2.0 Introduction to Non Linear Effects in Optical Fibre.

Fibres are usually considered as passive or linear media - in which we would expect to see a proportional increase in the output power as we increase the input power. However this is not true, various non linear effects in optical fibres had been seen and reported. Among the non linear effects reported in optical fibres are stimulated Raman scattering [1,11,39,43] second harmonic generation [28], stimulated Brillouin scattering [5,15,36], four photon mixing [13,14,37,40,41], continuum generation [18,21,22,30 - 33] and many others. These non linear effects causes the desecration of the laser light. The proliferation of these non linear effects in optical fibres depends on two main factors:

- the intensity of the laser light and
- the fibre parameters e.g.. interaction length and core diameter.

The study of non linear effects is particularly interesting in optical fibres due to the long confinement length of the laser light in an optical fibre which is conducive for the proliferation of non linear effects, hence even with modest laser power various non linear effects can be observed. Non linear effects are detrimental to optical communication because it sets a limit to the maximum laser power, above which, various non linear effects would proliferate and cause the optical signal to be desecrated e.g. frequency conversion, loss of signal power and induced cross talk in multiplexed system [5], while on the other hand these same effects which are detrimental in some aspects shows great potential in other aspects such as in optical amplifiers, oscillators and modulators, [36]. Hence by understanding the drawback and potential of what these non linear effects in optical fibre have to offer, we can utilise them to our best advantage. We would now briefly discuss a few non linear effects commonly encountered (unless otherwise stated) in optical fibres and their advantages where applicable.

2.1 Stimulated Raman Scattering.

One of the most dominating non linear effect seen in optical fibre is stimulated Raman scattering. The Stokes and Anti-Stokes frequency shift is usually a few hundreds of cm^{-1}, usually for silica dioxide it ranges from 400 - 460 cm^{-1} , depending on the relative index difference between the core and the cladding of the fibre sample, as given in table 3.1. Raman scattering is caused by the modulation of light by molecular vibrations which produces sidebands which are separated from the incident frequency (pump) by a frequency shift which is equal to that of the molecular vibration. The lower frequency sidebands are called the Stokes line and the higher frequency sidebands are called the Anti-Stokes line, typically the Stokes lines are significantly stronger than that of the Anti-Stokes lines. The creation and amplification of Stokes lines will be covered to some extent in chapter 3. The Stokes lines formed from stimulated Raman scattering are self-phase matched, hence we would be able to observe both the forward and backward stimulated Raman scattering in the fibre.

The advantages of stimulated Raman scattering are in tuneable sources where Stokes lines due to stimulated Raman up to the fifth order can be observed. These Stokes lines are laser in character and by tuning the output of the oscillator, various Stokes lines can be selected. High efficient tuneable CW Raman oscillator had been reported by Jain R.K. et. al. 1977, [16] and Labudde P. et. al. 1980, [20]. The second and more interesting application of stimulated Raman scattering in optical fibre, is in optical fibre amplifier [4,6,7,19,23,25], where if a signal which is at Stokes frequency, is co-injected into the fibre together with the pump, either co-propagating or counter propagating, there will be amplification of the Stokes signal at the expense of the pump. The characteristics of a Raman fibre amplifier would be discussed in more detail in chapter 5.

2.2 Four Photon Mixing

Four photon mixing, also known as parametric mixing or three wave mixing, is another non linear effect commonly seen in optical fibres. The Stokes and Anti-Stokes frequency shift is from a few cm^{-1} to thousands of cm^{-1}, depending on the phase matching conditions. Stokes and Anti-Stokes lines are created at the annihilation of two pump photons. Unlike stimulated Raman scattering, four photon mixing is critical to phase matching, as such Stokes and Anti-Stokes lines created by four photon mixing can only be observed in the forward direction, [10]. The various methods of achieving phase matching will be discussed in more detail in chapter 4. Generally, in short length of fibres, four photon mixing is perceptibly the dominant of the two non linear processes discussed so far, [37]. This is because in short length of fibre, prior to the Stokes and Anti-Stokes getting out of step, the Stokes and Anti-Stokes would have already exited the fibre. In long lengths of fibres, stimulated Raman scattering would dominate over four photon mixing because the coherence length for four photon mixing is less than the fibre length, where there will be some point along the fibre where the Stokes photon get out of step and annihilate one another.

The advantages of four photon mixing are in frequency conversion of the pump and optical amplifier. Ohashi M. et. al. 1982, [27].

2.3 Stimulated Brillouin Scattering.

Brillouin scattering is similar to Raman scattering, the difference being that in Brillouin scattering, acoustic phonons are involved instead of high frequency optical phonons. The frequency shift is usually a few cm^{-1} away from the pump, in the region of 12.7 GHz (0.42 cm^{-1}). The gain for Brillouin scattering is at its maximum only in the backward pump configuration and zero in the forward direction, as such to we can only observe stimulated Brillouin scattering in the backward pump configuration. The gain of the stimulated Brillouin scattering is two orders of magnitude larger than that of stimulated Raman scattering [36], but despite this larger gain, stimulated Raman is still the dominant process because the pump linewidth of stimulated Raman is larger than that of stimulated Brillouin scattering.

Application of Brillouin scattering is in optical amplifier where amplification was achieved in the backward pump configuration, however this amplifier requires a narrow linewidth pump laser and precise control of the difference between the frequency of the pump and that of the signal.

2.4 Continuum Generation.

This non linear effect is a rare occurrence in optical fibres, usually seen when pumped with high power in long lengths of fibre. The frequency shift is thousands of cm^{-1} away from the pump. Figure 2.1 shows the continuum generated when a 1 km length of fibre was pumped with intense 1064 nm from a Nd-YAG laser, the peak input power coupled into the fibre was measured to be 35.5 kW, after taking into consideration the coupling efficiency etc. Figure 2.2 shows the same fibre, when the peak input power coupled into the fibre was increased to 80.3 kW. There are two peaks seen from both figures, the first was centred around 820 nm and the second peak was centred around 920 nm. The threshold power for this continuum generation was observed to be higher than that of stimulated Raman scattering, as such these continuum generation happens after stimulated Raman scattering. In figures 2.1 and 2.2, neutral density filters were used to block the intense pump (1064 nm) and first stimulated Raman (1116 nm) to avoid the optical multichannel from being damaged, this explains why we see the continuum in both figure 2.1 and figure 2.2 having higher relative intensity than that of the first stimulated Raman scattering. We also see slight discontinuity in figure 2.1 and figure 2.2 because both these figures were made up of composites of different frames, each frame was about 100 nm wide. In order to view the whole region of interest, from 720 nm to 1220 nm, these frames were composited on a computer, the discontinuity arises from the points where the frames overlap. Continuum generation was also observed by Poumellec B. et.al. [30 - 33], when pumped with intense 1064 nm, these continuum generation or as it was called as anomalous florescence by Poumellec B.et. al. was attributed to the O- Si- O bonds

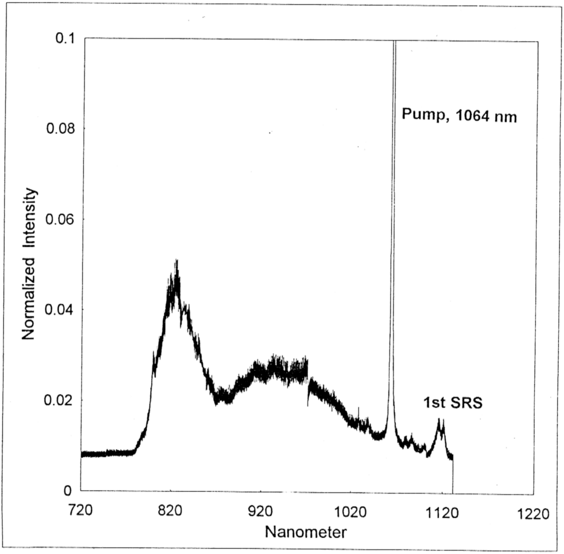

Figure 2.1 **Shows the continuum generated from a 1 km fibre pumped with 1064 nm at peak input lower at 35 kW.**

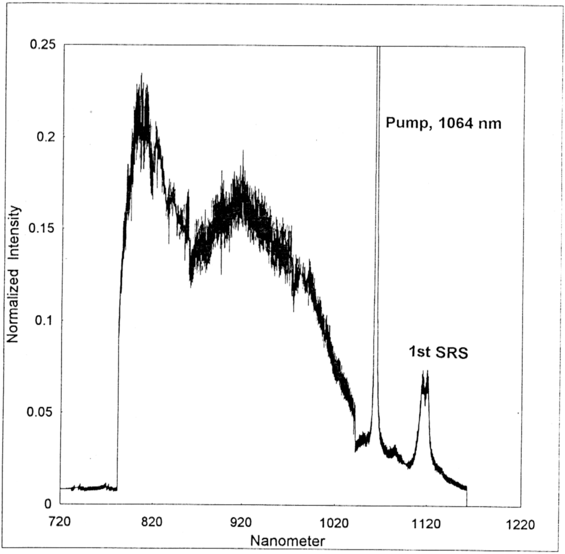

Figure 2.2 **Shows the continuum generated from a 1 km fibre pumped with 1064 nm at peak input power at 80 kW.**

in the silica fibre. We could not observe the second order stimulated Raman scattering when pumped with 1064 nm because the optical multichannel analyser used has a sensitivity of only till 1130 nm. Figure 2.3 shows the output from the fibre when this same fibre was pumped with frequency doubled 532 nm. This figure is a composite of three different spectrums, this was done to shows that the peaks seen in figure 2.3 are distinct peaks and not noise created by the optical multi-channel analyser. At higher frequency shifts, around 560 nm (940 cm^{-1}), we see that the peaks are not easily distinguished and forms a continuum.

2.5 Second harmonic generation.

Second harmonic generation is not likely to be seen in an isotropic material like glass, this is because isotropic material do not have a dipole allowed second order non-linearity, however all isotropic materials possess electric quadrupole and magnetic dipole nonlinearities and these can act as a source for second harmonic generation in an isotropic material. Normally these higher order multipoles moments are considered too weak to be of any interest, however in single mode optical fibres, where high optical power densities are maintained over long lenghts, these higher order multipoles begin to play a role in generating non linear effect in optical fibres. A detail explanation is given by Payne F.P 1987, [28].

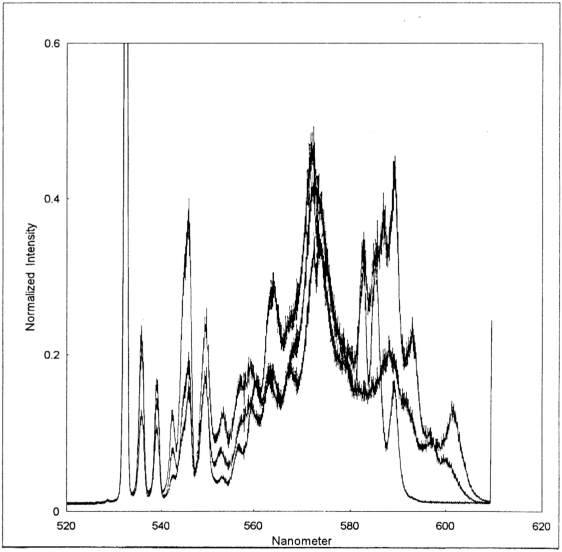

Figure 2.3 **Shows the continuum generated from a 1 km fibre pumped with 532 nm.**