5.0 Raman Fibre amplifier.

5.1 Introduction to Raman fibre amplifier.

Raman fibre amplifier is one strong contender to repeaterless optical communication. Fibre optic Raman amplification offers the possibility of replacing conventional regenerators with simple amplifiers consisting of a pump laser and a wavelength selective coupler. This would lead to extremely large repeater spacing. The transmission medium also acts as an amplifying medium (this is referred to as active transmission lines), thereby eliminating various optical and electronic components currently needed to amplify optical signals, this creates simplicity in designing and maintaining optical amplifiers, another plus point of having optical amplifiers over conventional electro-optic amplifiers.

A schematic representation of a Raman amplification is shown in figure 5.1. The information bearing signal is transmitted in the usual manner, however in addition to the usual signal, a shorted wavelength is injected into the fibre, either co-propogating or counter-propogating with the direction of signal. The signal is of a lower frequency light than that of the pump and the signal has to be multiples of Raman shift away from the pump, ie. amplification of the signal is also possible if the signal is at 450 cm^{-1}, 900 cm^{-1} and 1350 cm^{-1}, which coincidentally is the first order, second order and third order stimulated Raman scattering. Amplification of higher order stimulated Raman was also reported, [25], using the fourth order stimulated Raman scattering. Therefore, any signal can be amplified provided a suitable pump source can be found.

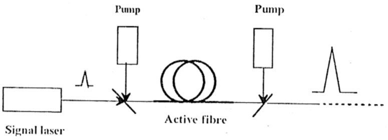

Figure 5.1. A schematic representation of a Raman fibre amplifier

As mentioned in section 3.2.2.1 , if a signal at the Stokes frequency is co-injected with a pump into an active medium, there will be amplification of the Stokes frequency light at the expense of the pump. The strength of this amplification is exponentially dependant on the pump intensity [5, 25] and this can be written as follows:

$$P_S\,(L) = P_S\,(0)\,\exp \frac{gL_e\,P}{bA_e} \qquad (5.1)$$

where P / A_e - is the pump intensity , A_e is the effective area. A_e can be calculated as per Stolen 1973 , [38] . The effective area for this fibre had been calculated to be 2.82×10^{-7} cm^2.

L_e - is the effective fibre length.

b - this factor accounts for the relative polarisation of the pump and signal and the relative polarisation of the fibre. In polarisation maintaining fibre, where the pump and signal polarisation are the same, b = 1, and when the fibre is a conventional non polarisation maintaining fibre b = 2. As determined in section 4.2.2, the fibre was found to be not polarisation preserving, hence b = 2 in this case.

g - Raman gain.

5.2 Experimental set up - Backward Raman fibre amplifier.

Figure 5.3 shows the experimental set up to study backward stimulated Raman scattering amplification in optical fibres. This configuration uses a frequency doubled Nd-YAG laser operating at 10 Hz. The pump is at 532 nm and the signal, at 546 nm (the first Raman shift) was taken from a dye laser. The dye used was Coumarine 540A with a molarity of 1×10^{-2}, using methanol as the solvent. The dye laser was pumped with 355 nm, the third harmonic generation from a Nd-YAG laser. The tuning range from this dye laser was measured to be from 523 nm to 600 nm, fluorescence peak was measured at 537 nm. The power measured in the region of interest is shown in figure 5.2. The region of interest is the region from 533 nm to 548 nm which is the region of the first stimulated Raman spectrum of silica dioxide.

The pump was measured to be ahead of the signal by 3.4 ns. Extreme care was taken so as not to introduce 'delay' caused by using different photodiodes and co-axial cables into the final measurement results. This was done by taking two measurements i.e. swapping the co-axial cable and the photodiodes prior to taking the second measurement. By deducing the difference between the two measurements and using algebraic calculations, the actual time difference between the 532 nm pump and the 546 nm signal can be determined.

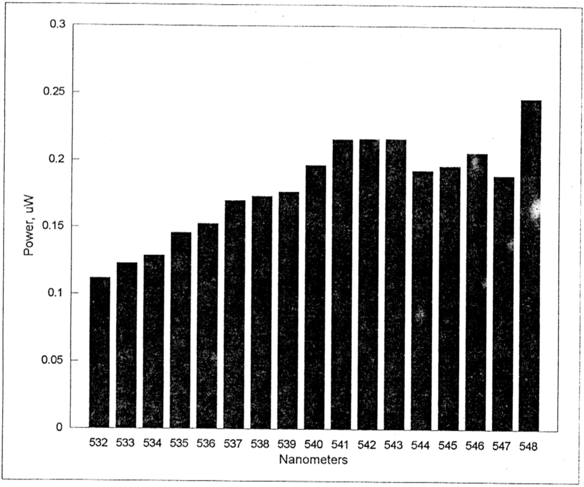

Figure 5.2 Shows the power output from the dye laser.

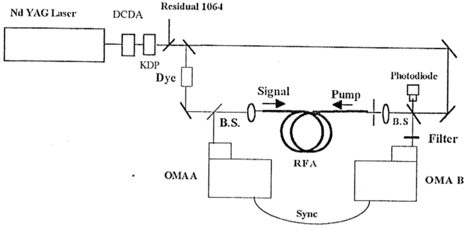

Figure 5.3 Raman fibre amplifier, backward single pass configuration.

Figure 5.3 shows a schematic representation of the Raman fibre amplifier (RFA). The pump at 532 nm was pumped in a backward direction from that of the signal via a beam splitter. The beam splitter was measured to transmit 72.3 % and reflect 27.7 % at 532 nm and at the other beam splitter plane, the beam splitter was measured to transmit 79.3% and reflect 20.7% at 546 nm. Both measurements were made using an OPHIR power meter model NOVA with the capability of measuring in the 30 nW range. The due date for re-calibration is four months away, 27 July 1995.

Using beam steering optics, the 532 nm laser light was coupled in the active fibre, power was varied using neutral density filters at the pump input end. At the other extreme, the dye laser pump (355 nm) was pumped using 355 mirrors.to steer the beam into the dye laser. The fibre studied as a Raman fibre amplifier was a Newport silica fibre. The characteristics are given in appendix B.

5.2.1 Experimental results.

The dye laser was tuned to the region of interest using a grating, from 537 nm to 548 nm, this region of interest is within the first Raman gain of silica dioxide. Figure 5.4 shows the amplification of the signal at different wavelengths. Coincidentally this figure shows similarities with the Raman gain spectrum in figure 3.3. There are two peaks seen mainly at 543 nm and 546 nm, signal injected into the Raman fibre amplifier, at these two frequencies will have the maximum gain. The insert of figure 5.4 shows the spectrum of stimulated Raman scattering, where the Stokes components for stimulated Raman scattering for forward and backward pumping configuration happens at 542 nm (347 cm^{-1}) and 546 nm (482 cm^{-1}). The Raman gain g, can be determined from equation 5.1. Rewriting equation 5.1 we get :

$$\ln\left(\frac{P_s(L)}{P_s(0)}\right) = \frac{gP\,L_e}{b\,A_e} \tag{5.2}$$

By studying the characteristic of the amplified signal versus pump power, we were able to calculate the Raman gain of the fibre. An experiment was carried out to study the characteristic of a Raman fibre amplifier when parameters as given in equation 5.1 were varied. The output from the RFA was observed using an optical multichannel analyser, via a birefringent filter. By tuning the angle of this filter, the transmission band width can be set to transmit only the 532 nm or the 546 nm range. By plotting the relationship between the natural logarithm and the input pump power, the Raman gain, g can be deduced from the slope of this plot, knowing the effective length, L_e (fibre length), polarisation factor, b and effective fibre area, A_e.

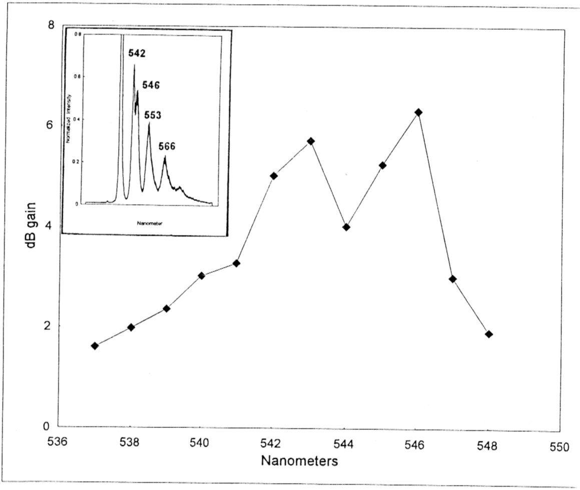

Figure 5.4 **Shows the amplification of the various signal by the Raman fibre amplifier.**

5.2.1.1 Raman Gain

Care was taken to ensure that the input signal power was kept constant by constantly measuring the signal power. The signal power was kept constant using neutral density filters at 0.144 micro watts. The fibre was aligned to achieve maximum coupling efficiency each time. The pump power was measured prior to launching the pump into the fibre and the pump power was varied using neutral density filters at the pump input end, care was taken so as not to change the coupling of the fibre once maximum coupling was achieved. (Coupling efficiency was measured by measuring the pump power transmitted through approximately 20 cm of the fibre. The fibre was cleaved after the end of the experiment - knowing the pump power prior to launching and the transmitted power after launching , the efficiency can be deduced). The pump pulse width was measured using a photodiode at the pump input end as depicted in figure 5.3, care was taken to ensure that the photodiode does not saturate by using neutral density filters to reduce the incident power to the photodiode. The pulse width was measured at full width at half maximum (FWHM). Hence by knowing the coupling efficiency, pump power prior to launching the light into the fibre and the pulse width, the maximum power transmitted into the fibre can be deduced.

Figure 5.5 shows the output spectrum when the signal power $P_s(0)$ was kept constant while varying the input pump power and the fibre length. As expected in figure 5.5, the relation of the natural logarithm of the gain vs the input power for different lengths is linear. At higher pump power we see the gain of the signal starts saturating, this same behaviour can be seen for all different lengths of fibre tested.

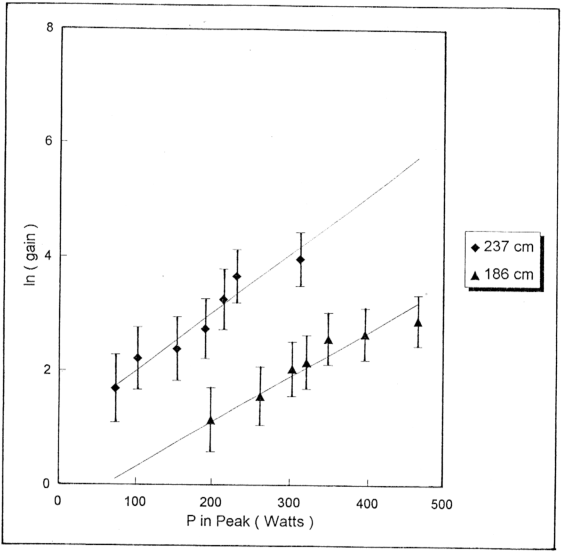

Figure 5.5 **Shows the gain of the backward Raman fibre amplifier at various input pump power.**

Unfortunately the pump power could not be increased further beyond the saturation point because the fibre end (at the pump end) gets damaged first. A best fit line had been plotted along side the experimental data. The slope of this best fit line is given in equation 5.2 and by solving this equation, the Raman gain can be deduced. Table 5.1 shows the summary of figure 5.5, showing the Raman gain calculated from two different lengths of fibre. The Raman gain calculated corresponds to the standard value reported else where for silica dioxide fibres. The previous reported value for silica dioxide ranges from (0.7×10^{-11} - 17×10^{-11}) cm/W,[1,6,7,11,19]. The error calculated ranges from a minimum of 19 % to a maximum of 27 %. This matches the error calculated else where by Davidson et. al. 1987, [6]. Please refer to appendix A for a detail analysis of the error calculations.

Fibre length (cm)	Coupling efficiency	P_{in} peak (Watts)	Raman gain $\times 10^{-11}$ cm/W	Maximum gain (dB)
237.4	18.23 %	231.65	2.44	15.89
186.3	18.94 %	395.19	2.39	11.53

Table 5.1 **Shows the Raman gain calculated for Newport silica fibre using backward Raman amplifier.**

P_{in} peak is the maximum input power in the fibre prior to the gain saturating. This saturation point is the point where the signal becomes sufficiently intense and it now becomes a new pump source to pump the second stimulated Raman in the fibre, this second stimulated Raman due to the intense signal is seen at 556 nm. If we recall in the preceding chapter, figure 4.9 shows the first stimulated Raman at 542 nm and the second stimulated Raman at 553 nm respectively. Table 5.1 also shows the gain of the amplifier in decibels prior to the gain reaching the saturation point. The maximum gain recorded in the backward Raman fibre amplifier was 17 dB. Table 5.1, shows that by increasing the length of the fibre in the Raman fibre amplifier by 27.42%, the gain of the of the signal increased significantly by 37.81%, furthermore the peak input power needed to achieve saturation point dropped by 41.38%. This data shows that a longer fibre has a higher gain even when pumped with relatively lower power.

5.2.1.2 Pump depletion in backward Raman fibre amplifier.

The experimental set up is as per figure 5.3. Observation of the pump depletion was observed on OMA A, and observation of the amplified signal was observed on OMA B. Both optical multichannel analyser had been time synchronised to observe the same pulse, this synchronisation is critical to ensure that the measurements made on amplification and pump depletion are actually that of the same event. The signal had been selected to be 546 nm, as per figure 5.4 , 546 nm shows the maximum gain when the pump power, fibre length and the signal power were kept constant, varying only the signal frequency and measuring the maximum gain at these various frequencies. The first stimulated Raman for the fibre is seen at 542 nm as per figure 4.9 and the signal injected into the fibre is at 546 nm, a frequency shift of 135 cm^{-1} between the first stimulated Raman and the signal. Figure 5.6 shows the output from OMA A, the lightly shaded lines represents the pump at 532 nm and the first stimulated Raman at 542 nm, without the signal. The dark shaded lines in figure 5.6 shows the output from the fibre when the signal was introduced into the fibre in a counter propagating direction. There are two

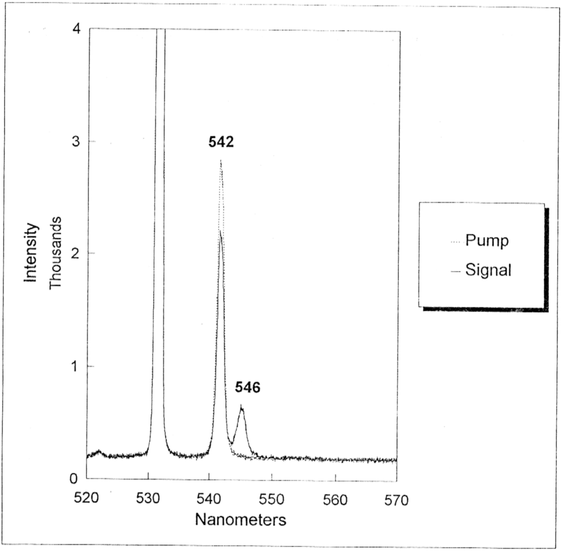

Figure 5.6 **Shows the reverse amplification of the signal in the backward pump configuration. It also shows the depletion of the 542 nm SRS.**

interesting points to note, firstly it can be seen that the first stimulated Raman at 542 nm in figure 5.6 has depleted significantly, there were no significant changes in the 532 nm pump intensity. Published papers have reported the amplification of the signal at the expense of the pump, but in this case, amplification is at the expense of the first stimulated Raman which is about 130 cm^{-1} shift away from the signal and this first stimulated Raman was pumped by a different mode, as mentioned in section 4.2.1, the dominating pump is LP_{11} , and this dominating pump, creates the first stimulated Raman at 542 nm. By actively creating mode selection, i.e. by bending the fibre, LP_{01} mode proliferate and this mode creates the first stimulated Raman at 546 nm, which is coincidentally the frequency of the signal used in this Raman fibre amplifier research. Figure 5.7 shows the relationship between the intensity of the first stimulated Raman at 542 nm and the gain of the signal (546 nm) in decibels. The relationship shows that part of the gain of the signal amplification comes from the 542 nm. A linear regression on the relationship between the pump depletion and the gain of the signal shows a negative slope and this slope has been calculated to be -3.27 +/- 0.45.

The other interesting point to note is that amplification of the signal was also observed in the reverse direction to that of the injected signal. This is clearly shown in figure 5.6, where we also see a peak at 546 nm. If we recall earlier, this spectrum is that of OMA A, OMA A is located at the signal input end of the fibre. The amplification of the signal in the backward and reverse direction had been studied in a 194.3 cm length fibre and the relationship between them is shown in figure 5.8. Figure 5.8 shows that there is significant gain of the signal in the reverse direction as

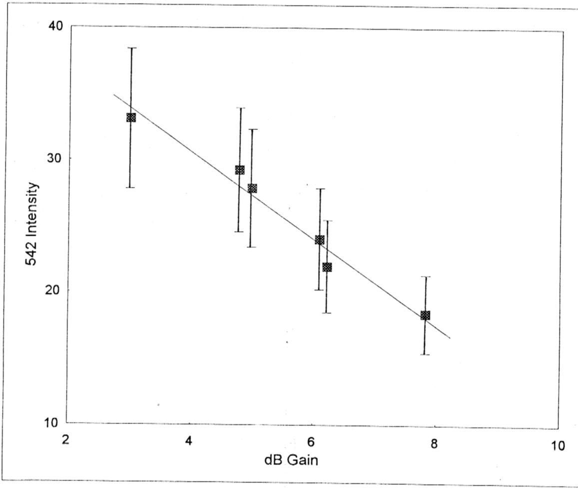

Figure 5.7 **Shows the depletion of the 542 nm SRS at various signal amplification.**

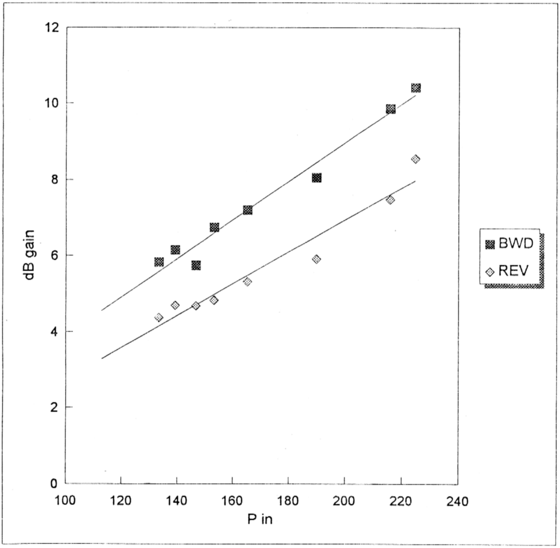

Figure 5.8 **Shows both the backward and reverse amplification.**

well, when we increase the input pump power. Linear regression on both the backward and reverse gain can be summarised in table 5.2:

	Slope	**Intersection point (dB)**
Backward gain	0.0507 +/- 0.0034	-1.18 +/- 0.31
Reverse gain	0.0419 +/- 0.0041	-1.45 +/- 0.38

Table 5.2 Shows the relationship between the reverse and backward gain.

Amplification in the reverse direction is possible when a light pulse propagates down a fibre, part of the photons would experience elastic scattering i.e. Rayleigh scattering, that changes the direction of propagation of the photon to the reverse direction and as these photons propagate down the fibre in this new direction, these photons gets amplified in the Raman fibre amplifier when these photons meets up with the strong pump which coincidentally is also travelling in the same direction as that of the scattered photons. The slope of the backward gain is 17.35% higher than that of the reverse gain, this shows that the efficiency of the backward gain is higher than that of the reverse gain, probably caused by the fact that the reverse gain has to depend on the exact timing from Rayleigh scattering and the pump pulse.

5.3 Experimental set up - Forward Raman fibre amplifier.

Figure 5.9 shows the experimental set up to study forward Raman fibre amplification in optical fibres. This configuration also uses a frequency doubled Nd-YAG laser operating at 10 Hz. The pump is at 532 nm and the signal, at 546 nm was taken from a dye laser.

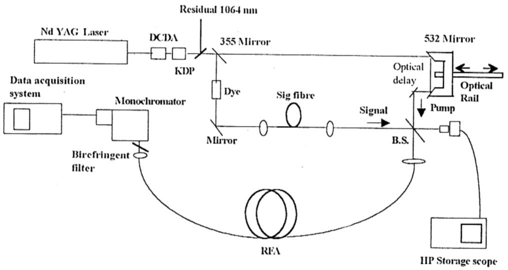

Figure 5.9 Raman fibre amplifier, forward single pass configuration.

For amplification of the signal pulse to take place, both the signal and the pump pulse must be synchronised to meet inside the fibre. Time synchronisation between the two pulses is the most critical aspect of this set up. As determined in section 4.3.1, the lifetime of the stimulated Raman was measured to be 12.32 ns, as such the pump has to be made to lead the signal within this time range, in other words for stimulated emission to happen, the signal has to be injected into the fibre within this time. The time difference between the pump and signal can be measured using a photo diode as shown in figure 5.9. By either blocking the pump or signal path, the time difference between them can be deduced.

To ensure proper time synchronisation, both the signal and pump were configured with optical delays. An optical fibre was used in the signal path and this fibre can be lengthened or shortened to increase or decrease the optical path of the signal in respect to the pump. As for the pump, an optical delay was built by mounting two mirrors on an optical rail as shown in figure 5.9. By moving the mirror mounting on the optical rail either right or left, the optical path length of the pump can be increased or decreased hence time synchronisation can be achieved. An optical fibre could not be used to delay the pump as in the signal's case, because of the high intensity of the pump. We need a high intensity pump as the pump source in a Raman fibre amplifier. By using an optical fibre, various problems would be faced like; non linear effects i.e. four photon mixing would proliferate and this non linear effect would desecrate the pump by introducing other frequencies, hence noise would be introduced into the Raman fibre amplifier. To a lesser extent, a reduction of the pump power would also be encountered due to coupling losses of the strong pump into the fibre. For these various reasons, an optical delay using mirror mounting on an optical rail was made to serve the purpose of delaying the optical path of the pump.

5.3.1 Experimental results.

By blocking either the path of the pump or the signal, the time difference between them can be determined. From adjustments of the optical delays (both of the signal and the pump), the 532 nm pump was made to lead the 546 nm signal from the dye laser by 6.4 ns. This time difference is within the limit of the stimulated Raman lifetime which as mentioned earlier is 12.32 ns.

5.3.1.1 Raman Gain

From equation 5.2, the Raman gain for the fibre can be determined as per the backward Raman amplifier. Again by keeping other parameters constant e.g. the fibre length and the signal power at 0.144 μW, the input pump power was varied and this effect on the gain can be studied quite extensively. Figure 5.10 shows the results for two lengths of fibre at 481 cm and at 609 cm respectively. The results in figure 5.10 can be summarised as in table 5.3 below:

Fibre length (cm)	Coupling efficiency	P_{in} peak (Watts)	Raman gain x 10^{-11} cm/W	Maximum gain (dB)
481	18.29 %	83.67	2.5	10.22
609	23.98 %	66.86	2.36	12.49

Table 5.3 **Shows the Raman gain calculated for Newport silica fibre using forward Raman amplifier.**

As mentioned in the preceding section, the input peak power is deduced from the coupling efficiency and the pump pulse width at FWHM. This peak input power is prior to the gain saturating.

Table 5.3 also shows the maximum gain in decibels measured from the forward Raman fibre amplifier, prior to the gain reaching saturation point. Table 5.3, also shows that by increasing the length of the fibre in the Raman fibre amplifier by 26.61%, the gain of the of the signal increased significantly by 22.21%, furthermore

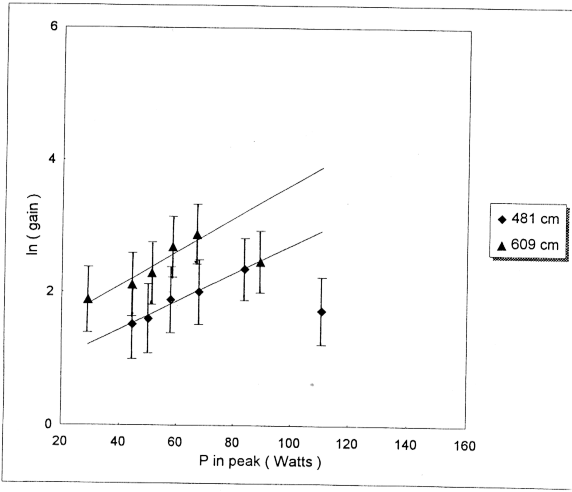

Figure 5.10 **Shows the gain of the forward Raman fibre amplifier at various input pump power.**

the peak input power needed to achieve saturation point dropped by 20.09%. This data also supports the observation made in the backward pumped Raman amplifier, where we see fibres with longer length recording higher gain even with relatively lower pump power.

5.3.1.2 Pump depletion in forward Raman fibre amplifier.

Figure 5.11 shows the output from the monochromator in figure 5.9. Figure 5.11 also shows the 542 nm peak in darker shade, which is the first stimulated Raman scattering for the fibre. The lighter shade shows the output from the monochromator once the signal is injected into the amplifying fibre. The top insert of figure 5.11 shows the signal alone. Notice that the signal without the pump is barely noticeable, even when the neutral density filter was removed. The bottom insert of figure 5.11 shows the region of interest, from 530 nm to 560 nm. This region of interest shows that the pump at 532 nm has no significant differences in intensity, whether or not the signal is present. A birefringent filter was used to block the high intensity 532 nm pump - hence only a small peak was observed in figure 5.11. The bottom insert shows a shoulder at 546 nm, this shoulder is seen without the signal, solely the pump and the stimulated Raman scattering alone but once the signal was introduced into the fibre, amplification of the signal takes place. Figure 5.12 shows the relationship between the 542 nm intensity and the gain of the signal in decibels. This relationship shows similar characteristics as that shown in figure 5.7 - backward Raman fibre amplifier. Linear regression on figure 5.12 gives a negative slope of -5.07 +/- 0.34. This also confirms our earlier findings on the backward Raman fibre

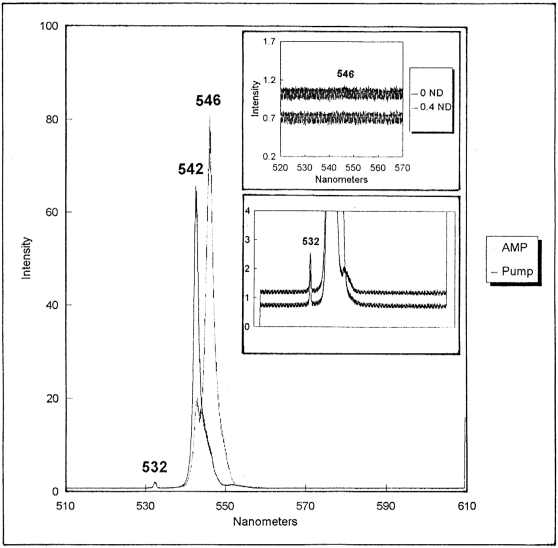

Figure 5.11 **Shows the depletion of the 542 nm SRS and amplification of the 546 nm signal in the forward pump configuration.**

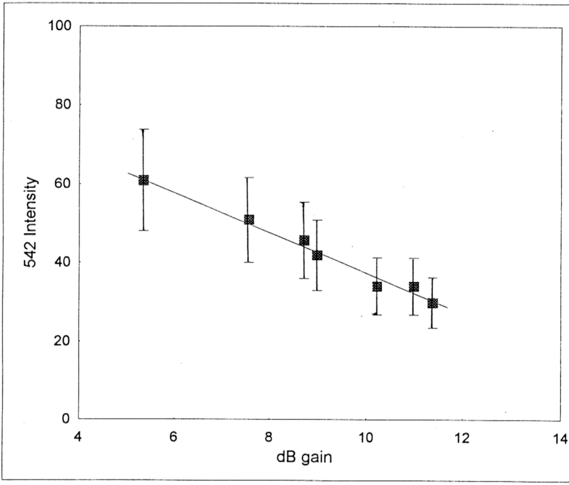

Figure 5.12 **Shows the depletion of the 542 nm SRS at various signal amplification.**

amplifier, where part of the energy used to amplify the signal comes from the 542 nm stimulated Raman.

5.4 Comparison between forward and backward Raman fibre amplifier.

In the preceding sections, amplification of the signal was observed when the pump and signal were injected into the amplifying fibre either co-propagating or counter propagating. In both cases, amplification was at the expense of the first stimulated Raman at 542 nm, which acts as a pump source for the amplified signal. Although there were certain similarities between the two types of Raman fibre amplifiers, we also observed distinct differences between them. Firstly the effective interaction length in both fibre amplifiers differs, this is because in the counter-propagating pump configuration, the signal sees the whole pump when both the pump and signal coincides inside the fibre, where as in the co-propagating pump configuration, the signal trails the pump and the signal would not see the whole pump until the signal catches up with the pump, due to dispersion of the fibre material. Amplification in both cases would happen due to stimulated emission of the excited molecules when the signal passes through, but the effective length in both cases differs, the effective length of the counter propagating direction is in the region of a few meters, this is due to the fact that amplification of the signal would not happen until both the pump and signal coincides inside the fibre. As the pump and signal travels on after coinciding inside the fibre, the signal would still be amplified because the molecules are still in an excited state (as determined in the preceding chapter in section 4.3.1, the life time is in the region of 12 ns), this means that the signal would still be amplified up to approximately 2.4 meters once the pump and signal crosses one another. In the co-propagating pump configuration, the effective length is in the region of a few hundred meters, depending on the time difference between the pump and the signal at injection point. (Due to dispersion of the fibre material, the lower frequency light would travel faster than that of a higher frequency light, hence Stokes frequency generated by the strong pump would eventually catch up with the pump, and this length is determined to be with in the region of 1.15 km in section 4.3.1.) When the signal is injected in the co-propagating direction, the signal has to be delayed in respect to the pump with in the excited lifetime of the molecules (12 ns), hence time synchronisation for pulse system is extremely important. The signal once injected into the fibre, would experience amplification (if the time difference between the pump and signal is within 12 ns) and it would be continuously amplified until the signal catches up with the strong pump, after a few hundred meters (depending on the time difference at injection point), hence the effective length of a co-propagating Raman fibre amplifier is with in a few hundred meters. Amplification would still take place even if the fibre is shorter than the effective length, provided that the time delay between the pump and signal is with in 12 ns, where the signal would still see molecules in the excited state and stimulated emission can take place. Figure 5.13 shows the relationship between the input pump power to the Raman fibre amplifier in the preceding sections vs the fibre length. The maximum P_{in} (Watts) is the input power prior to the signal reaching the saturation point. Figure 5.13 shows that for longer fibres, the input power needed to reach saturation point is much lower than that for shorter lengths of fibre, this is due to the

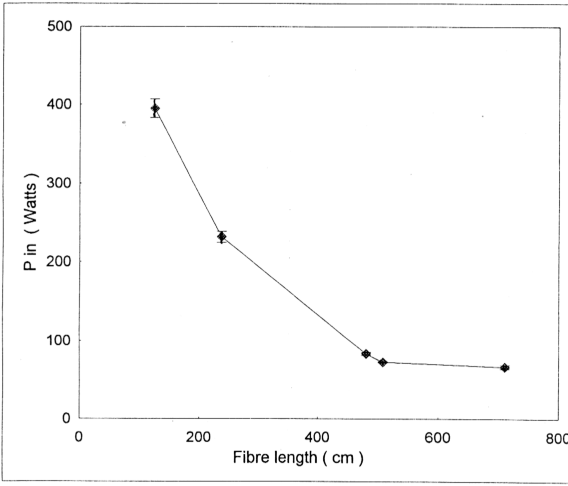

Figure 5.13 **Shows the relationship between the signal saturation point at various fibre length.**

fact that the intense pump can be confined in a longer interaction length hence the threshold power needed to produce stimulated Raman scattering in longer lengths of fibre will be much lower. The second distinct differences observed between both Raman fibre amplifiers are in their relative efficiencies, which will be discussed in more detail in section 5.4.1.

5.4.1 Efficiency comparison between forward and backward Raman fibre amplifier.

Figure 5.14 shows the 542 nm intensity versus the gain of the respective Raman fibre amplifier. Figure 5.14 is the composite of figure 5.7 (counter propagation - backward) and figure 5.11 (co-propagation - forward). These results has been summarised in table 5.4

	Slope	Percentage error	Y-axis intersection	Error (+/-)
Backward	-3.27	13.76 %	43.63	1.19
Forward	-5.07	6.71 %	88.06	1.68

Table 5.4 Shows the relative efficiency of the forward and backward Raman fibre amplifier.

Table 5.4 shows the slope of the backward and forward Raman fibre amplifier. The slope of the backward amplifier is 55 % higher that that of the forward Raman fibre amplifier. In other words this data shows that the backward Raman amplifier has better efficiency than that of the forward Raman amplifier. It has been reported by Lin C. et al 1976, [23], that in a backward Raman fibre amplifier, pump depletion up to 90% had been achieved. It is expected that the efficiency of the backward Raman amplifier to be more efficient than that of the

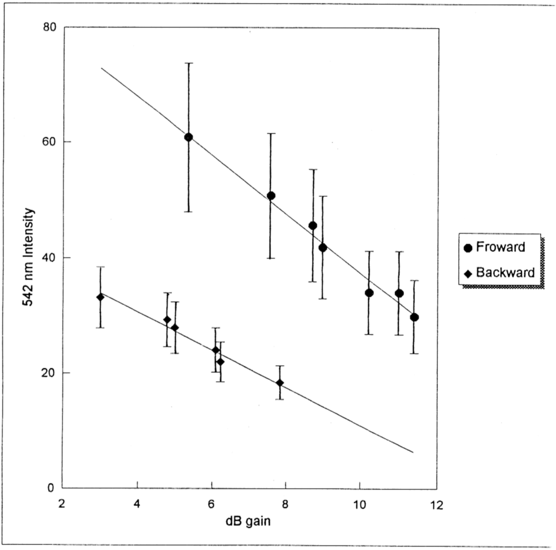

Figure 5.14 Shows the relative efficiency between the forward and backward Raman fibre amplifier.

forward Raman fibre amplifier because in the backward Raman fibre amplifier, the signal pulse gets to see the whole pump pulse inside the fibre amplifier, hence effective energy transfer can occur between the two pulses, even when the pump and signal pulse passes each other, the signal pulse would still see freshly excited molecules in its virtual state, this enhances the amplification of the signal further through stimulated emission. In the forward Raman fibre amplifier, the situation is slightly different, the signal lags the pump by a few nanoseconds hence the signal only sees the molecule in the virtual state (excited state) and not the intense pump. Due to dispersion of the fibre material, the signal would eventually catch up with the intense pump, but this does not happen until a few hundred meters. The efficiency of the forward Raman fibre amplifier would be expected to drop further if the time difference between the pump and signal increases because the signal pulse would now meet up with the tail end of the excited molecules i.e. less excited molecules leads to less amplification due to stimulated emission.

5.4.2 Raman Gain.

The Raman gain for the fibre has been determined by solving equation 5.2 in section 5.2.1.1 and 5.3.1.1 respectively. The average Raman gain as determined in both these experiments is 2.42 x 10^{-11} cm/W with a maximum error of 27 percent. Both these experiments confirms the observation made in section 4.2.1 where both forward and backward stimulated Raman scattering were observed simultaneously (using time synchronised OMAs) when the input pump power was increased to the threshold level. The gain, g (cm /Watts) is related to the differential cross section by [35,38];

$$g = \frac{\sigma\lambda^3}{c^2 h\varepsilon\,(n+1)} \tag{5.3}$$

where	σ	differential cross section
	λ	is the Stokes wavelength
	c	velocity of light
	h	Plank's constant
	ε	dielectric constant at Stokes frequency
	n	Bose-Einstein population factor.

The differential cross section, σ is related to v^4 [36], hence the Raman gain from equation 5.3 is linearly proportional to the frequency. From equation 5.3, the Raman gain can be increased by increasing the differential cross section of the fibre, by decreasing the dielectric constant at Stokes frequency of the fibre material and by operating at higher frequency.