j=M} g_{ij} \right) mW^{-1}. \tag{15}$$

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

3. Results and Discussion

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. 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 four different models; namely, four, five, six and the fifteen 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.

Case I

Table I Number of amplifiers = 4
$\lambda_1 - \lambda_o$ = fixed value (0.0922705) and $\lambda_2 - \lambda_1$ = 15 nm

λ_p	λ_o	λ_1	λ_2	P_p(W)
1.4	1.432	1.5242705	1.5392705	0.2
1.42	1.452	1.5442705	1.5592705	0.3
1.467	1.499	1.5912705	1.6062705	0.25
1.5	1.52	1.6122705	1.6272705	0.25

Differential gain
Figure 2 displays the differential Raman gain, g, with wavelength, λ, at different values of the relative refractive index difference and Fig.3 depicts the relation between Raman gain, g m/w and pumping wavelength.

Figure 4 displays Raman gain, g, against the relative refractive index difference.

Gain coefficient per unit watt
The gain coefficient/unit watt, ∑ gi / Ai, m^{-1} W^{-1} against wavelength is shown in Fig. 5 at different values of relative refractive index difference.

Total gain coefficient

Figure 6 displays the variation of the total gain coefficient with wavelength. In this case, a bandwidth of 130 nm is obtained.

Case II

Table II Number of amplifiers = 5
λ1 – λo = fixed value (0.097275) and λ2 – λ1 = 15 nm

λ_p	λ_o	λ_1	λ_2	P_p(W)
1.4	1.439	1.5362705	1.5512705	0.17
1.44	1.456	1.5532705	1.5682705	0.25
1.46	1.492	1.5892705	1.6042705	0.18
1.48	1.502	1.5992705	1.6142705	0.24
1.5	1.512	1.6092705	1.6242705	0.16

Similar to case I, the differential Raman gain is displayed in Fig. 7 against wavelength at different values of the relative refractive index difference while the gain coefficient per unit watt is displayed in Fig. 8. The total gain coefficient is drawn with wavelength in Fig. 9, where a bandwidth of 100 nm is obtained.

Case III

Table III Number of amplifiers = 6
$\lambda_1 - \lambda_o$ = fixed value (0.0922705) and $\lambda_2 - \lambda_1$ = 15 nm

λ_p	λ_o	λ_1	λ_2	P_p(W)
1.4	1.432	1.5242705	1.5392705	0.20
1.42	1.452	1.5442705	1.5592705	0.15
1.44	1.472	1.5642705	1.5792705	0.15
1.467	1.499	1.5912705	1.6062705	0.20
1.48	1.512	1.6042705	1.6242705	0.15
1.5	1.52	1.6122705	1.6272705	0.15

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 120 nm bandwidth is obtained.

Case IV

Table IV Number of amplifiers = 15
$\lambda_1 - \lambda_o$ = fixed value (0.0452705) and $\lambda_2 - \lambda_1$ = 15 nm

λ_p	λ_o	λ_1	λ_2	P_p(W)
1.403	1.415	1.4602705	1.4752705	0.08
1.406	1.425	1.4702705	1.4852705	0.07
1.409	1.435	1.4802705	1.4952705	0.08
1.412	1.445	1.4902705	1.5052705	0.09
1.415	1.455	1.5002705	1.5152705	0.07
1.418	1.465	1.5102705	1.5252705	0.08
1.421	1.475	1.5202705	1.5352705	0.06
1.424	1.485	1.5302705	1.5452705	0.06
1.427	1.495	1.5402705	1.5552705	0.09
1.43	1.505	1.5502705	1.5652705	0.08
1.433	1.515	1.5602705	1.5752705	0.05
1.436	1.525	1.5702705	1.5852705	0.0.4
1.439	1.535	1.5802705	1.592705	0.05
1.442	1.545	1.5902705	1.6052705	0.04
1.445	1.55	1.592705	1.6102705	0.06

The results in this case are shown in Figs. 13-15, where the obtained bandwidth is 150 nm.

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 15 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, 100, 120, 130, and 150 nm at different value of Δ % for use 5, 6, 4 and 15 optical Raman amplifiers, respectively. 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 number of optical amplifiers and with the relative refractive index difference.

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

N	g_{max}	Δ %	BW(nm)
4	2.9372×10^{-13} 3.9299×10^{-13} 4.4351×10^{-13}	0.2 0.27 0.3	130
5	4.4648×10^{-13} 5.9739×10^{-13} 6.7418×10^{-13}	0.4 0.5 0.6	100
6	4.4263×10^{-13} 3.3197×10^{-13} 2.2131×10^{-13}	0.47 0.35 0.23	120
15	2.9653×10^{-13} 3.2619×10^{-13} 3.7067×10^{-13}	0.79 0.87 0.99	150

5. References

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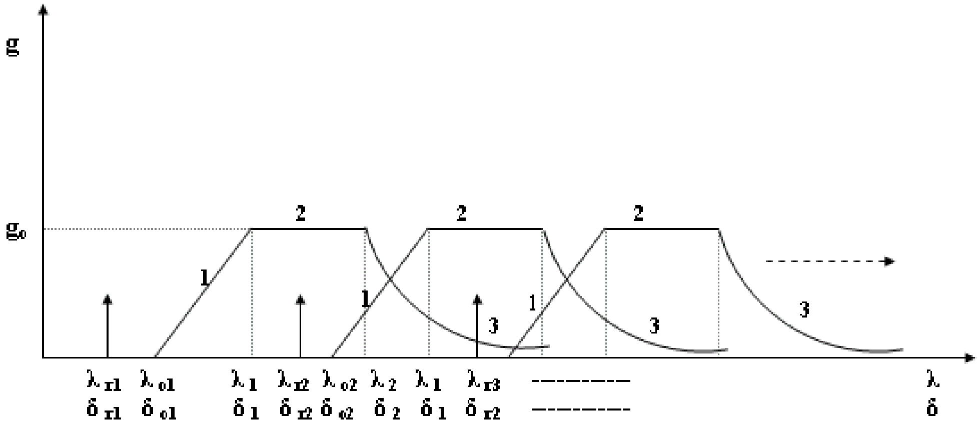

Figure 1 Gain, g, of multi-pump Raman amplifier.

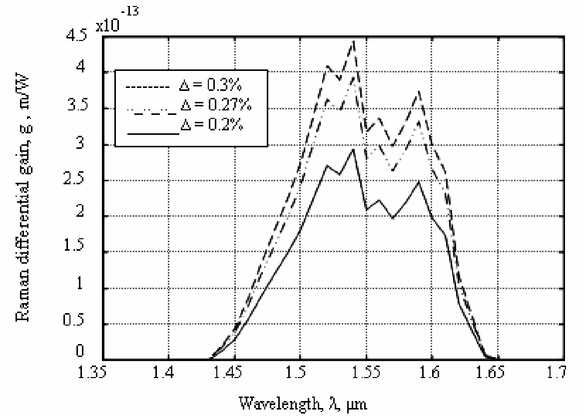

Figure 2 Variation of differential Raman gain with wavelength.

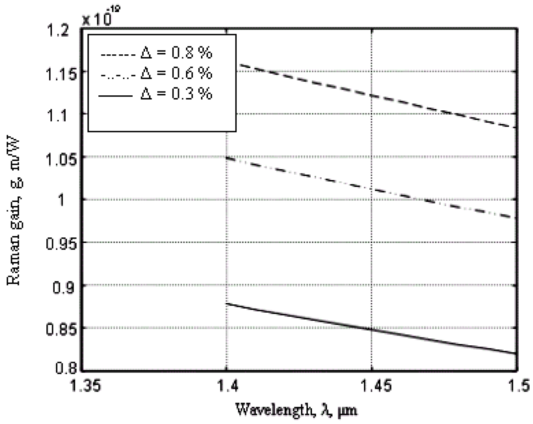

Figure 3 Raman gain against pumping wavelength.

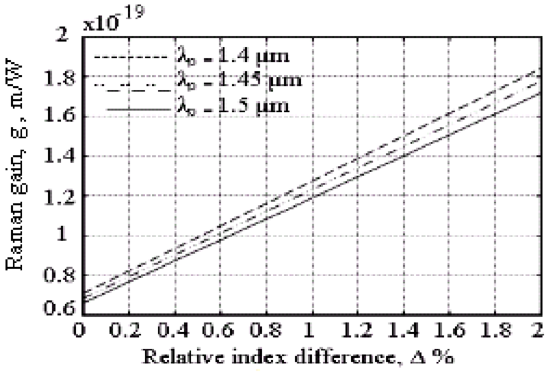

Figure 4 Raman gain versus relative refractive index difference.

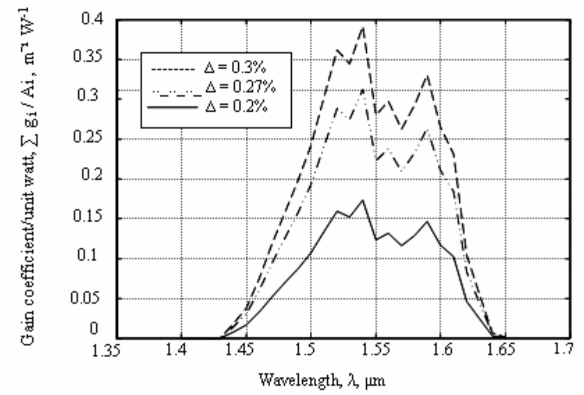

Figure 5 Gain coefficient per unit watt against wavelength.

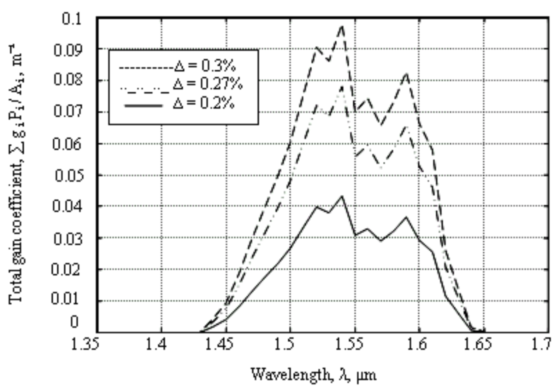

Figure 6 Variation of total gain coefficient with wavelength.

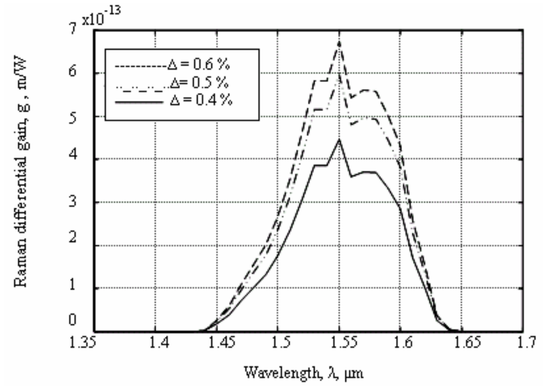

Figure 7 Differential Raman gain versus wavelength.

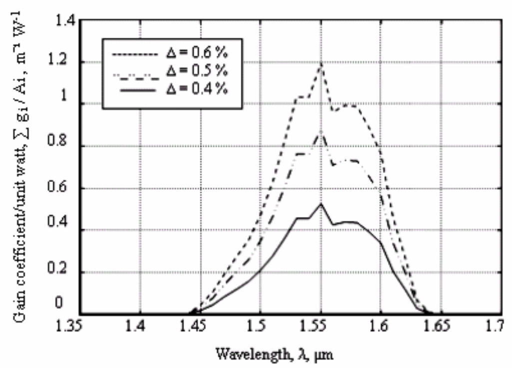

Figure 8 Gain coefficient per unit watt against wavelength.

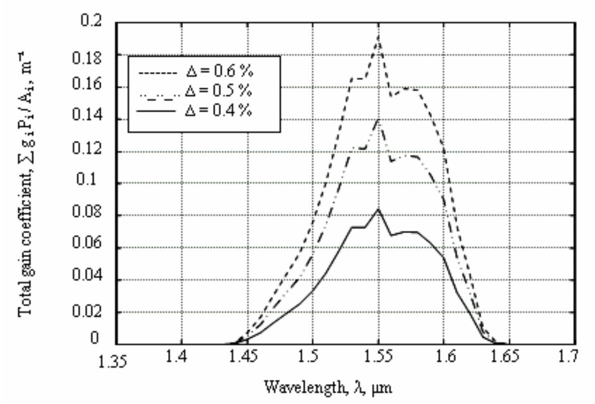

Figure 9 Total gain coefficient versus wavelength.

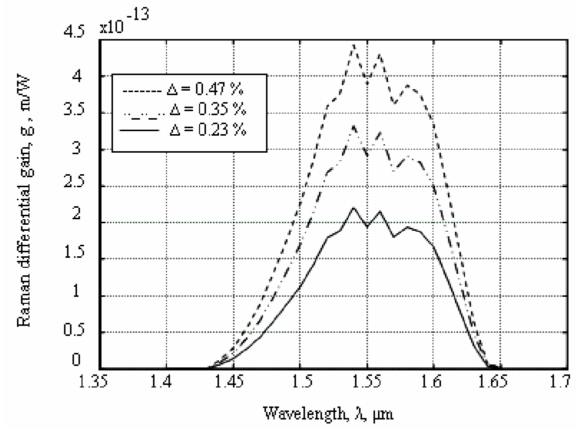

Figure 10 Variation of differential Raman gain with wavelength.

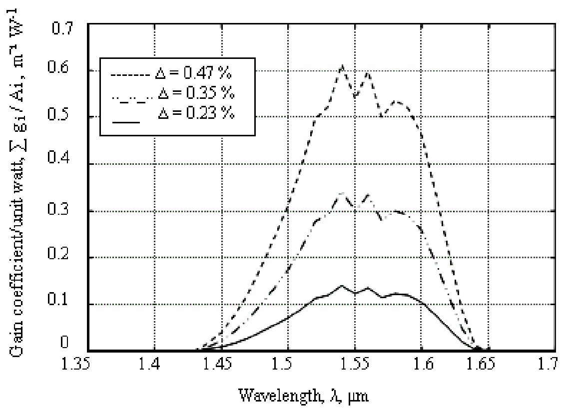

Figure 11 Gain coefficient per unit watt against wavelength.

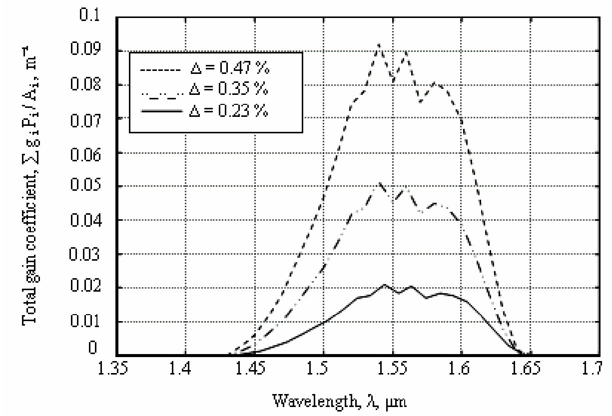

Figure 12 Variation of total gain coefficient with wavelength.

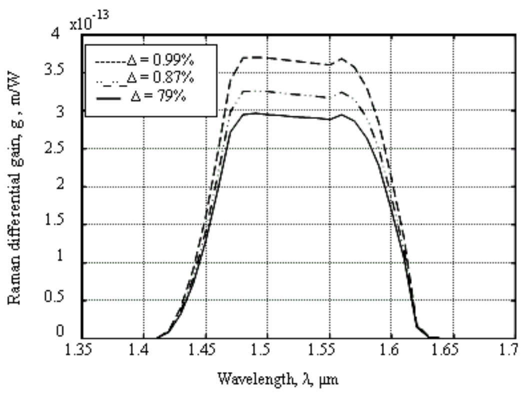

Figure 13 Variation of differential Raman gain with wavelength.

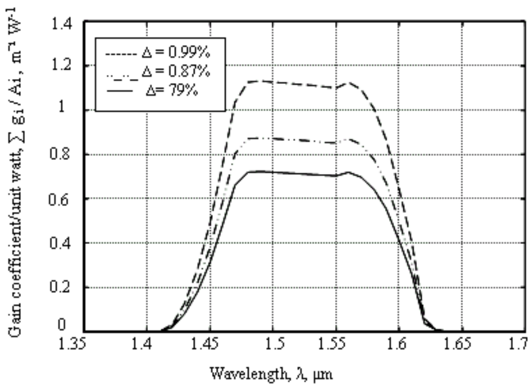

Figure 14 Gain coefficient per unit watt against wavelength.

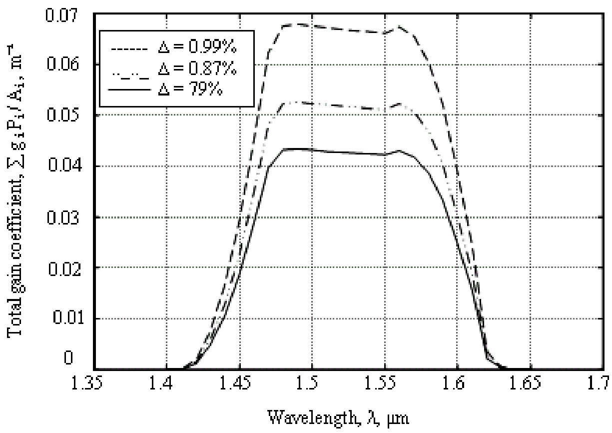

Figure 15 Variation of total gain coefficient with wavelength.