CHAPTER 4

MULTI-WAVELENGTH BRILLOUIN BISMUTH /ERBIUM FIBER LASER

4.1 Introduction

The telecommunications industry has tremendous progress for capacity over the last few years due to the rapid growing usage of the internet and data transfer, in particular. The demand of this capacity can be met by dense wavelength division multiplexing (DWDM) light-wave systems which consist of a large number of wavelength sources spaced at 100, 50 and/or 12.5 GHz. Currently, sophisticated laser modules are used as optical sources in this system. They comprise of highly stabilized laser diodes utilizing complex and advanced circuitry, which has raised the cost of both implementation and maintenance of such optical transmission systems. These systems require sophisticated monitoring units of the laser output to prevent cross talk from occur. Besides the laser diodes, fiber lasers are a promising choice of a laser source due to their various advantages such as their tunability features [5].

Brillouin Fiber Laser (BFL) have been the subject of considerable research in recent years for many applications. BFLs have the property of a narrow line width, arising from the narrow bandwidth and homogeneous nature of the gain, which makes them attractive for sensor applications. A multi-wavelength comb can also be generated using the BFL. The BFL can be constructed using any types of fiber as a nonlinear gain medium. The nonlinear effect in play here is called the Stimulated Brillouin Scattering (SBS) which give the result of the interaction between the intense pump light and acoustic waves in a medium. This interaction gives the backward propagating frequency-shifted light.

In this chapter, Brillouin fiber laser is generated using a ring configuration. In the first section a BFL generation is demonstrated using a standard single-mode fiber as a gain medium. The effect of Brillouin pump (BP) power for Stokes generation is also studied. The amplified BP is used in the following section to allow a multi-wavelength operation. In the last part of this chapter, a Brillouin erbium fiber laser is proposed for multi-wavelength operation. The BEFL combines two gain media - the nonlinear Brillouin gain in the Photonic Crystal Fiber (PCF) and the Bismuth-erbium doped fiber (Bi-EDF) as a linear gain medium. The Bi-EDF has been extensively studied recently for a realization of compact amplifiers with short gain medium length. The proposed BEFL is compact since it only uses a very short length of PCF and Bi-EDF as a gain media.

4.2 Brillouin Fiber Laser Generation with A Ring Configuration

In this section, the characteristics of a standard BFL system were studied. A configuration of a standard BFL system is shown in figure 4.1. The resonator consists of a circulator, a Single Mode Fiber (SMF) as long as 25km, and a coupler. The SMF used in the experiment has Mode Field Diameter (MFD) of 9.36 μm and cut off wavelength 1161nm with a zero dispersion wavelength of 1315nm. The external Tunable Laser Source (TLS) is used as a Brillouin pump (BP) in this BFL system. The output is tapered out from the output configuration and characterized using an Optical Spectrum Analyzer (OSA). A narrow line-width, the BP is injected into the SMF through a circulator to generate a narrow bandwidth Brillouin gain in the clockwise (CW) direction. The backward Brillouin scattering operates at a Stoke-shifted frequency which is about 0.09nm longer than the BP wavelength. The output spectrum is measured by an OSA with a resolution of 0.01nm.

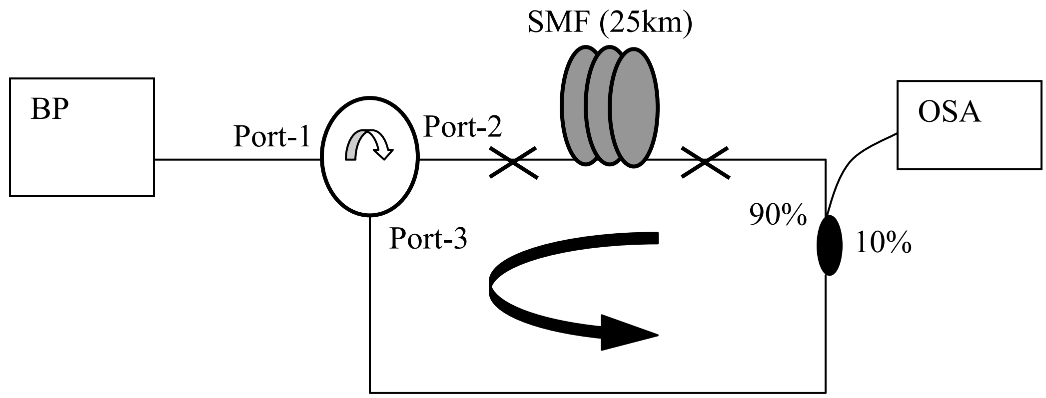

Figure 4.1: Configuration of Conventional Brillouin Fiber Laser System.

The output spectrum of the BFL is shown in figure 4.2 at various BP power. In this experiment, the BP wavelength was set at around 1550nm, and the BP power were varied from -8dBm to 8dBm. The output power increases as the BP increases. The maximum output power was obtained at -15dBm. As shown in the figure, BP power of -2dBm and below no Brillouin stokes was observed. However, when the BP power exceeds the threshold value of approximately 0dBm, a Stokes is generated at a wavelength of 1550.08nm. This was attributed to the Brillouin gain, which exceeds the cavity loss. This allow the back scattered Brillouin signal to oscillate in the cavity and generate laser as shown in figure 4.2. The output power is 35dB higher than the Rayleigh backscattered residual BP power. In the next section, an amplified BP is used to generate an additional stokes and anti-stokes.

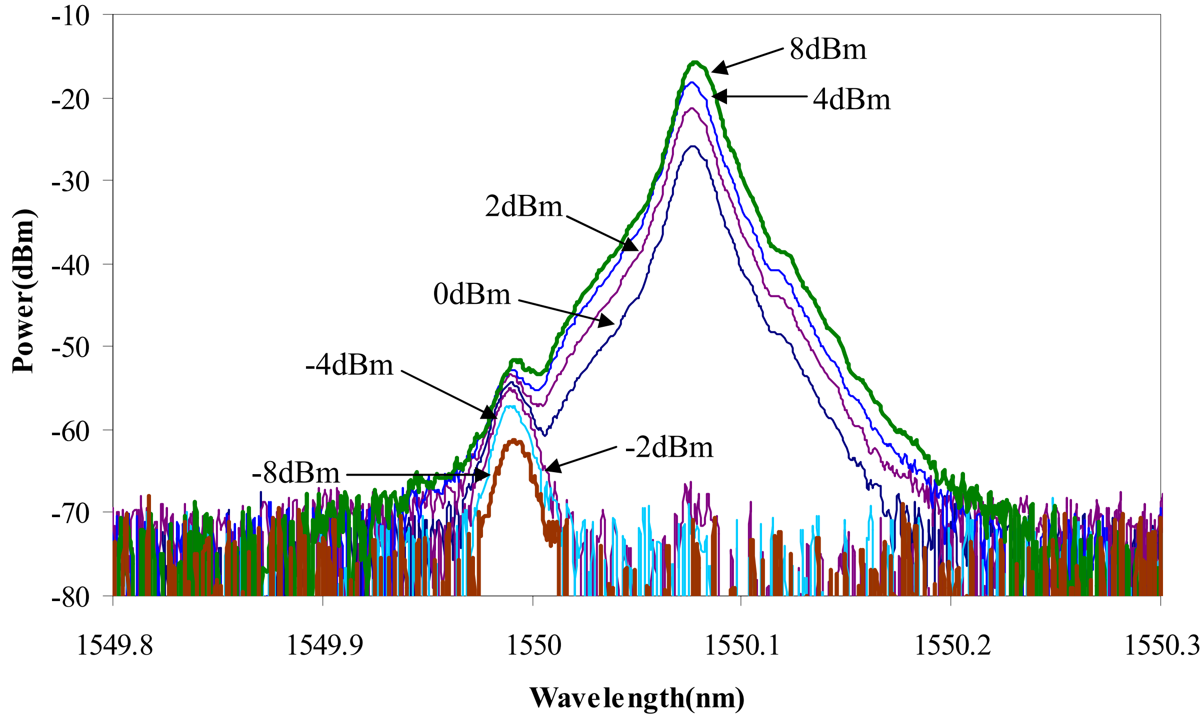

Figure 4.2: Brillouin Fiber Laser in SMF (25km)

4.3 BFL with A Pre-amplified Brillouin Pump

The SBS can be used to generate a multi-wavelength comb with the assistance of feedback mechanism. The BFL can achieve a stable multiple wavelengths output with regular 10GHz spacing at room temperatures. The Brillouin generation of a multi-wavelength comb has two special advantages over other multi-wavelength generation methods in that the wavelength spacing is rigid and the line-width is very narrow [9]. In this work, we describe the operation and characteristics of a BFL with the use of amplified Brillouin pump power. With the assistant of the erbium gain from the EDF, the BFL can support multiple wavelength operation with ~10 GHz spacing at room temperature with the employment of the same resonator as the previous set-up of figure 4.1.

The schematic configuration of the ring BFL with the amplified BP is shown Fig. 4.3. The ring cavity BFL consists of an optical circulator, 25km long SMF with cutoff wavelength of 1161nm, and MFD of 9.36µm. A 10/90 taper coupler is used as a output coupler. The EDFA is used to amplify the BP power before it is injected into the SMF. A 12 m long EDF with erbium ion concentration of 400ppm is used as gain medium for the EDFA. The EDF is pumped by 980nm laser diode via a WDM. The BFL uses to same components and operates on the same manner as the BFL in the previous section.

The light from the tunable laser source is amplified by the Erbium-doped fiber amplifier (EDFA) to serve as the Brillouin pump (BP). The BP is injected into the ring to the SMF via the circulator. The narrow bandwidth gain is generated in the clockwise (CW) direction and produces a backward Brillouin scattering light at a Stokes shift frequency from the BP frequency. The Brillouin Stokes is about 0.09nm longer than BP wavelength. The output is tapped out from the 10% port of the output coupler and then is measured and characterized by an OSA with a resolution 0.01nm.

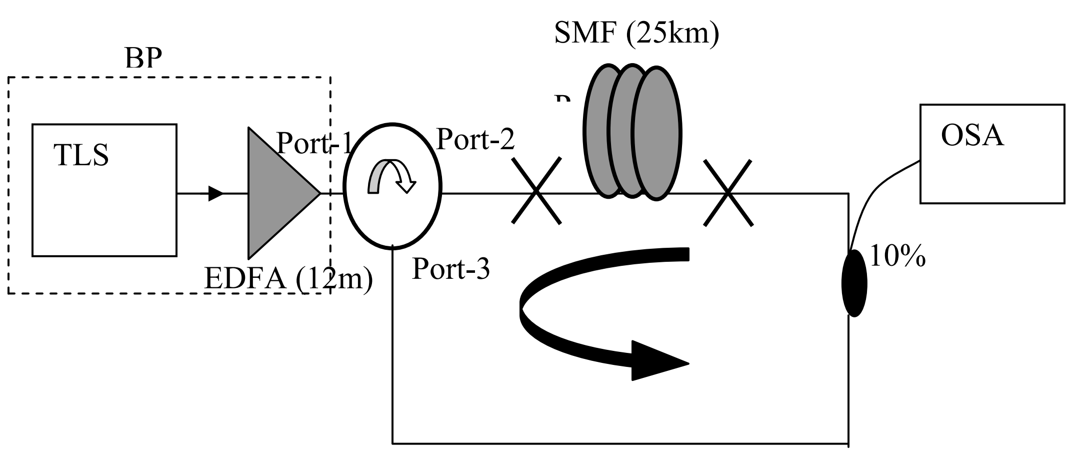

Figure 4.3: Multi-wavelength generation in BFL system using the amplified BP

Figure 4.4 shows the output spectrum of the BFL, which is generated in a 25 km long of SMF at various pump power. The BP is set at 1549.966nm wavelength and power of the BP varies from 3mW until 35mW. It can be seen that the generation of Stokes and anti-Stokes is increased by increasing the BP power. The generation of anti-Stokes is due to the FWM effect between the BP and first stokes [11]. The first Stoke has the highest peak power due to the high BP power, which is boosted by the amplifier. The next stokes is generated by the previous stokes and therefore the power is lower than the earlier stokes. It is also because higher order Brillouin Stokes has higher threshold power compared to the lower orders of Brillouin Stokes. The power threshold of the SMF is as low as 3mW. This result is similar to and has been demonstrated before by M.R.Shirazi, whereby the threshold for the first order Brillouin Stokes to begin manifesting is at 2mW and increases as the order of Stokes increases. [15].

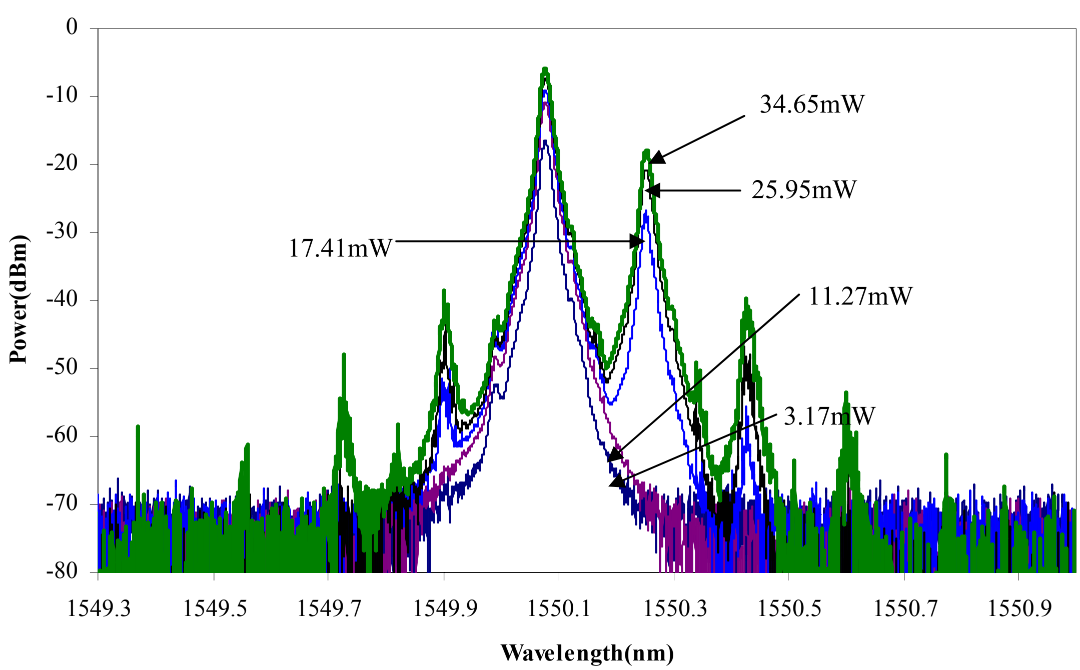

Figure 4.4: Brillouin Fiber Laser in SMF (25km) by tuning pump power.

4.4 Multiwavelength Brillouin Erbium Fiber Laser Using a Piece of PCF

4.4.1 Introduction

Multi-wavelength lasers have application in DWDM system as a light source. The multiple wavelength combs can be achieved using a Brillouin/erbium fiber laser (BEFL). The BEFL combines the linear gain from EDFA and nonlinear gain from a SMF or nonlinear fiber for multi-wavelength generation. In this section, a BEFL is proposed using a piece of PCF as a nonlinear gain medium and Bi-EDF as a linear gain. In this BEFL, a 20m long PCF in conjunction with a 49cm Bi-EDF is used as a Brillouin gain medium. The PCF has a very high nonlinearity property, which allows us to shorten the fiber length and to reduce the required optical power [16]. The Bi-EDF used has also a promising amplification characteristic at around 1550nm region [17].

4.4.2 Experimental Set-up

Fig. 4.5 shows the configuration of the proposed BEFL. It use a piece of PCF to generate a Brillouin Stokes which is frequency-downshifted from the pump by 10GHz. The bi-directional Bi-EDFA amplifies the generated Stokes, which is then used as BP to generate another Stokes. The multiple Stokes oscillates in the ring cavity to generate a BEFL. The PCF used in this experiment and throughout this dissertation has a nonlinear coefficient of 11 $(W.\ km)^{-1}$, numerical aperture (NA) of 0.2, effective core area of $3.093 \times 10^{-11}\ m^2$ and effective refractive index of $8.447 \times 10^{-20}\ m^2/W$. The stable multiple Brillouin wavelengths with 10-GHz regular spacing can be achieved at room temperature. In order to achieve the maximum interaction, the polarization directions of the Stokes wave optical carrier are maintained by adjusting the Polarization Controller (PC).

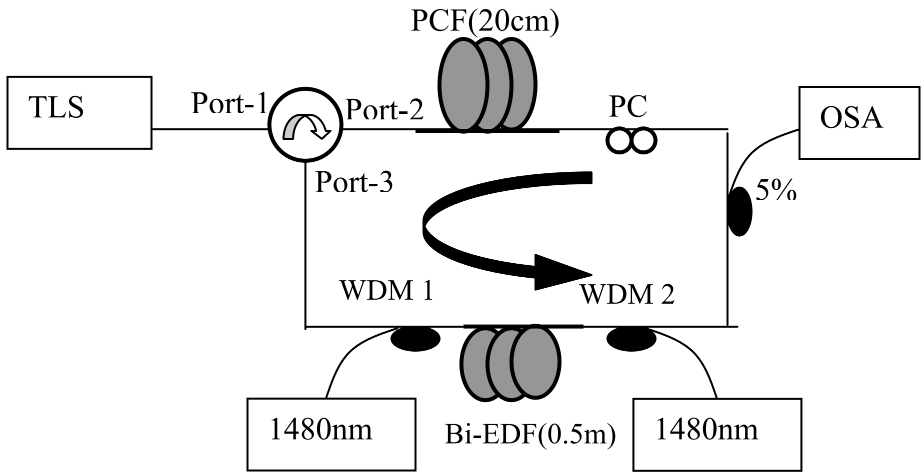

Figure 4.5: Schematic configuration of the PCF-based BEFL

4.4.3 Brillouin Stokes Threshold in PCF

The threshold of the Brillouin Stokes is defined as the minimum power required to generate Brillouin Stokes. There are two categories of threshold values that have to be considered for Brillouin Stokes, which is laser diode (LD) pump power and BP power. The threshold pump power for Stimulated Brillouin Scattering (SBS) depends on the spectral width associated with the pump wave [2]. Brillouin threshold is found to occur at the critical pump power P_{th}. However, the threshold level from that equation is only approximate as the effective Brillouin gain can be reduced by many factors such as doping level, inhomogeneities, medium (Bi-EDF) length and cavity loss. The SBS threshold can be increased when the state of polarization of the pump becomes completely scrambled [2]. The Brillouin pump threshold in a standard SMF is approximately around 3 dBm [15] and in PCF is around 16 dBm[21]. Therefore the BP power must be set above this value.

4.4.4 Free Running EDF Laser

Free running laser is a lasing emission in an optical fiber loop without the injection of any wavelength from an external signal. It is usually unstable due to broad ASE fluorescence bandwidth from the gain medium [14]. It is also sensitive to temperature and polarization conditions. In this experiment, when the plate of the polarization controller (PC) of Fig. 4.5 is changed, so does the polarization state. So the self lasing region is also changed to some other wavelength since the EDFA's gain is polarization dependent. The lasing gain in an EDFA is very important to consider the effective regions to generate multiple Brillouin Stokes.

Fig. 4.6 shows the free running spectrum of the EDF laser. Self lasing occurs at a region in the range of 1558nm until 1562nm. All the modes oscillate independently of one another with a random phase. Self lasing occurs for every mode with a mode separation wavelength is determined by a free spectral range (FSR). The FSR is given by [18,19]:

$$FSR = \frac{c}{2nL_{eff}} \tag{4.1}$$

where c is the velocity of light, n is the refractive index of the glass, L_{eff} is the effective length. As shown in Fig. 4.6, the FSR is obtained at around 0.525nm. However the obtained value separations modes are not only 0.525nm. There were various separations between the lasing modes are observed from figure 4.6. This is attributed to the FWM effect between various interference modes.

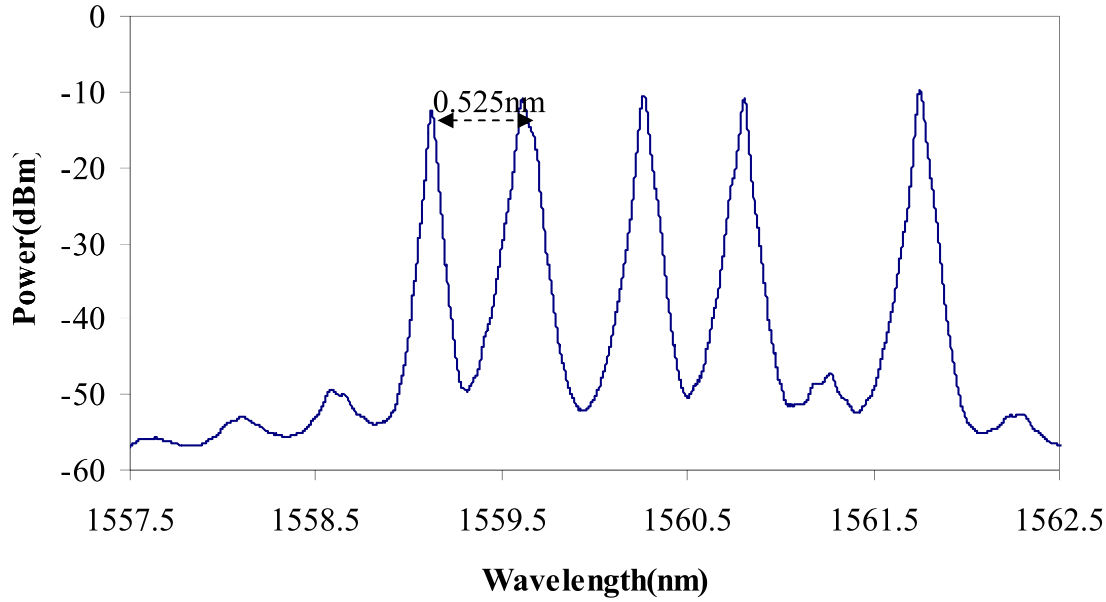

Figure 4.6: Free running spectrum

4.4.5 Effect of 1480nm Pump Power on the BEFL

The laser diode pump power plays the most important role in the BEFL. It provides a linear gain to assist in multi-wavelength Brillouin Stokes generation. The erbium gain controls the number and output power of Brillouin Stokes generated. In this section, the effect of the LD power on the MWBEFL performance is investigated. The bismuth based erbium doped fiber is bi-directionally pumped by two 1480nm laser diodes as shown in Fig. 4.5 to amplify the generated Stokes so that the power is above the Brillouin threshold. The generated Stokes can be used as a Brillouin pump to generate another Stokes and this process continues to produce multi-wavelength laser.

Fig. 4.7 shows the output spectrum of the multi-wavelength Bismuth-Based Erbium Fiber Laser (Bi-BEFL) at various 1480nm pump power. The Brillouin pump was fixed at 8dBm and the laser diode power was varied from 189mW up until 272mW. The BP wavelength is set at 1559.9 nm, which is within the free-running lasing wavelength region. It shows that the peak power of the Brillouin Stokes slightly increases with increasing pump power. For instance, the first Stokes peak power can be increased from -3.43dBm to -1.64dBm by increasing the laser diode pump power from 189mW to 272mW. The maximum peak power improved by 19dB is obtained at the second Stokes as the pump power increases from 189mW to 272mW as shown in Figs. 4.7 and 4.8. Fig. 4.8 shows the peak power against the 1480nm pump power for each of Stokes and anti-Stokes. At pump power below 189mW, the improvement is minimum because of the erbium gain is very small and not sufficient to support an efficient multi-wavelength generation. As shown in Figs. 4.7 and 4.8, this laser cavity generates the strongest Brillouin Stokes at the first Brillouin Stokes. The higher order Brillouin Stokes also disappears when the pump power is lowered. Even though the higher order Brillouin Stokes lines have a lower power threshold, the lossy resonator cannot support more lines if the erbium gain is not sufficient. An anti-Stokes generation is also observed due to the four wave mixing (FWM) effect and bidirectional operation.

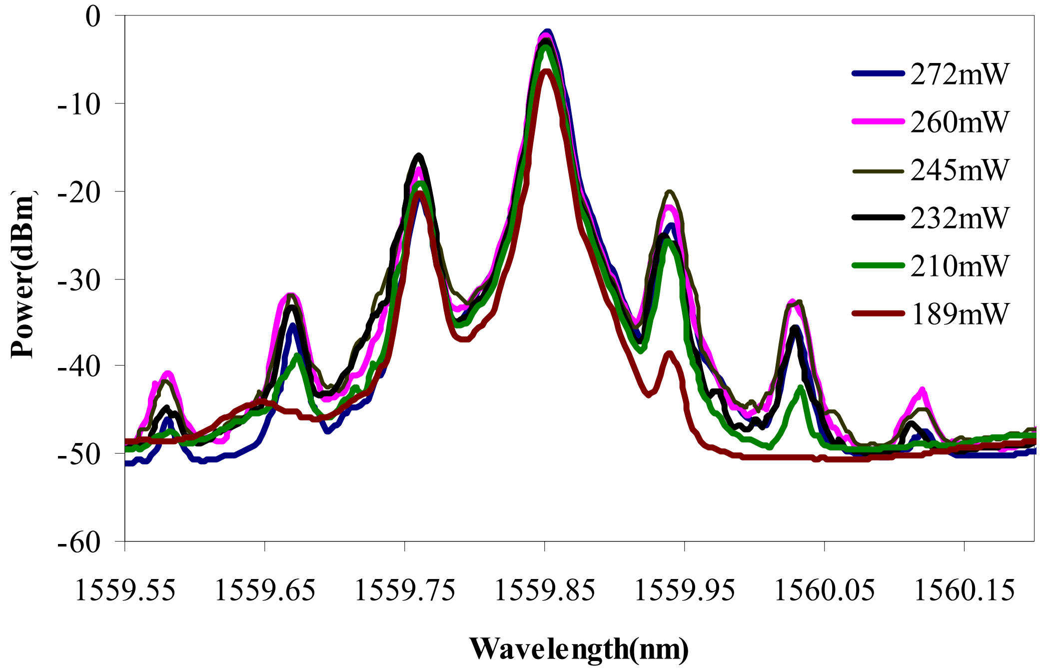

Figure 4.7: Output spectra of the Multiwavelength BEFL at various 1480nm pump power.

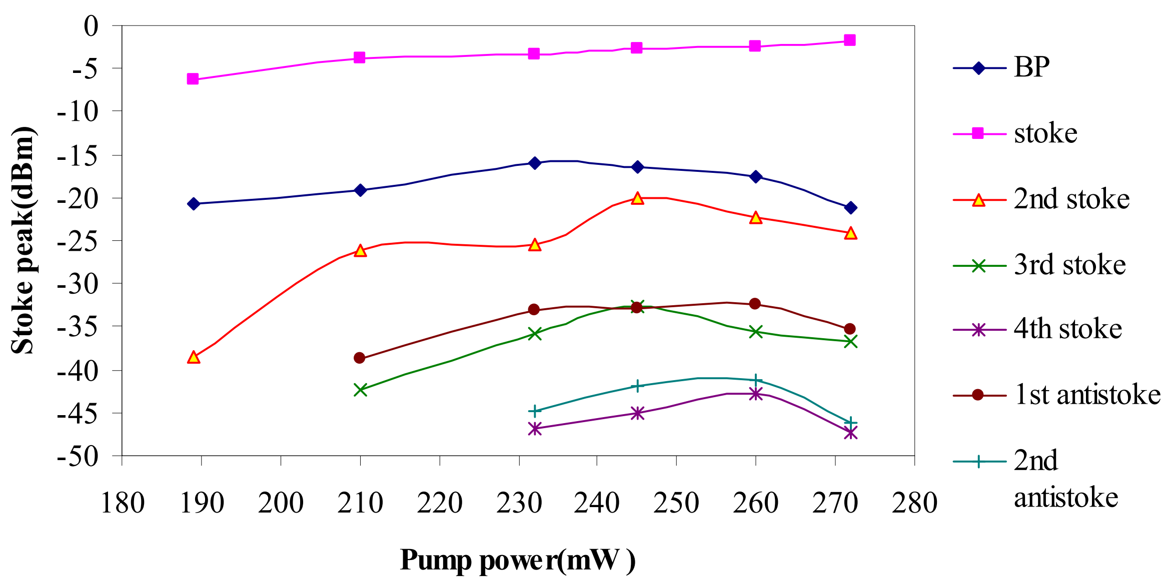

Figure 4.8: The peak power for each Brillouin Stoke at different LD power

The peak power for each Brillouin Stokes and anti-Stokes increases with the increment of 1480nm pump powers as shown in Fig. 4.8. Brillouin Stokes and anti-Stokes are achieved through the process of stimulated Brillouin scattering (SBS) and four-wave mixing respectively. Figure 4.9 shows the number of Brillouin Stokes and anti-Stokes which are generated by both processes with increasing pump power. At the pump power of 189mW, there are only two lines are observed. However, the number of lines increases to 6 lines at the pump power of 230mW. Further increase of pump power, however, does not increase the number of lines. When the pump power is tuned from 230mW all the way till the maximum pump power of 272mW, the number of Brillouin Stokes and anti-Stokes are maintained only at 6 lines and cannot. It is because of the limitation BP. If we use a high power BP, maybe the number of stokes lines will be increase.

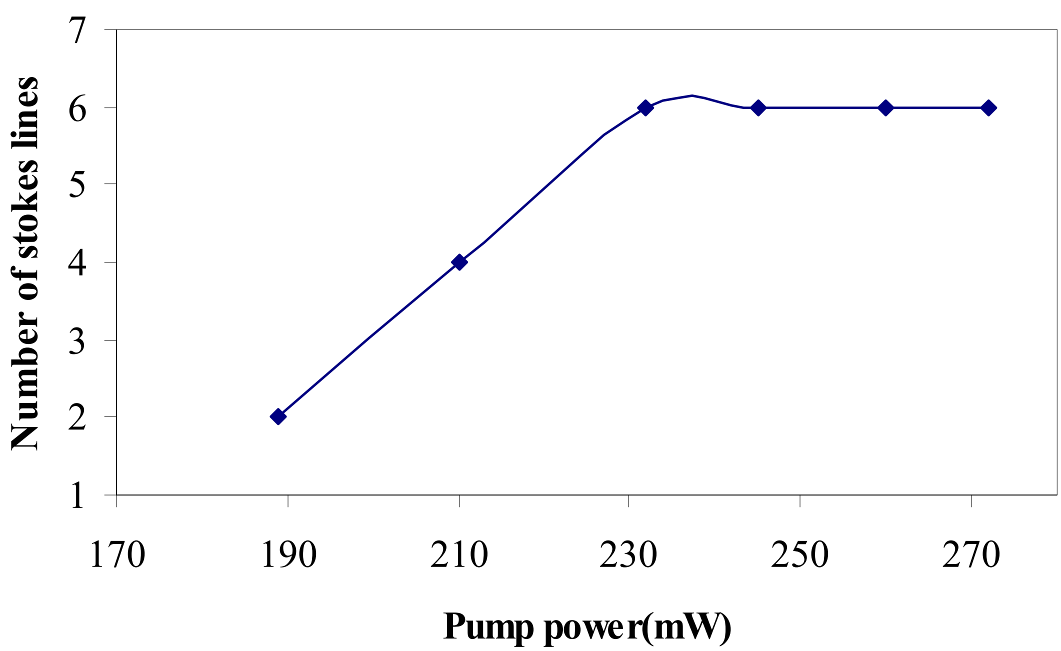

Figure 4.9: The number of generated Brillouin Stoke at different LD pump power.

4.4.6 Effect of BP Power on Performance of BEFL

From the previous section, the 1480nm pumping plays the important role of providing a linear gain in order to produce multiple wavelengths in the MWBEFL system. In this section, we discuss about the effect of BP on the MWBEFL system. Brillouin pump (BP) also plays an important role in the generation of the MWBEFL. In this experiment, the pump power of the 1480nm pump is fixed at the maximum power of 272mW. The BP wavelength is fixed at 1559.75nm. The performance of Stoke lines generation is studied at different BP powers from 3dBm to 8dBm. Fig. 4.10 shows the output spectrum of the BEFL at various BP powers. As shown in the figure, the maximum number of Brillouin Stokes is generated when the BP is around 7~ 8dBm. 7 Brillouin Stokes and anti-Stokes including the BP are observed. At BP power of 3 dBm, only 4 Brillouin Stokes and anti-Stokes lines including the BP are generated.

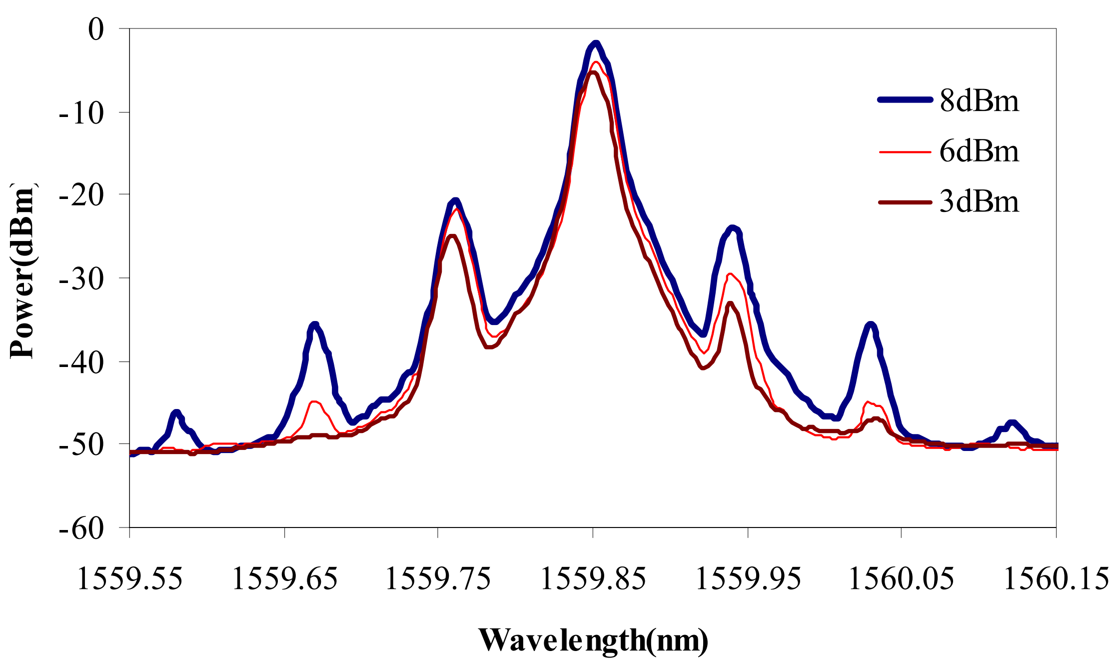

Figure 4.10: MWBEFL spectra at different BP

Fig. 4.11 shows the peak power characteristic for each Stokes as a function of BP power. The figure shows that the peak power of each Brillouin Stokes slightly increased as the BP power increase from as low as 3dBm up to as high as 8dBm. From that figure, we can see that the third stokes and first anti-stokes were separated at between 4dBm BP power and 6dBm BP power. They were no connection at 5dBm that launched because of this range power is not suitable to generate Brillouin stokes.

Fig. 4.12 shows the number of lines against the BP power. At lower BP, only 3 or 4 lines are observed. The number of lines increases as the BP power increases up to 7~8dBm. However, further increment of BP power does not increase the number of lines. The better arrangement of the BEFL resonator is required to obtain a higher number of lines. This result shows that a suitable BP to generate the maximum number of Brillouin Stokes is around 7~8 dBm in the proposed resonator.

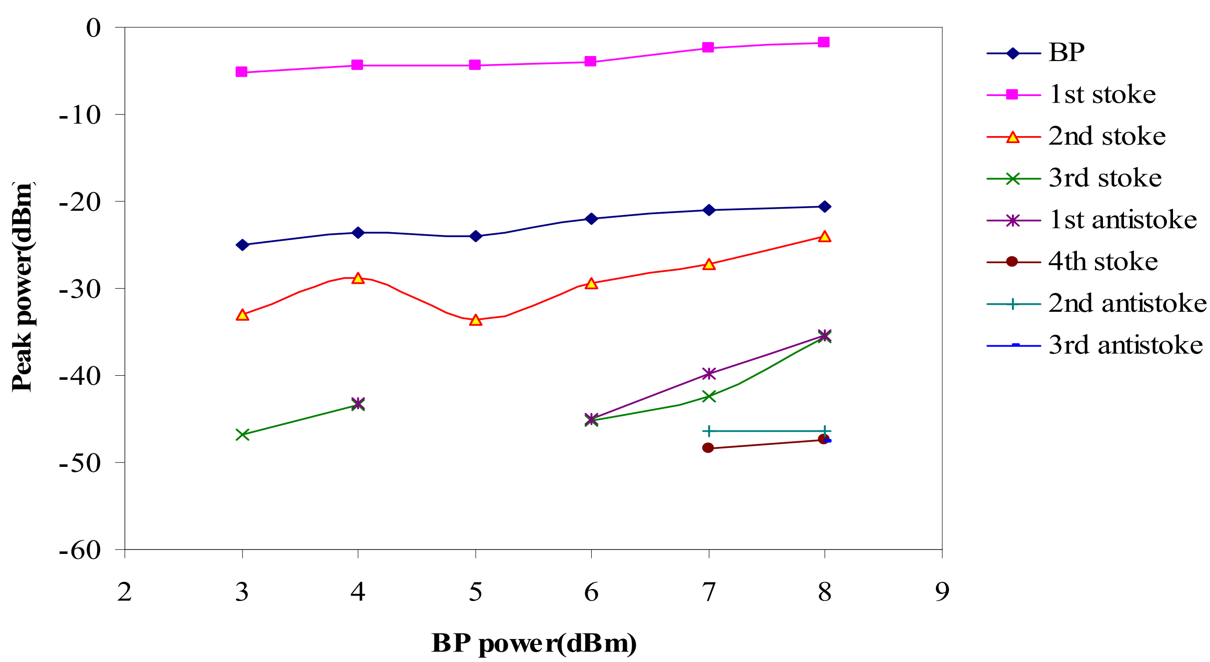

Figure 4.11: The peak power for each Brillouin Stokes at different BP power.

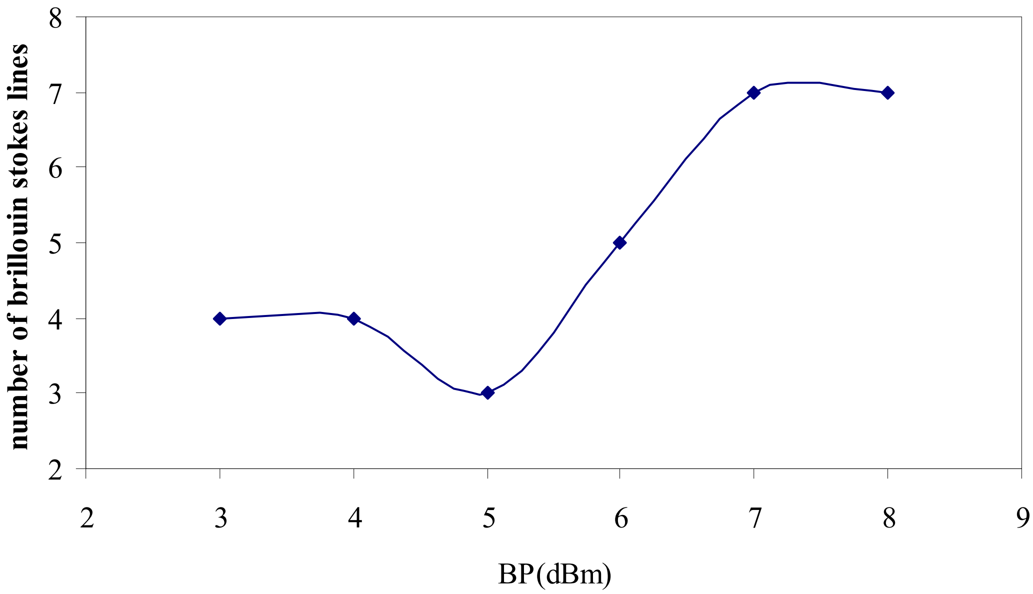

Figure 4.12: Number generated of Brillouin Stokes at different BP

4.4.7 Tuning Range of the BEFL

In a MWBEFL system, tuning characteristics are important for many applications such as WDM and sensors. In this study the BEFL is tuned over the whole lasing gain spectrum range of the free running Bi-based EDFL region. In this experiment, the 1480nm pump and BP powers are fixed at maximum values of 270mW and 8dBm respectively. The wavelength from the TLS was tuned across the free running Bi-based EDFL spectrum, which is about 3nm bandwidth. Each Stokes and anti-Stokes peak powers are measured during the tuning of the BP wavelength. Fig. 4.13 shows the tuning characteristic of the BEFL. As shown in the figure, the Stokes and anti-Stokes lines are still obtained within the tuning range of around 2.5nm. However, from this investigation, we found that the peak of each Stokes and anti-Stokes were randomly generated for every wavelength. This is suspected to be due to the PCF fiber used which has a short length and high nonlinearity characteristics. The PCF has a microstructure which is normally made from a single material with a periodic array of air holes running along their entire length. However, the structure of the holey fiber/PCF is changing along the length with different air holes diameter [1], which have different value of the modal index along the length [2,3]. For every tuning wavelength, the spectrum of MWBEFL also change together or is completely distorted. So to maintain the spectrum to become uniform at every wavelength, the polarization state of light in PCF has to be controlled by a PC.

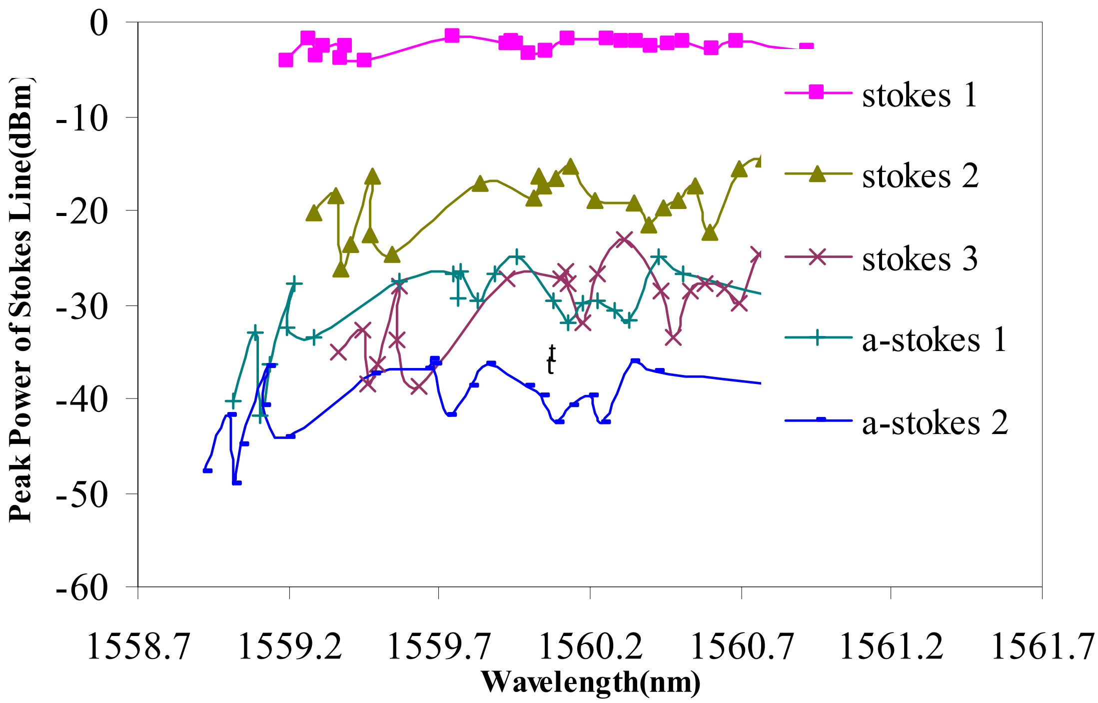

Figure 4.12: Tuning characteristics of the BEFL

The result contradicts with other works compared by other works using the normal single mode fiber (SMF -28), which was demonstrated by Cheng Xiau San et. al. [13]. They show that peak power is flat within the tuning wavelength. This is suspected to be caused by the microstructure/air holes of the PCF used. However, the microstructure properties were not investigated in this dissertation.

4.5 Summary

In this chapter, a 25km normal SMF and 49cm PCF were studied by using a conventional simple BFL design. The performance both of SMF and PCF were studied through the several of BP powers, LD pump power and wavelength effect. The BFL effect can achieved when it reach threshold power. Without booster from Bi/EDFA, the BFL can only generate a single wavelength fiber laser. However, by injected a suitable power from amplifier, it can generate a comb of multiple-wavelength BFL. Generations of higher order are depending on the power of Bi/EDFA. Many order of Brillouin stokes and anti-stokes be generated with various LD pump and BP power. Using different injected wavelength were also studied on PCF fiber, and give a different value of peak for every Brillouin stokes. It suspected because of the different polarization state and microstucture of PCF. The next chapter will discuss on the enhancement and modification of BFL design.

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