CHAPTER 5

MODIFICATION /ENHANCEMENT DESIGN OF MULTI-WAVELENGTH BEFL

5.1 Introduction

Chapter 4 presented a thorough analysis of the characteristic of standard design Brillouin erbium fiber laser (BEFL) for single wavelength and multiwavelength operation. The previous designs were very important to study, in term of working principle of BEFL operation in a standard design and the used as a guideline to make an enhancement in generation of multiple wavelength Brillouin fiber laser. This chapter discussed on the study of modification to enhance the performance of generation for multiple wavelength Brillouin fiber laser. In this chapter, we also study the Brillouin fiber laser with Raman amplification.

5.2 Enhancement BFL Resonator

The schematic diagram is similar to the previous configuration except for the additional loop across the PCF through a pair of couplers with a splitting ratio 95/5. This ratio is selected in this research based on the higher value which is achieved when we tested the performance of the coupler ratio. This configuration use the new development of amplifier, the Bi-Si-EDFA in figure 3.12 to replace the previous Bi-EDFA. Bi-Si-EDFA was designed to give a power as high as 19 dBm and the performance of this amplifier were discussed in detail in chapter 3. An optical circulator is used as a bridge to inject the Brillouin pump (BP) into the main cavity and to force unidirectional operation of the laser in the cavity. Two optical couplers (C1 and C2) are incorporated in the resonator and joined in a loop arrangement to act as a looping arm in order to improve the multiple wavelengths of Brillouin Stokes. The length of PCF as the fiber under testing is fixed at 20m.

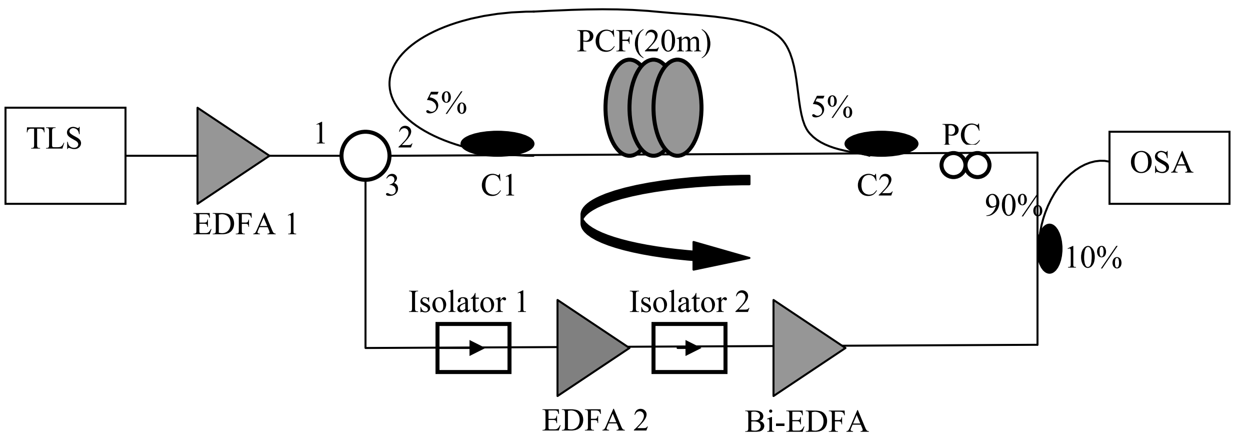

Figure 5.1: Enhancement of Bi-Si-EDFL ring cavity

A narrow line-width signal with a wavelength of 1562.955nm from the TLS is amplified by the EDFA which is pumped by a laser diode at 980nm to act as the BP source, and is launched into the main cavity through port-1 to port-2 of the optical circulator in the clockwise direction of the system. The incident light with acoustical vibrations interacts with particles in the PCF and changes the density of the material in the PCF. It causes the different refractive indices in the PCF due to backscattering [4]. It further causes Brillouin scattering in the opposite direction. The BP will obtain a nonlinear gain via SBS in the PCF.

The Brillouin Stokes will be generated in the counter clock wise (CCW) direction at a frequency shift from the Brillouin pump by a Stokes shift in the PCF. The Brillouin gain is then amplified when it passes through the Si-Bi-EDFA. 10% of the light was extracted out via a 10% port of the coupler and displayed as a first Stoke. The remaining 90% of the BEFL light travels until it is dissociated by a 5/95 optical coupler. 5% of light from it is then re-injected into the main cavity and combined with the BP signal from the external cavity. The combination of both light signals act as the BP and is re-injected into the PCF in the clockwise direction to generate additional frequencies. This process will be repeated until the power of the amplifier is lossy and cannot further generate Brillouin Stokes.

Several reports had shown by using a polarization controller (PC) in the laser cavity, stability can be enhanced and output power can be maximized [5,8]. In this research, a polarization controller (PC) was placed near the PCF to control the polarization state of light. It works by using the Faraday rotator principle that has been explained in chapter 2. The polarization condition of the laser can be changed by tuning the wave plate angle slightly. The output of multi-wavelength Brillouin is measured and characterized by an optical spectrum analyzer (OSA) with resolution of 0.01nm. Similar to the analysis in the previous experiment, we study the effect of the LD power and BP power on the Brillouin Stokes generated and Brillouin threshold.

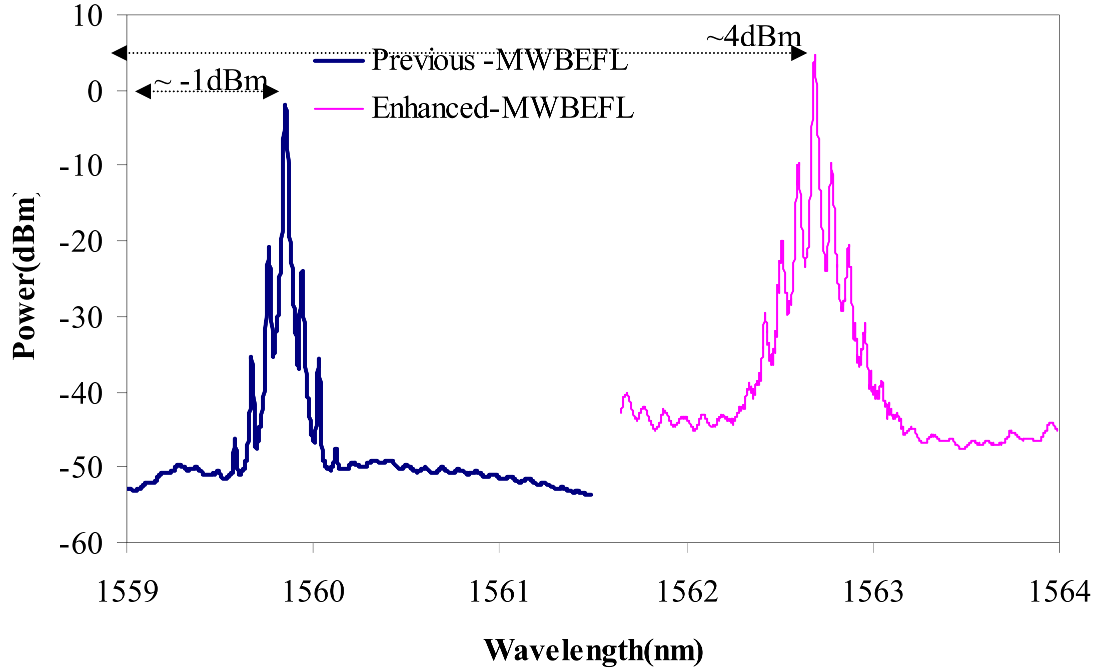

Figure 5.2: Comparison of the previous MWBEFL and enhanced MWBEFL

Figure 5.2 shows the MWBEFL output comb against wavelength for two different MWBEFL schemes. As shown in the figure, the simultaneous laser lines separated by 0.09nm are generated in both of the MWBEFL schemes. The external signal at both spectrums is launched at different selective wavelengths. The external signal for the previous MWBEFL is launched at 1559.766nm while a wavelength of 1562.955nm is used for enhanced-MWBEFL. A different selective wavelength has been chosen because of the different active regions required to generate the MWBEFL. As shown in the figure, the enhancement MWBEFL system generates Brillouin Stokes higher than the Brillouin Stokes generated by the previous MWBEFL; as high as 4dBm while Stokes in the previous MWBEFL can only achieve a maximum value of -1dBm. The number of generated Brillouin Stokes for the enhanced system is higher than the previous system. The enhanced system can generate up to 9 Brillouin Stokes lines, while the previous system can only generate 7. This is a clear improvement with this modification of the system.

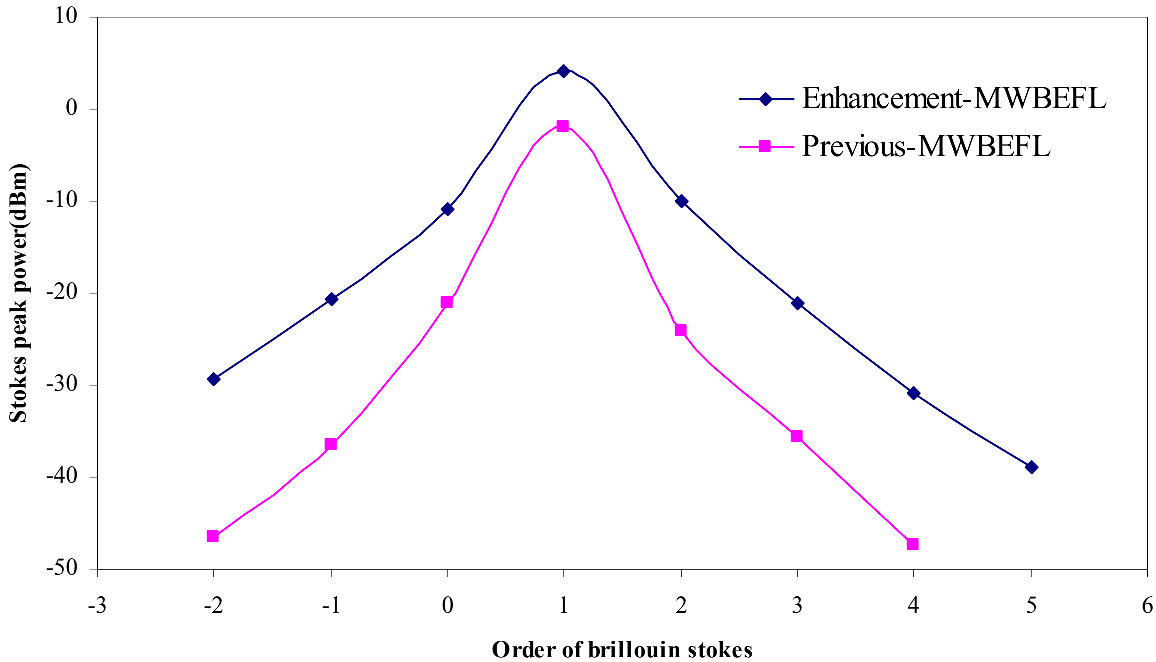

Figure 5.3: Comparison of Stokes peak power for each order Brillouin lines

The comparison clearly can be seen in figure 5.3 above. From the figure, we can see that the peak power for the enhancement MWBEFL system is higher than the peak power for the previous MWBEFL system as mentioned in the past paragraph. At the x-axis, negative numbers are defined as Brillouin anti-Stokes lines. Positive numbers are defined as the Brillouin Stokes lines while the line at x = 0 is the BP. As we can see, both of the spectra are symmetrical about the peak value, which is the highest value belongs to the first line generated.

5.3 Effect of Laser Diode and BP

Laser diodes and BP play the important role of generating the many orders of Brillouin lines Stokes as mentioned in the previous chapter. In this enhancement system, we also studied the influence of laser diodes and BP in the generation of Brillouin Stokes lines. In this configuration, we placed an EDFA which feature Er^{3+} ions pumped by a 980nm laser diode acting as a BP combined with a TLS source. We fix the total BP power at 20dBm and launch it into a laser cavity at 1562.955nm.

The total power of all laser diodes at 1480nm is increased slightly from 67.42mW till 95.59mW. It is shown in figure 4.18 below with the total BP power fixed at the maximum power of 20dBm. From the experimental work for this configuration, the suitable power of the amplifier in the laser cavity is around 67mW. If we increase the pump power to anything more than that, the Brillouin Stokes will be destroyed and the number of the Brillouin Stokes lines will decrease until the system is only be able to generate the 1st Stoke at 95.59mW of total power for the 1480nm laser diode. This is due to the already high BP power that caused saturation.

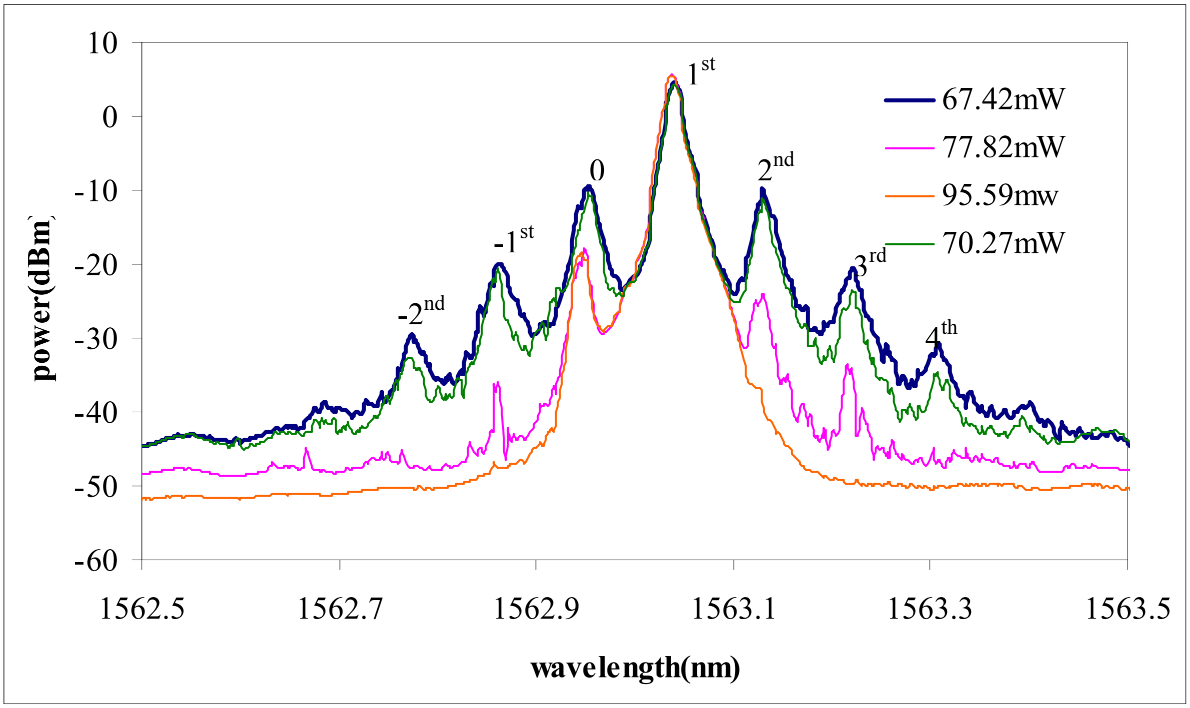

Figure 5.4: Multiwavelength BEFL at different pump power at 21dBm of laser diode

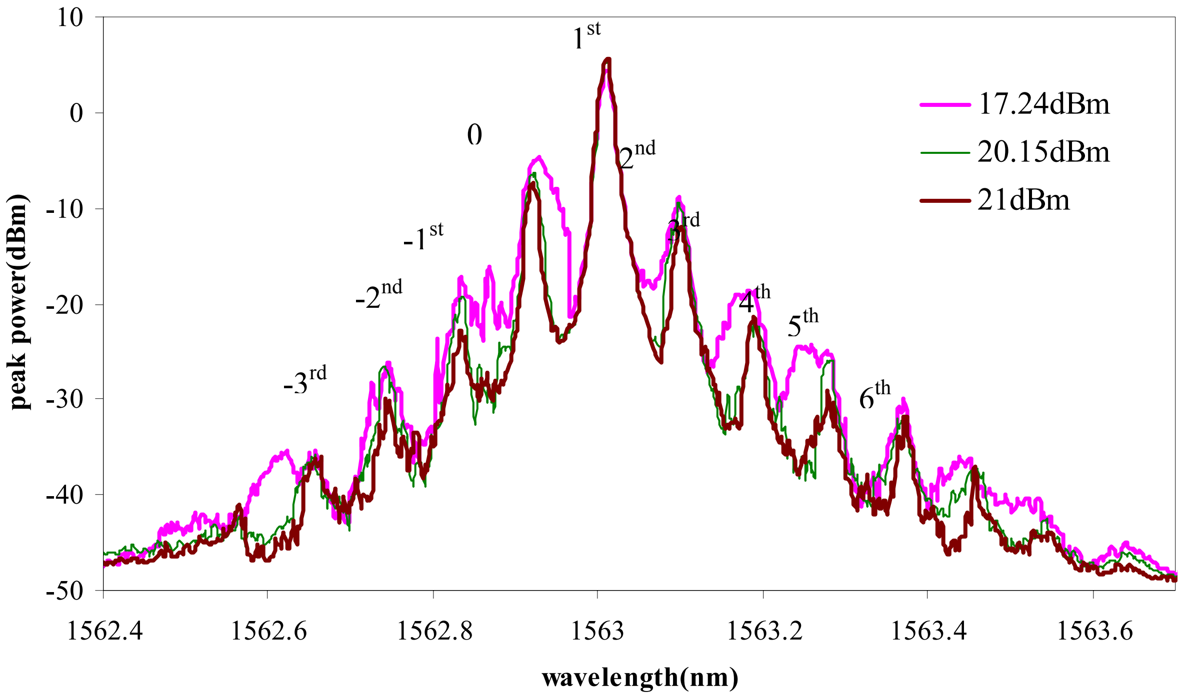

Figure 5.5: Multiwavelength BEFL at different BP

To study the BP effect, the pump power of the amplifier is fixed at 67.47mW and we changed the BP power from a maximum to much lower values. The output spectrum is shown in figure 5.5. The optimum MWBEFL spectrum with a maximum number of generated Brillouin Stokes was obtained at a BP power of 20 dBm. BP powers below 20dB are insufficient to injection-lock which the strong lasing gain of the free running EDFL because of the high LD power applied to the MWBEFL system. The number of lines generated is limited to approximately 9 lines including Stokes and anti-Stokes lines because of the resonator configuration and the availability of the pump power. The number of lines generated is labeled as shown in figure 5.7.

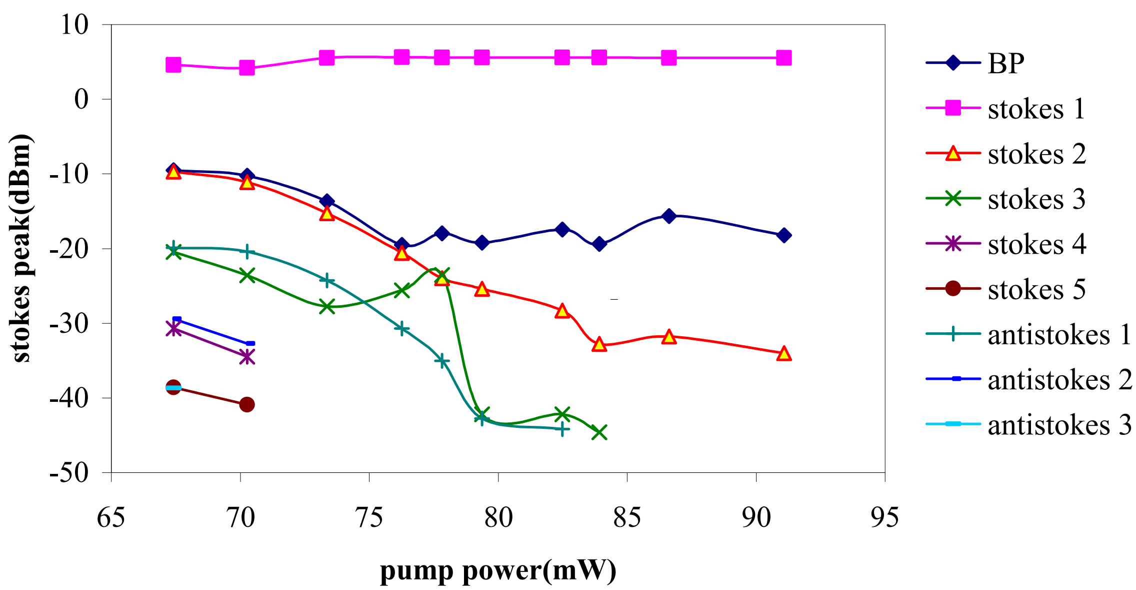

Figure 5.6: Distribution of Stokes peak power against increasing pump power

The distribution of Stokes peak power against the different pump powers are displayed in figure 5.6. The BP power was fixed at 20dBm while the pump power of the amplifier is tuned from lower to higher values. It can be noticed that at 67mW pump power, all nine Brillouin Stokes lines were generated and these lines diminish with increasing pump power. As we can see generally, the value of the Stokes peak power also decreases with increasing pump powers. This phenomenon is due to the saturation power achieved while combining the amplifier power in the ring cavity and high power supplied by BP from the external cavity. Although by exchanging the pump power value, the peak of the first Brillouin Stoke is flattened. It is because the threshold power to generate the first Stokes is low and thus the generation of the lower orders of Stokes is generally possible.

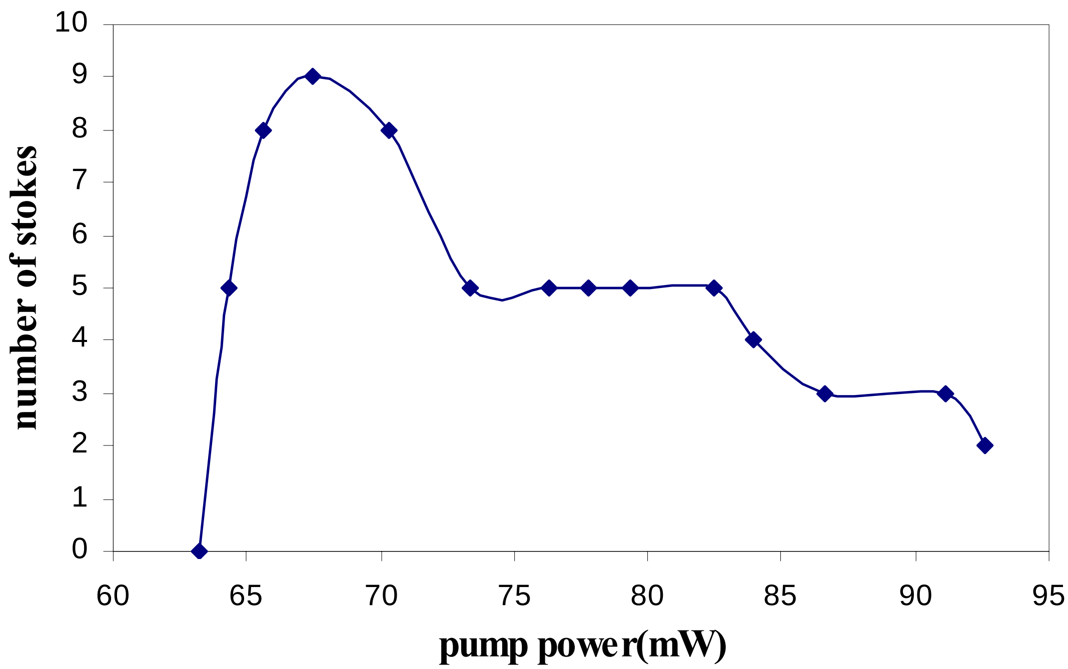

Figure 5.7: Number generated of Brillouin Stokes lines

The number of Brillouin Stokes lines including stokes and anti-Stokes generated as a relation of BP power is depicted in figure 5.7 above. It can be noticed that the number of generated Brillouin Stokes increases from zero at lower pump power. It increased rapidly to nine Stokes at around 67mW pump power. The number of Stokes slightly decreased with increasing pump power until a maximum value of pump power with only two Stokes lines at above 90mW. So, with the analysis from figure 5.7 and 5.7, we can say that the most suitable power to generate the best comb of MWBEFL is at around ~67mW with BP power fixed at 20dBm injected at a fixed TLS wavelength of 1562.955nm.

5.4 Output Position

In this section, the position of the output coupler in the Bi-BEFL system was investigated. The output position which comes after Bi-BEFL is defined as position 1, while the output position which comes before the Bi-BEFL is defined as position 2 as shown in figure 5.8. The effect of output position on the peak power for various BP and LD power values is investigated.

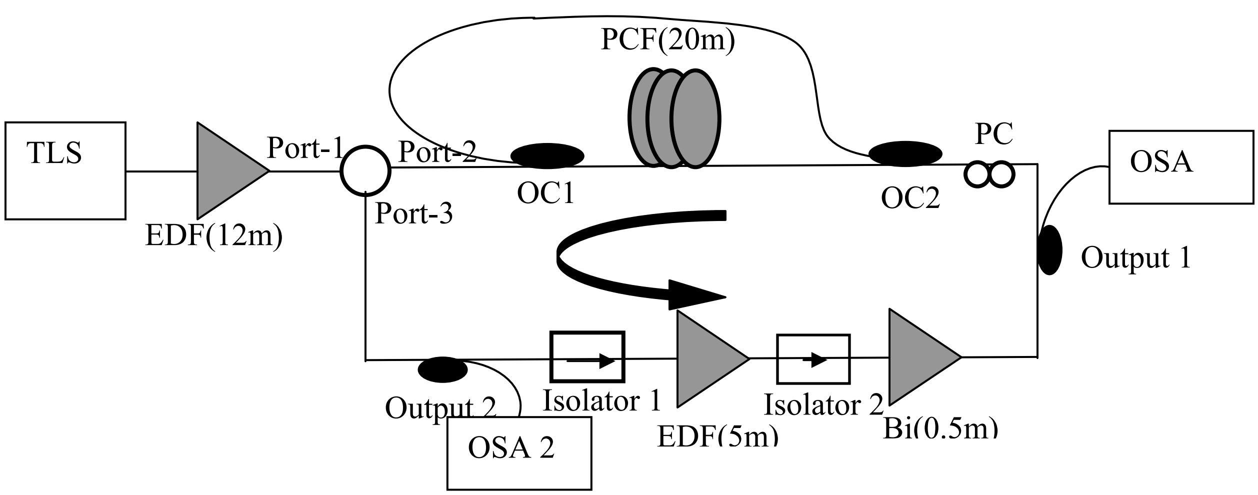

Figure 5.8: the Bi-BEFL system showing two different output position

Figure 5.9(a) and 5.9(b) shows the BEFL output power against LD power and BP power respectively for two different output positions. On the basis of the result acquired from the experiment, we find that the output power for output position-1 is higher than the value of output power gained from position-2. This is because the Brillouin Stokes signal was being amplified by the Bi-EDfA before it is tapered through the output at position-1.

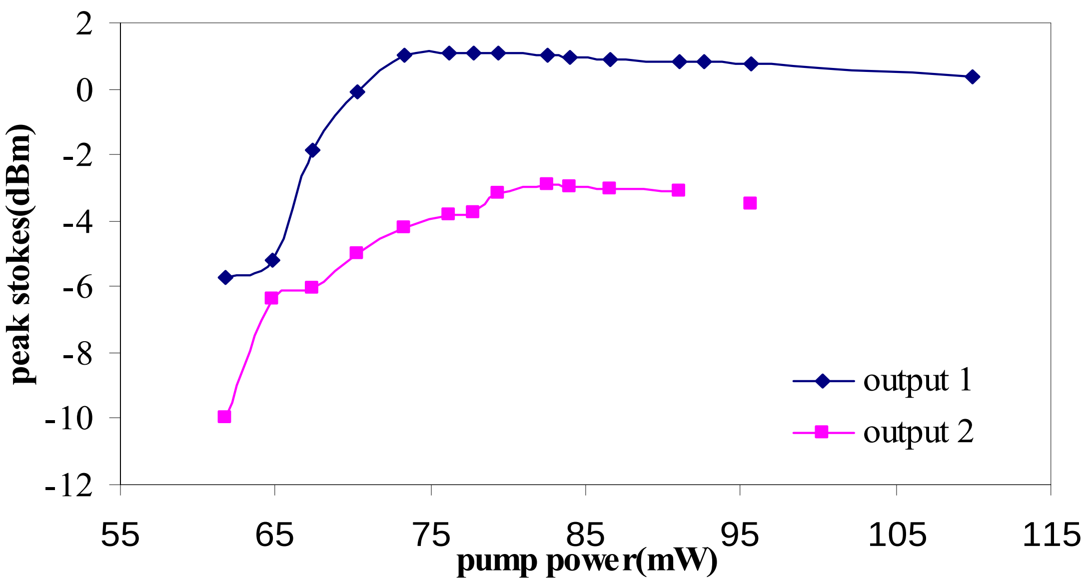

Figure 5.9(a): Comparison of peak power of Stokes with different output position by tuning pump power

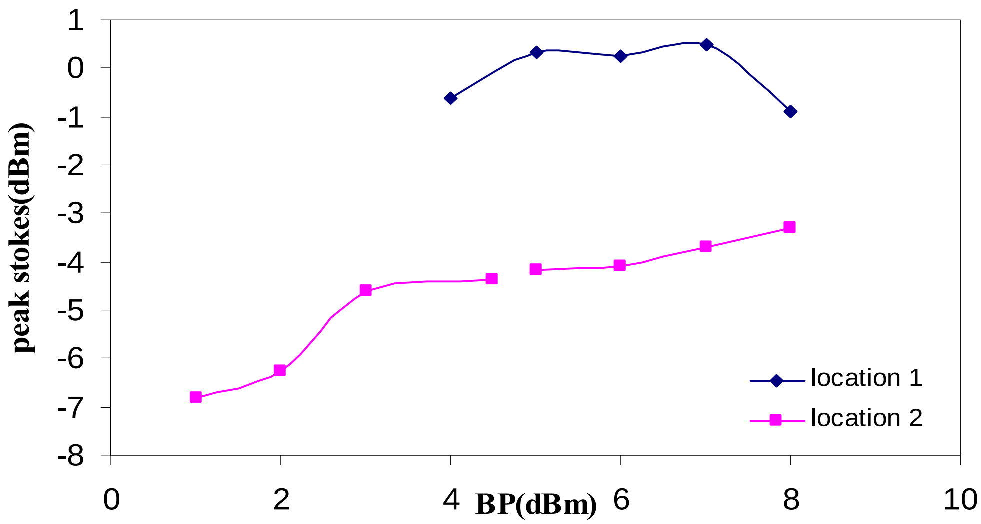

Figure 5.9(b): Comparison of peak power of Stokes with different output position by tuning BP

From the result in figure 5.9(a), we found that the value of the Stokes peak power rapidly increases with pump power and when the pump power reaches a value of around 75mW, the output peak powers flatten out. The situation is different for the result in figure 5.9(b) where we changed the BP power instead. The values of peak power with changing BP power increases with increasing BP power and it cannot be flat. Thus, the BP power plays a vital role in determining a suitable power for the system.

5.5 Changing Circulator with Optical Coupler

In this dissertation, the configuration of the experiments involved used a circulator to transfer a signal from the BP to the PCF through port-1 to port-2. In this chapter, we discuss the differences bound to arise in using an optical circulator or an optical coupler to transfer the BP signal through it. We use the same configuration as depicted in figure 5.10 with the exception that we change the coupler, C1 to a circulator, OC.

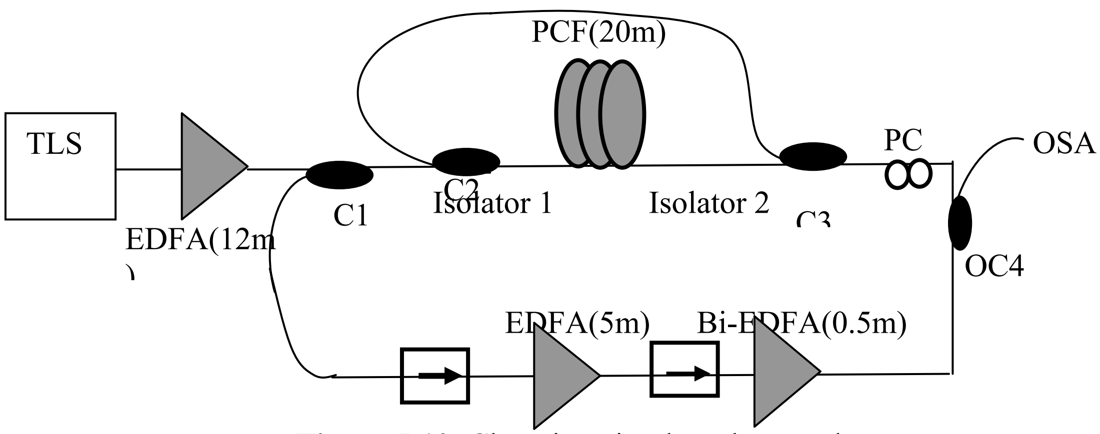

Figure 5.10: Changing circulator by coupler

The result of the comparison between optical circulator and coupler is depicted in figure 5.11 below. We can see that the peak power of the configuration using an optical circulator shows that the spectrum increases rapidly by increasing the pump power until the value of the pump power reached around 74mW, after which the trend reverses and the peak power slightly decreases with increasing pump power. It is also similar to the peak power distribution of the configuration using a 3dB optical coupler. However, the value of the peak power for the configuration using a circulator is marginally higher than that of the peak power for the configuration using an optical coupler. We can see that from the whole spectrum, the optical circulator can contribute towards a lower threshold power to generate Stokes, around 65-75mW, compared to the optical coupler which needs a high power to generate Stokes.

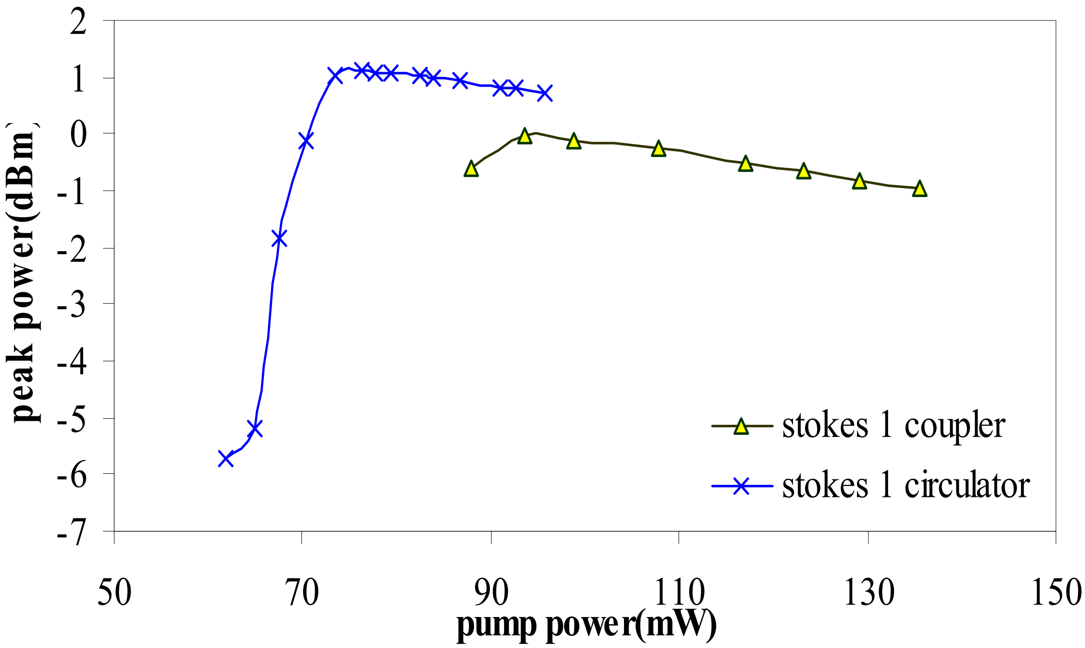

Figure 5.11: Comparison peak power of Stokes between using coupler and circulator

5.6 Brillouin Fiber Laser with Raman Amplification

Raman and Brillouin scattering are inelastic processes[3,4] in which part of the optical wave power is absorbed by the transmission medium while the remaining energy is reemitted as a wave (Stokes wave) with a down-shifted frequency called a Stokes shift. The growth of Brillouin and Raman Stokes waves is governed by the Brillouin-gain g_B and the Raman-gain g_R. For silica fibers, the peak values of g_B and g_R are about $g_B = 6 \times 10^{-11}$m/W and $g_R = 7 \times 10^{-14}$m/W and occur for the Brillouin and Raman Stokes shifts by about 13 THz and 10 GHz, respectively [1]. Although stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) can be detrimental in coherent optical communication systems [2,4] they do serve many useful applications, in particular the realization of very narrow linewidth Brillouin fiber lasers (BFL) and Raman amplifier.

In this chapter, BFL is demonstrated under a new approach using a Raman gain. With the use of SRS in a single-mode fiber (SMF), a Brillouin Stokes is amplified to generate a BFL. SMF were chosen to use because of the Raman gain efficiency which is higher than other fiber such as PCF. The performance of the BFL is investigated under a different ratio of coupler, which determines the amount of injected pumps powers and resonator cavity loss. Raman amplification in the Brillouin generating fiber has several advantages over erbium-doped fiber amplifiers (EDFAs) as well as unamplified systems. First, the lasing threshold is lower because of Raman amplification can provide higher gain and simultaneously eliminate the need for a separate amplifier. Secondly, the laser configuration can be used at wider range of wavelengths than the bandwidth of an EDFA[4]. Finally, this configuration does not put strict high-output power and narrow linewidth requirements on the Brillouin pump and requires only a high-powered Raman pump, which is readily and commercially available [3].

5.7 Experimental set-up

A configuration of the BFL is shown in Fig. 5.12, which consists of a hybrid component of isolator wavelength division multiplexer (IWDM), couplers and a 25 km long SMF as a nonlinear gain medium. The SMF has a cut-off wavelength of 1161 nm, zero dispersion wavelength of 1315 nm and a mode field diameter of 9.36 μm. The BFL is pumped by an external cavity tunable laser source (TLS) with a linewidth of approximately 20 MHz and a maximum power of approximately 8 dBm. Two laser diodes are used as a Raman pump module with a maximum combined pump power of

350 mW and operating at wavelength of 1440nm. A 1440/1550 nm IWDM is used to inject a Brillouin pump (BP) and Raman pump into the SMF.

The injected BP generates backward propagating Brillouin Stokes, which is amplified by the Raman gain and oscillates in the loop of couplers to generate a BFL. An optical isolator is inserted inside the loop to block the Raman pump and BP from oscillating in the loop. By using a single fiber for Raman amplification and Brillouin Stokes generation, we are simultaneously amplifying the BP and Brillouin signal in this cavity. This allows longer lengths of fiber to be used while maintaining a more distributed intra-cavity power level so that reduced the limiting effects of pump depletion. A 10% output coupler is used to extract BFL output, which is characterized using an optical spectrum analyzer (OSA).

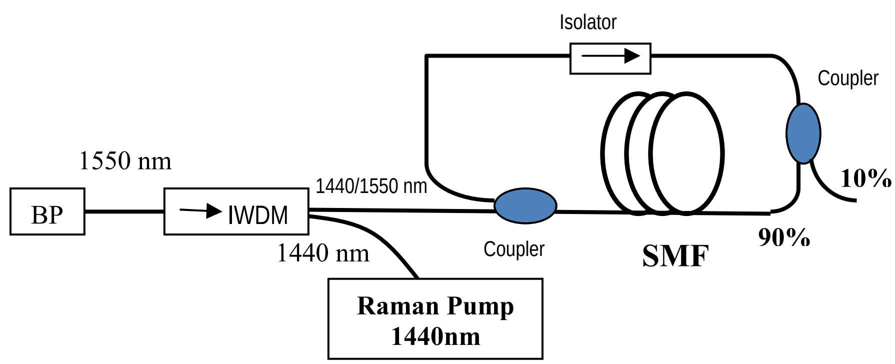

Figure 5.12: BFL based Raman pumping system

Fig. 5.12 compares the BFL output spectrum at different coupler ratios, which the port with higher power is connected to the IWDM. The BP and Raman pumps powers are fixed at 8 dBm and 350mW, respectively. If the total gain obtained due to SBS and SRS is equal to or higher than the cavity loss, a laser oscillation can be formed in the loop. As shown in Fig. 5.12, the BFL is generated with all couplers used except for 50%. The laser cannot be generated with the 50% (3dB) coupler because of the high loss. This reduces the BP and Raman pump powers that reach the SMF. The highest peak is obtained with a 80% coupler, which allow a sufficient BP and Raman pump powers to reach SMF to generate and amplify the Brillouin Stokes. The 80% coupler also provides the highest total gain in the loop. A single-wavelength Stokes is obtained at wavelength of 1550.09nm with a peak power of -26.2 dBm and a side mode suppression ratio (SMSR) of more than 12 dB with the BP and 1440nm pump powers of 8dBm and 350mW, respectively. The spacing between the BP and Stokes line is 0.08nm, as measured by an optical spectrum analyser with 0.015 nm resolution. Anti-Stokes line is also generated through four wave mixing between the BP and Stokes line as shown in Fig. 5.13

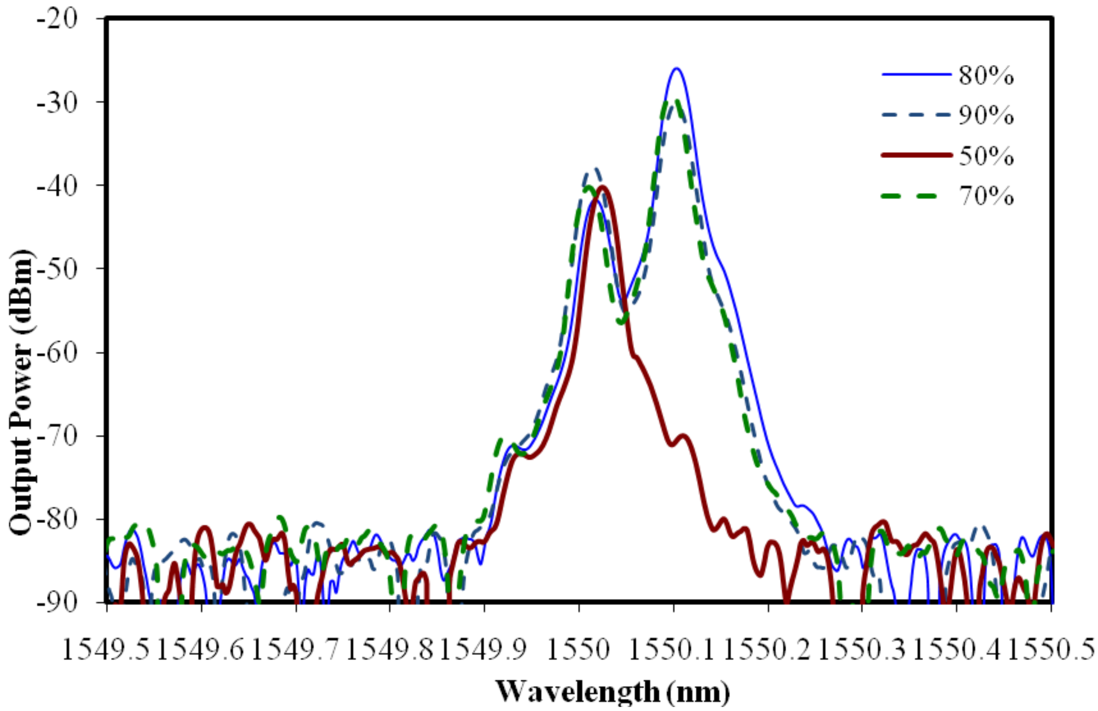

Figure 5.13: BFL output spectrum for different coupling ratios

Fig. 5.13 shows the output Brillouin Stokes peak power against the input signal BP power, with a 1440 nm Raman pump in various coupler ratios. In the experiment, the Raman pump power is fixed at 350mW. Before the Brillouin Stokes starts to increase quickly at SBS threshold power, the output power of the SBS increases in accordance with the increase of the BP power. The BFL threshold power is obtained at around 5~6dBm for the coupler ratio between 70~90% coupler. The combination of Brillouin and Raman gains is higher than the cavity loss at these coupling ratios so that the BFL has been generated and increases with the BP power as the threshold power reached. With a 3dB coupler, only a spontaneous Brillouin scattering is observed which increases in accordance with the increase of the BP power as shown in Fig. 5.13. The BFL cannot be obtained due to the injected BP power into SMF is below the SBS threshold power.

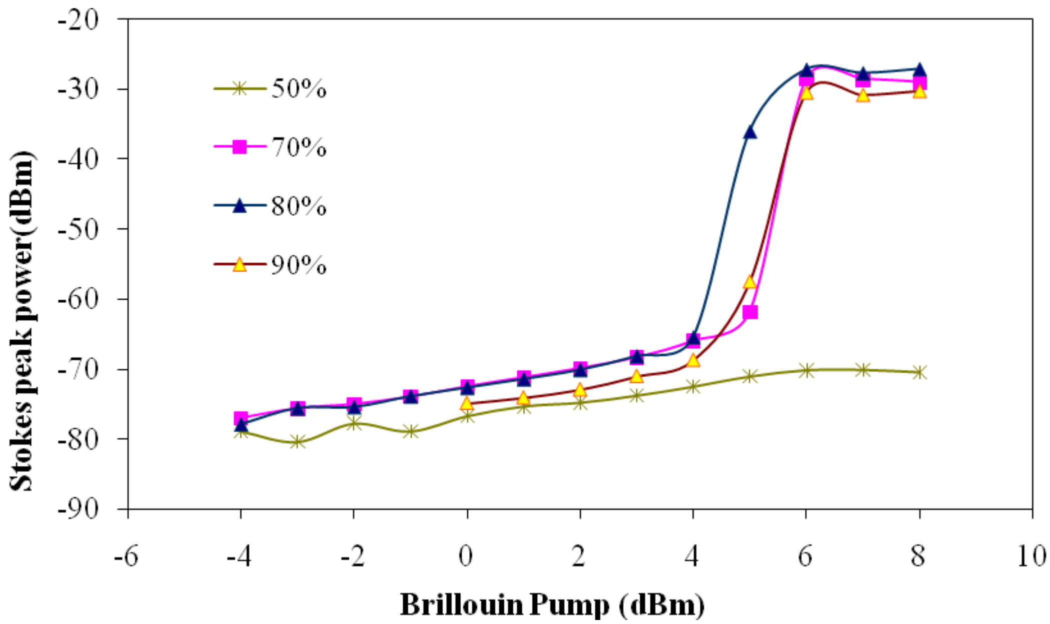

Figure 5.14: The Brillouin stokes peak power against BP power for different coupling ratios

Figure 5.14 shows the output Brillouin Stokes peak power against the input signal Raman pump power for various coupler ratios. In the experiment, the BP power is fixed at the maximum power of 8 dBm. Without Raman pumping, a Brillouin pump produces only a very weak spontaneous Brillouin scattering signal. As the Raman pump power increases, the power of the signal also increases before it starts to increase quickly at a certain pump power (around 250mW) except for the system with 50% (3dB) coupler. The threshold pump power reduces with the increase of the coupling ratio, which increases the actual Raman pump that reached the SMF region. The 1440nm pump power will generate Raman gain at 1550nm region, which is used to amplify the Brillouin scattering signal and assists in BFL generation. The BFL has a very narrow linewidth and low technical noise which makes it suitable for sensing applications [5,6]. The BFL is also able to operate at any wavelength within the Raman gain bandwidth [7]. Furthermore, the BFL can be made in compact form with the use of highly non-linear fibers such as holey fibers and Bismuth-oxide fibers for the generation of SBS instead of SMF.

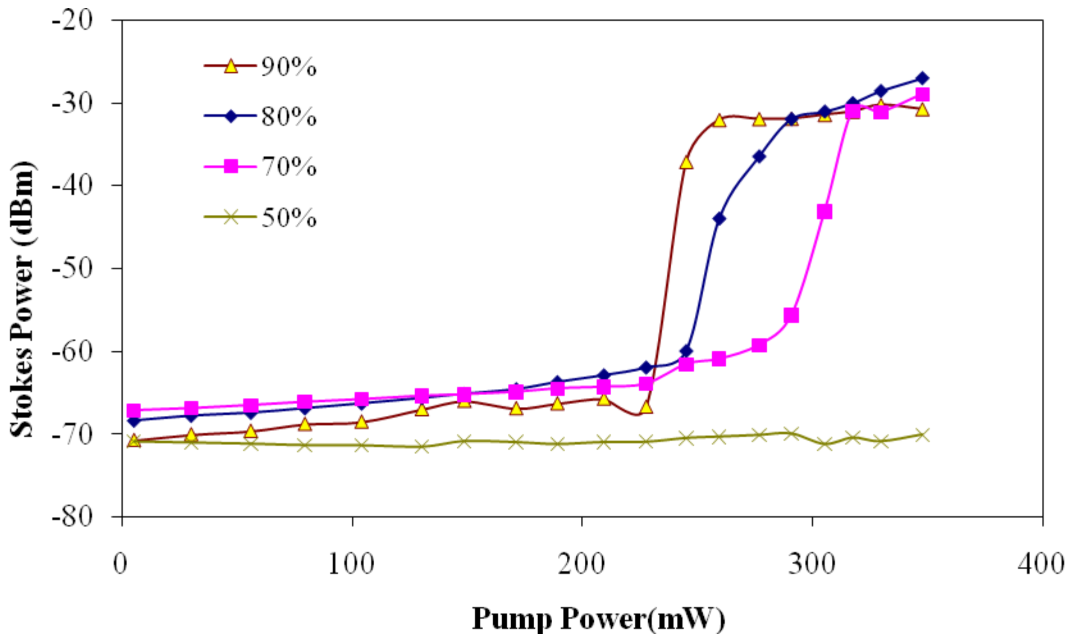

Figure 5.15: The Brillouin stokes peak power against pump power for different coupling ratios

4.5 Summary

The optimum balancing of cavity gain profile and Brillouin pump injection signals plays an important role in achieving multiple wavelength generation to the higher order Stokes lines over wide spectra width. So, by using this enhanced configuration of resonator, the number of Brillouin Stokes is increased. It also can generate a comb of multiwavelength Brillouin fiber lasers with higher peak power Brillouin lines at longer wavelength. This configuration was applied on the normal single mode fiber (SMF-28) demonstrated by a previous researcher, Cheng Xiao San, where it can generate multiple wavelengths with three Stokes and one anti-Stokes. In this dissertation, the location of the output coupler is also investigated and we found that suitable measurements can be read while the output coupler is placed at the back end of the amplifier which then causes the signals to be amplified by the Bi-Si-EDFA before it is measured by the OSA. Besides that, the potential of an optical coupler is tested and compared with an optical circulator and we find that an optical circulator give the best potential as bridging an input signal into the resonator and as an isolator. So an optical circulator is the best solution in this ring resonator. Beside that, we also have demonstrated a single wavelength BFL enhanced by Raman amplification. The BFL is obtained at wavelength of 1550.09 with a peak power of 26.6dBm and a side mode suppression ratio (SMSR) of more than 12 dB with the BP and 1440nm pump powers of 8dBm and 350mW, respectively.

References

[1] G.P. Agrawal, “Nonlinear fiber optics”, 3rd ed., Academic Press, San Diego, CA Chapter 9, 2001.

[2] A.R. Chraplyvy, “Limitations in lightwave communications imposed by optical-fiber nonlinearities,” J. Lightwave Technol, Vol.10, pp.1548, 1990.

[3] J.W. Lou, F.K. Fatemi and M. Currie, “Brillouin fibre laser enhanced by Raman amplification”, Electronics letters, Vol. 40 No. 17, Aug 2004.

[4] Grigorios Antonopoulos, “Super-enhances stimulated Raman scattering and particle guidance in hollow core photonic crystal fiber”, Dissertation for the degree of Doctor of Philosophy of the University of Bath, 2006.

[5] M R Shirazi, M Biglary, S W Harun, K Thambiratnam and H Ahmad, “Bidirectional multiwavelength Brillouin fiber laser generation in a ring cavity”, J. Opt. A: Pure Appl. Opt. 10, pp.3m, 2008

[6] S. W. Harun, S. Shahi, and H. Ahmad "Compact Brillouin–erbium fiber laser," Opt. Lett. Vol. 34, pp.46-48 , 2009.

[7] J.D. Ania-Castanon, S.M. Kobtsev, A.A. Pustovskikh, and S.K. Turitsyn, “Simple design method for gain-flattened three-pump Raman amplifiers”, Optical and Quantum Electronics, Vol. 39, No. 3. pp. 213-220, Feb2007.

[8] Sarun Sumriddetchkajorn, “Polarization insensitive tunable-contrast fiber-optic polarization interferometers with a polarization controller”, Optics communications, Vol.217, issues 1-6, pp.197-203, March 2003.