4.0 Stimulated Raman scattering in pure silica fibre.

4.1 Experimental set up.

The experimental set up is schematically represented in figure 4.1. The output from the Q-switched Nd-YAG laser is coupled into the fibre input using an objective microscope lens with 20 times (20X) magnification. Figure 4.1 shows a schematic representation of the coupling of the frequency doubled 532 nm into the fibre, we used a KDP crystal to generate the second harmonic and a mirror to eliminate the residual 1064 nm from the Nd-YAG laser.

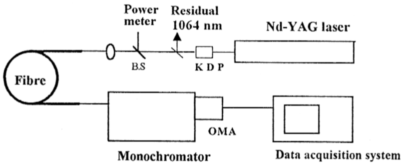

Figure 4.1 **A schematic representation of the experimental set up. This experiment shows a single pass configuration.**

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The Nd-YAG laser used in this experiment is by Lumonics, HY 600 system with a pulse repetition rate of 10 Hz. The output from the fibre was analysed using a optical multichannel analyser (OMA) by Princeton Instruments model RY-1024 and a detector controller model ST-121, the monochromator has a diffraction grating of 1200 lines per milli-meter. The OMA was mounted onto the monochromator and calibrated using a standard mercury lamp. The fibre was mounted onto a chuck and aligned using a Newport fibre micro alignment chuck holder model M-F-915T to ensure that perfect alignment of the fibre core to the beam waist of the laser beam. The fibre used was a Newport fibre model F- SV-20, the fibre parameters of this particular fibre is given in appendix B. The V - number as per calculated from appendix B shows that this fibre is single mode when this fibre is pumped with 1064 nm out put from a Nd-YAG laser, the V number calculated is 1.18 and at frequency doubled 532 nm the V number calculated is 2.36. Frequency doubling was done using a KDP crystal placed at the laser output. The conversion efficiency was measured to be 2.89 %, after eliminating the residual 1064 nm. The beam splitter was measured to transmit 62.77% and reflect 37.23% at 532 nm. This represents an average reading , varying the input energy and measuring the transmittance and reflectance at 532 nm. An OPHIR power meter model NOVA, was placed at the pump input end, to measure the reflected pump from the beam splitter, as depicted in figure 4.1. The fibre was aligned to achieve maximum coupling. Maximum coupling was achieved when the maximum laser light intensity was observed at the fibre output end and care was taken to ensure that no adjustments were made to the coupling through out this experiment once the maximum coupling had been achieved. The input power was varied using neutral density filters at the fibre input end and the corresponding input power change was recorded on the power meter. The output from the fibre was observed on the OMA. At the end of this experiment, the fibre was cleaved approximately 20 cm from the fibre chuck and the coupling efficiency was measured, again care was taken to ensure that no adjustments were made to the coupling. The exact power transmitted through the fibre optic can be deduced by knowing the transmittance of the beam splitter and the coupling efficiency.

4.2 Forward and backward stimulated Raman scattering in pure silica fibre.

Figure 4.2 shows the schematic representation of the experimental set up used to study both the forward and backward stimulated Raman scattering simultaneously. Synchronisation was achieved by setting one OMA as the master and the other OMA as the slave, this set up enabled us to observe what was happening at the input and at the output of the fibre simultaneously when the pump power was gradually increased.

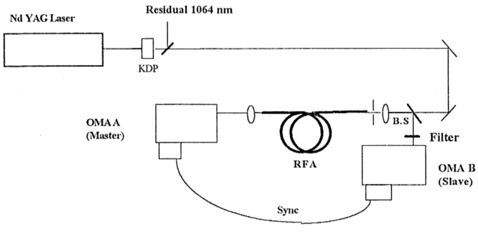


Figure 4.2 **A schematic representation of the experimental set up to study forward and backward stimulated Raman scattering.**

Figure 4.3 shows both the spectrum of forward stimulated Raman scattering and backward stimulated Raman scattering. Under the same input power, both forward and backward Stokes frequencies were observed simultaneously. This was verified by observing the input and the output of the fibre simultaneously using two OMAs

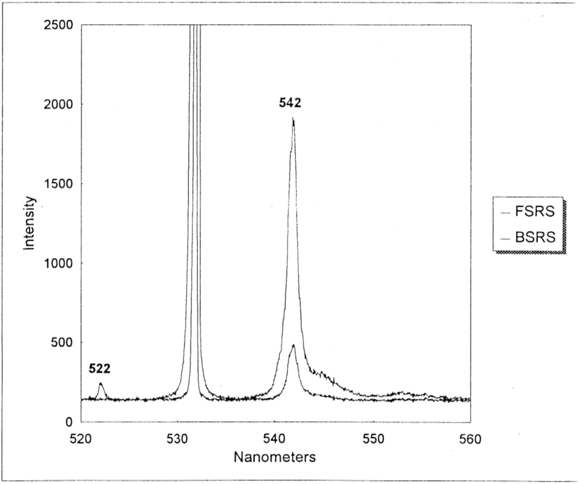


Figure 4.3 **Shows the forward and backward stimulated Raman scattering.**

which were time synchronised as per figure 4.2. Both forward and backward stimulated Raman scattering were seen on both OMAs when the input pump power was increased to 107.1 Watts. This observation shows that the Raman gain is the same, [36], both in the forward and backward pump configuration, this observation was later verified in section 5.4.2, where the Raman gain was measured both in the forward and backward pump configuration. The intensity for the forward is higher than that of the backward pump configuration because the backward Stokes components were observed via a beam splitter, where as the forward Stokes components were observed directly from the output of the fibre. The beam splitter used to observe the backward stimulated Raman scattering was measured to reflect 22.7% and transmit 77.3% of an incident laser beam at 546 nm. This explains the fact why we see the intensity of the backward stimulated Raman scattering to be about four to five times less than that of the forward stimulated Raman scattering.

4.2.1 Stimulated Raman scattering threshold.

Figure 4.4 shows a composite of five different spectrum when the launched power was varied using neutral density filters at the fibre input end. The fibre length was measured to be 2.2 meters. The lowest most spectrum shows the output from the fibre when the peak launched power into the fibre was only 43.8 Watts. There were no non-linear effects seen, only the pump at 532 nm. The first stimulated Raman scattering was observed intermittently when the peak launched power was increased to 107 Watts. The first stimulated Raman scattering was observed at 542 nm (346 cm^{-1}) away from the pump. Also observed was an Anti-Stokes stimulated

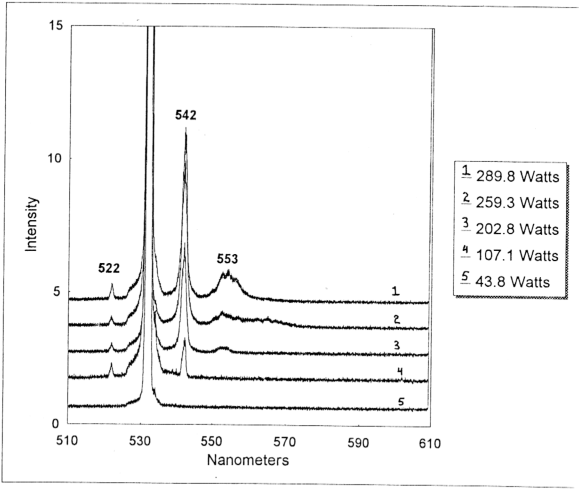
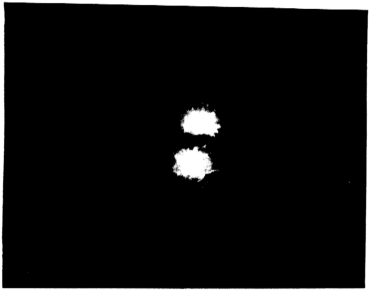


Figure 4.4 **Shows the generation of stimulated Raman scattering from a 2.2 meter optical fibre at various input pump power.**

Raman scattering at 522 nm (360 cm $^{-1}$). The Anti-Stokes observed was much lower in intensity compared to that of its Stokes counterpart. Anti-Stokes from stimulated Raman scattering was also observed by Barbosa F.R. 1983 [1] in multi mode fibres. Note that as per the V number calculated in appendix B, the V number is 2.36, this fibre is just about single mode at 532 nm. In actual fact two modes were observed to propagate down this fibre. The most dominating pump mode observed was that of LP_{11} as shown in the top picture of figure 4.5, (exposure time 2 seconds). Different modes can be selected by changing the coupling angle of the laser light into the fibre or by simply bending the fibre to a smaller radius of curvature as shown in the bottom picture of figure 4.5, this photograph shows the pump in the LP_{01} mode (exposure time 3 seconds) after bending the fibre. An interesting point to note is that these different modes of pump creates different stimulated Raman scattering, the LP_{11} pump mode creates the first stimulated Raman scattering at 542 nm (346 cm $^{-1}$), whereas the LP_{01} pump mode creates the first stimulated Raman scattering at 546 nm (483 cm $^{-1}$). Further confirmation was carried out using 1064 nm pump from the Nd-YAG laser to pump the fibre. From appendix B, the V number at 1064 nm is 1.18. This means that this fibre is single mode in this region. When pumped with 1064 nm, the first stimulated Raman scattering was observed at 1117 nm (446 cm $^{-1}$), this compares well with the case mentioned earlier when pumped with 532 nm, both results shows the first stimulated Raman scattering occurring from 446 cm $^{-1}$ to 483 cm $^{-1}$ when pumped with LP_{01} mode.



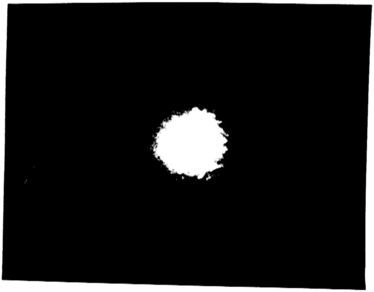


Figure 4.5 **Shows the different modes of the 532 nm pump inside the fibre. The top picture shows LP_{11} and the bottom picture shows LP_{01}.**

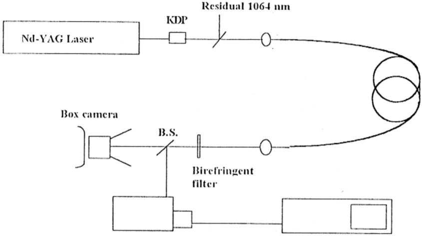
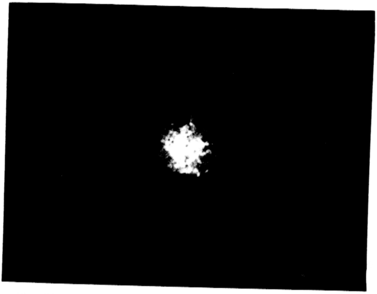


Figure 4.6 **A schematic representation of the experimental set up to study the different modes propagating in a fibre.**

Figure 4.6 shows a schematic representation of how the different modes propagating through the fibre were studied. A birefringent filter was used to select either the pump or the first stimulated Raman. The output from the birefringent filter was further confirmed on the OMA via a beam splitter. Using a Polaroid box camera, pictures of the laser beam were taken after passing through the fibre and the birefringent filter. Figure 4.7 shows the picture of the first stimulated Raman when pumped by LP_{11} (top picture, exposure time 12 seconds) and LP_{01} (bottom picture, exposure time 15 seconds). It also shows that both the first stimulated Raman scattering pumped by the LP_{11} and LP_{01} modes are of the LP_{01} modes. Figure 4.9 shows the first stimulated Raman scattering at 542 nm with a shoulder around 546 nm. As mentioned earlier, the intensity of this shoulder can be made higher by simply bending the fibre to a smaller diameter or by changing the coupling angle of the laser light into the fibre. When the fibre is bent, we are selectively eliminating different modes in a few mode fibre and the new dominating mode can be seen.



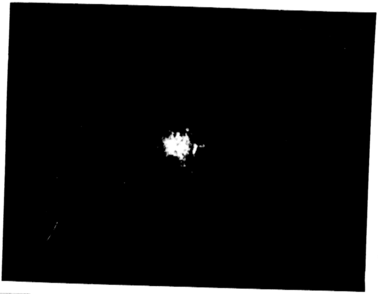


Figure 4.7 **Shows the modes of the first stimulated Raman scattering by different pump modes. The top picture shows the SRS generated by the LP_{11} pump and the bottom picture shows the SRS generated by the LP_{01} pump.**

To distinguish Stokes and Anti-Stokes frequencies generated by four photon mixing vs Stokes and Anti-Stokes frequencies generated by the stimulated Raman scattering, measurements were carried out in the backward pump configuration. Phase matching is impossible in the backward pump configuration and since four photon mixing is critical to phase matching, four photon mixing can only be observed in the forward direction, [10]. By confining our measurements in the backward pump configuration via a beam splitter at the pump input end, we observed similar but weak Stokes component. The frequency shift of the Stokes component seen is the same in either forward or backward pump configuration i.e. 542 nm (346 cm^{-1}). This confirms that the Anti-Stokes that we observed in figure 4.4 comes from stimulated Raman scattering and not from four photon mixing because if it was from four photon mixing, even the Stokes component would not be observed. The creation of an Anti-Stokes photon in stimulated Raman scattering comes from the mixing of a pump photon and a Stokes photon via the non linear polarisation susceptibility as mentioned in chapter 3. Subsequent spectrum in figure 4.4 shows the proliferation of higher order stimulated Raman scattering when the launched power was increased. Second order Stokes due to stimulated Raman scattering was observed intermittently at 553 nm (713 cm^{-1}) when the peak launched power was increased to 202 Watts and the third order Stokes due to stimulated Raman scattering was observed intermittently at 566 nm (1129 cm^{-1}) when the peak launched power was increased to 289 Watts.

Figure 4.8 shows that output from a 10 meter fibre optic. The first order Stokes due to stimulated Raman scattering was observed intermittently when the

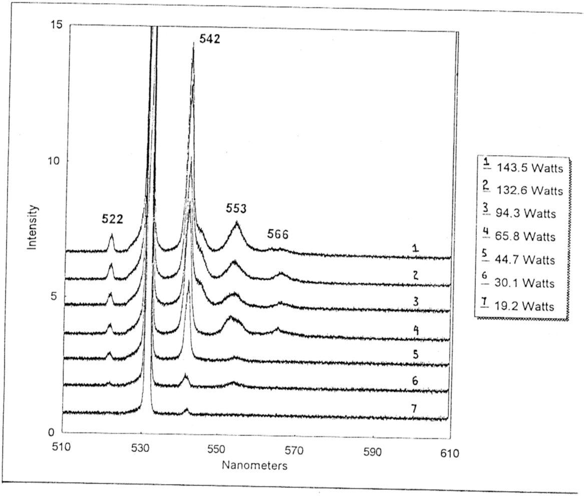


Figure 4.8 **Shows the generation of stimulated Raman scattering from a 10 meter optical fibre at various input pump power.**

peak launch power was only 19 Watts. The second Stokes due to stimulated Raman scattering was observed when the peak launch power was increased to 30 Watts. The third order Stokes due to stimulated Raman scattering was observed when the peak launched pump power was increased to 65 Watts. The longer the interaction length, the peak threshold power needed to reach saturation drops significantly. At 460 Watts peak launch power, the first Stokes at 542 nm, due to stimulated Raman scattering becomes almost as intense as the pump at 532 nm as shown in figure 4.9. Also shown in figure 4.9, is the second (553 nm) and third (566 nm) stimulated Raman scattering which are prominent and easily distinguished, higher order Stokes due to stimulated Raman scattering forms a continuum and not as easily distinguished as the first, second and third stimulated Raman scattering. This has also been observed by C. Lin et. al. 1976, [22].

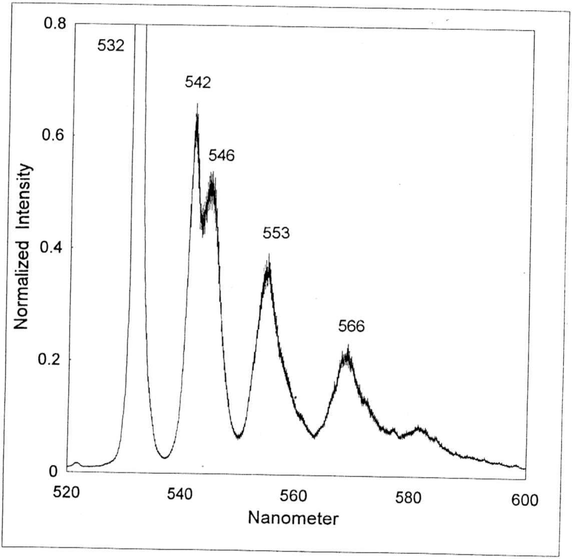


Figure 4.9 **Shows the generation of higher order stimulated Raman scattering.**

4.2.2 Polarisation dependence.

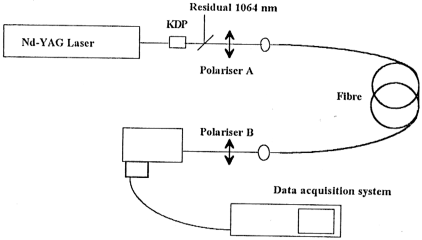


Figure 4.10 **A schematic representation of the experimental set up used to study polarisation dependence of the fibre output.**

Figure 4.10 shows a schematic representation of the experimental set-up to study the effect of polarised pump on stimulated Raman scattering and also to study the polarisation of the Stokes component created by stimulated Raman scattering. Figure 4.11 shows the output spectrum from a 10 meter fibre when polariser A was placed in the vertical direction at the fibre input end, prior to launching the laser light into the fibre. This spectrum shows a spectrum similar to that in figure 4.9. (Figure 4.9 shows the stimulated Raman scattering of this fibre without any polariser at the input or output of the fibre). Figure 4.12 shows the output spectrum when polariser A was placed in the horizontal position prior to launching the laser light into the fibre. These figures shows that the output from the Nd-YAG laser is linearly polarised in the vertical direction. Figure 4.13 shows the output from a 10 meter fibre when a polariser B was fixed at the fibre output prior to the monochromator. When polariser B was placed facing the vertical direction the intensity of the spectrum shows almost similar characteristics to that shown in figure 4.9 (without the polariser in place). Figure 4.14 shows the output from the fibre when polariser B was placed in the horizontal direction. The spectrum shows 75 % drop in intensity but there were no changes in all critical features like the first, second and third stimulated Raman scattering peaks. This observation shows that the fibre is not a polarisation maintaining fibre and part of the energy is transferred from one orthogonal axis to the other.

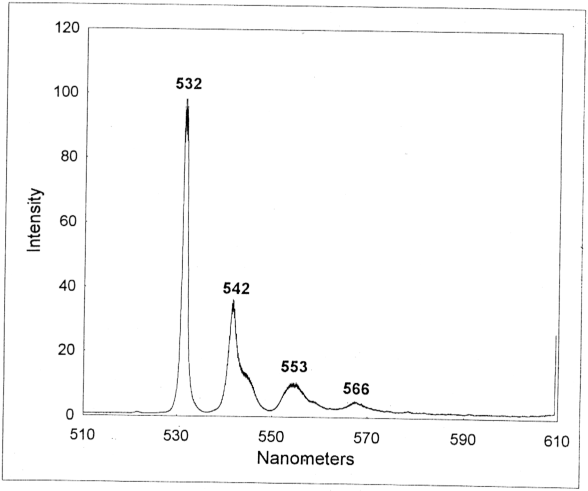


Figure 4.11 **Shows the output from a 10 meter fibre when a polariser was placed at the input end facing the vertical direction.**

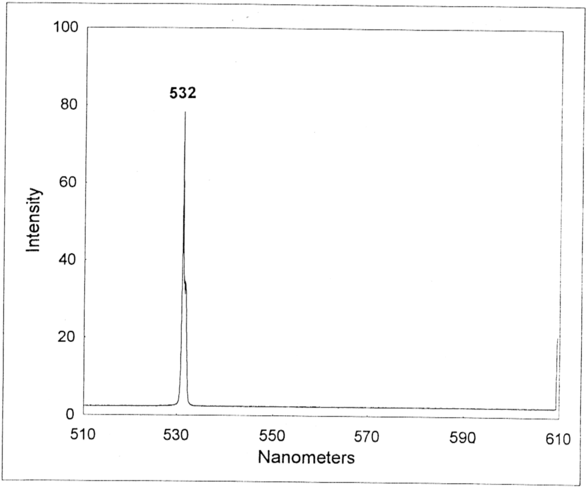


Figure 4.12 **Shows the output from a 10 meter fibre when a polariser was placed at the input end facing the horizontal direction.**

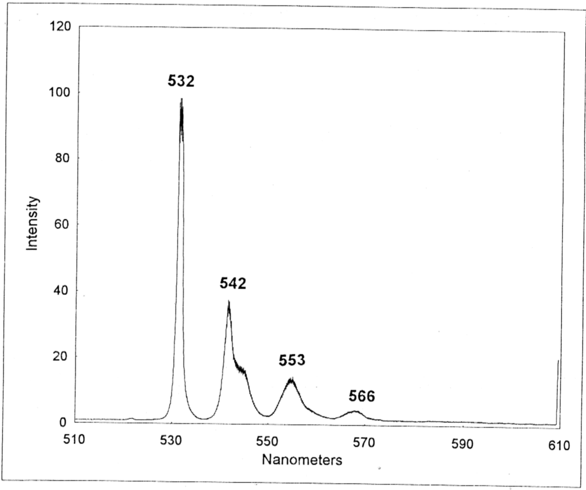


Figure 4.13 **Shows the output from a 10 meter fibre when a polariser was placed at the output end facing the vertical direction.**

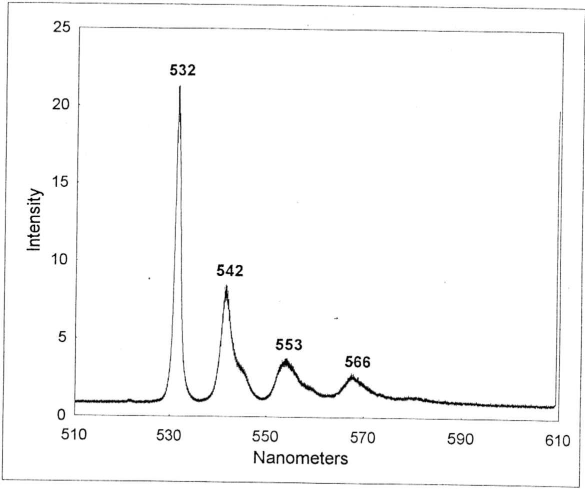


Figure 4.14 **Shows the output from a 10 meter fibre when a polariser was placed at the output end facing the horizontal direction.**

4.3 Dispersion Measurement in pure silica fibre.

The experiment set up to study dispersion in fibres is schematically represented in figure 4.15. This experiment was carried out using a different silica fibre, manufactured by OPCOM Malaysia.

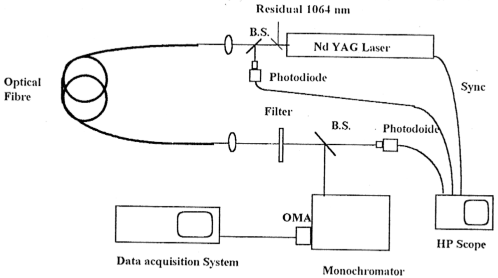


Figure 4.15 **A schematic representation of the experimental set-up used to measure the walkoff between Stokes generated from SRS and the pump.**

Figure 4.15 shows the set-up used to measure dispersion in a pure silica fibre by measuring the walkoff between the Stokes generated from the first stimulated Raman scattering and the pump pulse in the fibre. Light of slightly different frequencies travel at slightly different speeds in a dispersive medium, depending on the relative index of reflection for the different wavelengths, as such light of lower frequencies would travel faster than that of a higher frequency, Pedrotti 1978, [29]. Hence by pumping a fibre, we would expect to see the Stokes pulse generated from the first stimulated Raman scattering overtaking the pump, if the fibre is sufficiently long. These measurements were carried out using the set-up as depicted in figure 4.15. The length of the fibre was varied and the length can be deduced by measuring the time difference between the two photodiodes. The photodiodes were connected to a Hewlett-Packard digitising storage scope model 5410A, with capabilities of sampling 1G samples per second. This scope was time synchronised to the firing of the laser. A birefringence filter was placed at the output of the fibre, by tuning the angle of this filter, we were able to select either the first Stokes generated from the stimulated Raman scattering or the pump pulse, this was further confirmed by diverting part of the beam via a beam splitter after passing through the birefringence filter into the OMA. Neutral density filters were placed in front of the photodiodes to ensure that the incident power to both photodiodes were kept constant. This precaution was necessary when it was found that small variation of the pulse width could be observed with different incident powers to the photodiodes, Byron K.C. 1986, [4]. The timing of each pulse was taken from the time at full width at half maximum (FWHM).

4.3.1 Experimental results.

Figure 4.16 shows the plots of pulses seen from the oscilloscope for three different lengths of fibre. The first is 13.12 meters, second is 630.79 meter and the third is 2061.92 meters respectively. In the first length of fibre, the time difference between the first Stokes due to stimulated Raman scattering and the pump at 532 nm was measured to be 9 ns, with the pump leading the Stokes. In the second length of fibre, the pump was seen to be leading the Stokes by 3.8 ns and in the third length

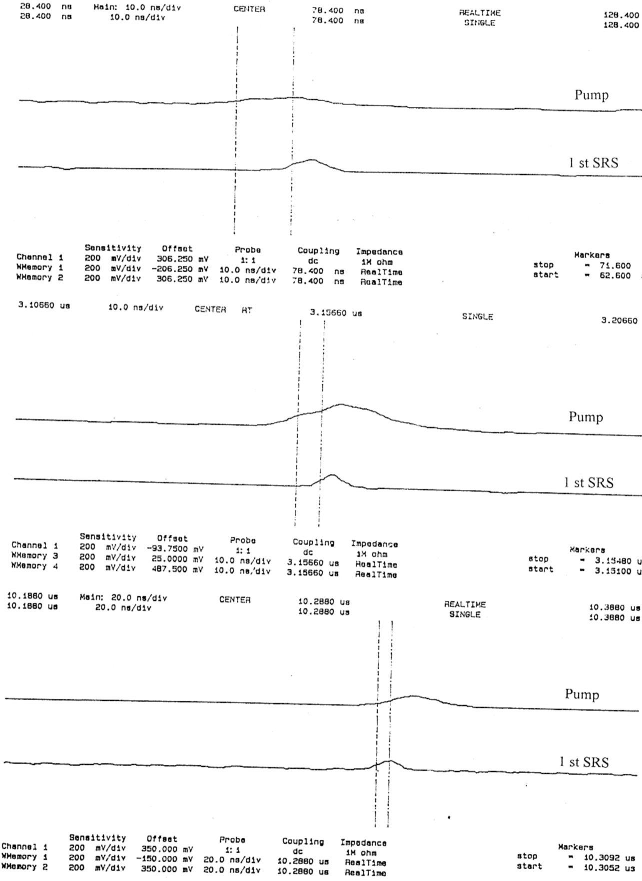


Figure 4.16 **Shows the plots seen from the oscilloscope at various fibre lengths, shown are the time difference between the first SRS and the 532 nm pump, at 13 meters, 630 meters and 2 km respectively.**

of fibre tested, it can be seen that the Stokes has now overtaken the pump and is now leading the pump by 4 ns. This results can be summarised in the table 4.3 below.

Fibre length (m)	532 pump ($t_{1/2}$)	1 st SRS ($t_{1/2}$)	delta $t_{1/2}$ (ns)
13.12	71.6	62.6	-9
630.76	3,154.7	3,151.1	-3.8
2,061.92	10,305.2	10,309.2	4

Table 4.3 Shows a summary of the walkoff between Stokes and pump in fibres of different lengths.

Figure 4.17 shows the relationship of the walkoff between the Stokes and pump. Figure 4.17 shows a linear relationship. There are three interesting points to note in this linear relationship. Firstly the slope of this linear relationship has a value of 10.703 ns/km. Secondly the intersection of this line to the X - axis shows the point where the Stokes and the pump coincides in the fibre, from the graph this value is 1.151 km. This point is also interesting because the amplification of the Stokes component would cease once the Stokes overtakes the pump because the Stokes would no longer see the pump and energy transfer from the pump to the Stokes cannot happen, [36]. In other words the Stokes would have achieved its maximum amplification. Thirdly we can estimate the excited time of the stimulated Raman scattering to be 12.32 ns. This excited time is the time from excitation of the pump to the time of decay of the molecule. It is crucial to know the lifetime of the excited state of the molecule, because for stimulated emission to happen, i.e. amplifying effect, the signal has to come in within this lifetime when the molecules are still in an

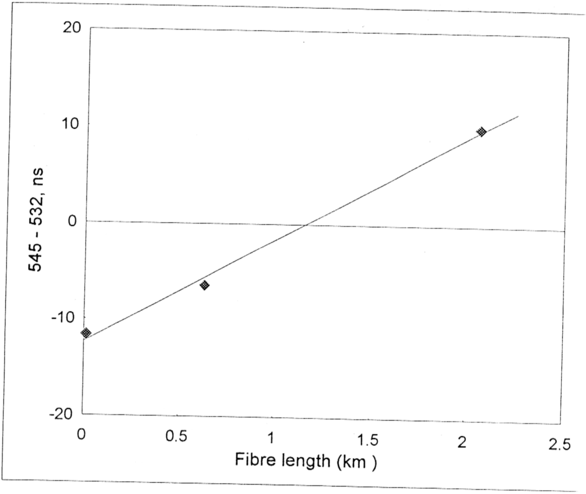


Figure 4.17 **Shows the relationship between the walkoff of the first SRS and the 532 nm pump at various fibre length.**

excited state. Stimulated Raman scattering has known to exhibit amplifying effect and this will be discussed in more detail in chapter 5.