CHAPTER 3

CHARACTERIZATION OF STIMULATED BRILLOUIN SCATTERING AND Bi-EDFA AS A CONVENTIONAL BRILLOUIN FIBER LASER

3.1 Introduction

Stimulated Brillouin Scattering (SBS) is one of the nonlinear process that can occur in optical fiber if the input power at low level [1,2]. It is a natural scattering process associate to the propagation of light in a medium. Due to the interaction of light with the propagation medium, different scattering components are generated: Rayleigh, Brillouin and Raman component. The resulting scattered optical wave as a result called as stimulated Brillouin scattering (SBS) is a Doppler shifted in a frequency [3]. The SBS can produce gain in an optical fiber that can be used to amplify a weak signal which the frequency is shift from the pump frequency which called Brillouin shift. Such amplifier were studied since 1980s [1].

A lasing characterization of a Brillouin/erbium fiber laser (BEFL) is experimentally discussed in this chapter. In the BEFL, an erbium-doped fiber amplifier (EDFA) is incorporated into the Brillouin laser resonator to enhance small Brillouin gain, which makes the configuration of the Brillouin laser resonator easy and flexible. EDFA are most familiar because of the operating wavelength region is near 1550nm [4]. The gain spectrum depends on the pumping scheme as well as on the presence of other dopants within the fiber core. The characteristics of EDFA such as gain and noise figure can be obtained from amplified spontaneous emission (ASE). The gain of an EDFA depends on the large number of device parameter such as erbium ions concentration, amplifier length, core radius and pump power [4-7]. In this chapter, we discuss about loss in the cavity due to reflection and the method to reduce it. We also discuss about occurring brillouin effect in the Photonic Crystal Fiber (PCF) by using Brillouin Fiber Laser(BFL) system. Besides that, we study the performance of the Bismuth-Silica-Erbium-doped fiber amplifier(Bi-Si-EDFA) and comparison its potential with the conventional Bismuth-Erbium-doped fiber amplifier(Bi-EDFA).

3.2 Loss in the Cavity

3.2.1 Fresnel Reflection

When optical fibers are connected, small portion of optical power may be reflected back into the source fiber. Light that is reflected back into the source fiber is lost. This reflection loss, called Fresnel reflection, occurs at every fiber interface. The Fresnel equations, deduced by Augustin-Jean Fresnel describe the behavior of light when moving between media of different refractive indices [10,20]. In our case, Fresnel reflection is caused by a step change in the refractive index that occurs at the fiber joints. In most of the cases, the step change in refractive index is caused by the ends of each fiber being separated by a small gap. This small gap is usually is air gap. In Fresnel reflection, a small portion of the incident light is reflected back into the source fiber at the fiber interface. The reflectivity (R), approximates the portion of incident light (light of normal incidence) that is reflected back into the source fiber and is given by;

$$R = \left(\frac{n_1 - n_o}{n_1 + n_o}\right)^2 \tag{3.1}$$

Where R is the fraction of the incident light reflected at the fiber, n_l is the refractive index of the fiber core and n_0 is the refractive index of the medium between the two fibers [19].

Fresnel reflection occurs twice in a fiber-to-fiber connection. A portion of the optical power is reflected when the light first exits the source fiber. Light is then reflected as the optical signal enters the receiving fiber. Fresnel reflection at each interface must be taken into account when calculating the total fiber-to-fiber coupling loss. Loss happened due to the Fresnel reflection may be significant in the cavity with a lossy connector. Index Matching Gel (IMG) is applied at the end of port 2 as shown in figure 3.1

3.2.2 Reduce Fresnel Reflection by an Index Matching Gel(IMG).

To reduce the amount of loss from Fresnel reflection, the air gap can be filled with an IMG. The refractive index of the (IMG) should match the refractive index of the fiber core. IMG reduce the step change in the refractive index at the fiber interface, thus reducing Fresnel reflection. The choice of IMG is important. Fiber-to-fiber connections are designed to be permanent and require no ammendment. Over the lifetime of the fiber connection, the IMG must meet specific optical and mechanical requirements. IMG should remain transparent. They should also resist flowing or dripping by remaining viscous. Some IMGs darken over time while others settle or leak out of fiber connections. If this requirement does not meet, then the fiber-to-fiber connection loss will increase over time.

In optics, specifically fiber optics, an IMG is a substance which has an index of refraction that closely approximates that of an optical element or fiber, and is used to reduce Fresnel reflection at the surface of the element. In fiber optics and telecommunications, an index-matching material may be used in conjunction with pairs of mated connectors, with mechanical splices at the ends of fibers. Without the use of an index-matching material, Fresnel reflections will occur at the smooth end faces of a fiber. When the reflected signal returns to the transmitting end, it is reflected again and returns to the receiving end at a level of 28dB below the direct signal [18,19].

Figure 3.1 shows an experimental set-up to study the effect of the IMG on the transmitted and reflected light at the fiber end. The transmitted light can be measured from port-2 of the optical circulator while reflected of light is measured from port-3 of the optical circulator by an optical power meter. The input signal was provided by a Tunable Laser Source (TLS). The use of IMG is expected to reduce the backreflected light from the fiber end.

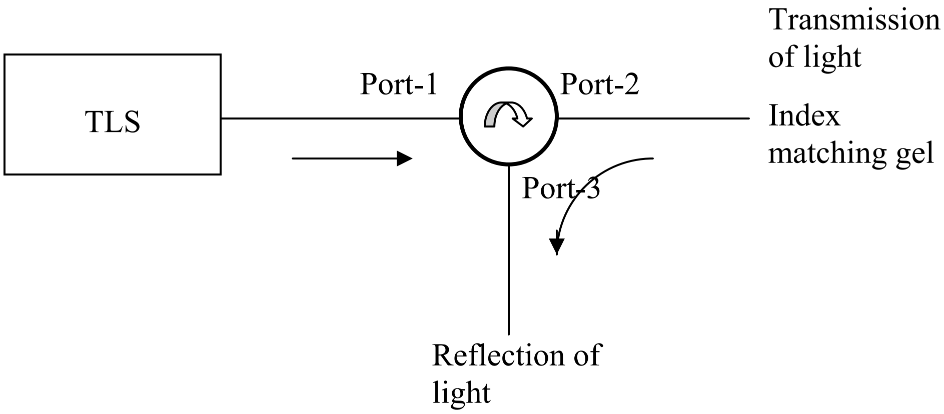

Figure 3.1: Experiment set-up to study the effect of IMG on the back reflected light.

Figure 3.2 shows the reflected light power at port-3 with and without the IMG. As shown in figure, the back reflected light power is significantly reduced by more than 30dB with the IMG. This is attributed to the smaller index difference at the fiber end which in turn reduces the Fresnel reflection as depicted in equation (3.1).

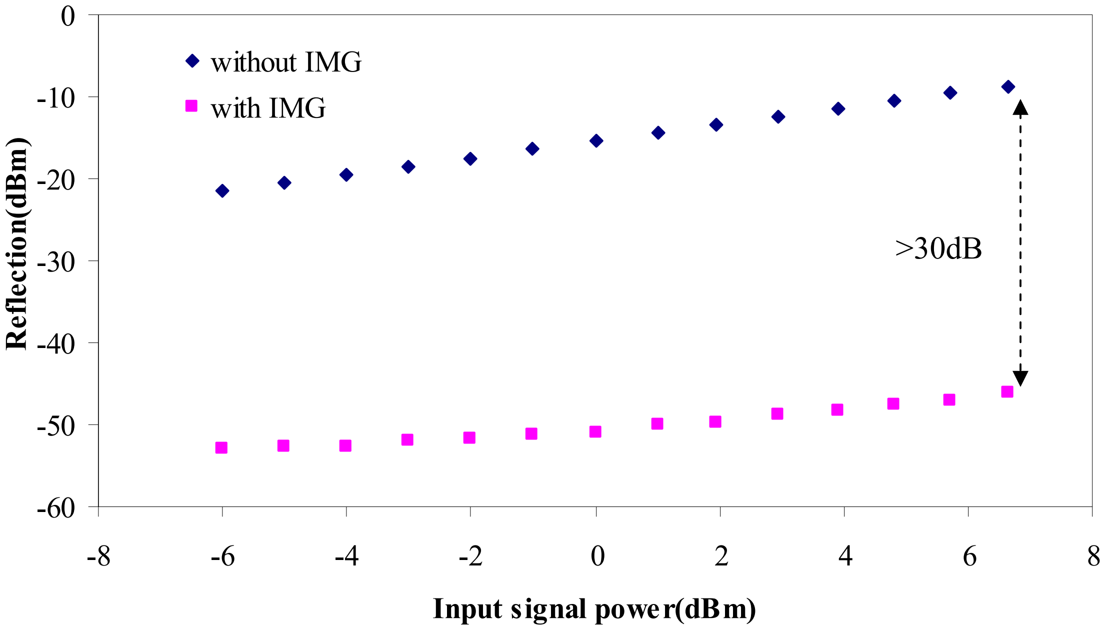

Figure 3.2: Back reflection of light distribution

3.3 Investigation of the Brillouin Effect in PCF

Brillouin scattering is a nonlinear effect which is normally observed in a glass medium. The incident Brillouin Pump (BP) waves generate acoustic waves through electrostriction, and coupling with acoustic waves causes the backscattered light to be downshifted via the Doppler frequency shift. The backscattered light (Brillouin Stokes light) propagates in the opposite direction with the BP. Stimulated Brillouin Scattering (SBS) occurs when the light launched into the fiber exceeds the threshold power level. Under the condition of SBS, the backscattered light is frequency shifted away from the

BP at approximately 10GHz. This means the power of transmitted light will no longer increase linearly with the BP power and will be converted to backscattered Stokes light.

Figure 3.3 shows the experimental set up to study the Brillouin effect in PCF. .It consists of a 20m PCF and a tunable laser source (TLS) which is used as a Brillouin pump (BP), a circulator and an Optical Spectrum Analyzer (OSA) with a resolution of 0.015nm. The PCF has a numerical aperture (NA) of 0.2, mode field diameter (MFD) of 4.0µm, cutoff of 1000nm and zero dispersion wavelength of 1040nm.

The BP from the TLS is injected into the PCF via the optical circulator through port-1 to port-2. A single frequency fiber laser from the TLS with appropriated power and narrow linewidth characteristic is a suitable light source for the BP. The backscattered light or Brillouin scattering should propagate in the opposite direction and should be shifted by around 0.09nm or 10GHz from the BP. The transmitted light was measured by OSA-1 while the backscattered light was measured by OSA-2 from port-2 to port-3 through the circulator. The output spectra of the transmitted and backscattered light are shown in figure 3.4. In this experiment, the BP power and wavelength was fixed at 8dBm and 1560nm. Transmitted and backscattered light has an output power of 4.4dBm and -14.4dBm respectively. The wavelength of the backscattered light or Brillouin Stokes is supposed to head towards longer wavelength. But in this experiment, the wavelength of the backscattered light occurs at the same wavelength with the BP and the transmitted light. This shows that no Brillouin scattering occurs in this fiber, which might be due to the length of this fiber, which is not sufficient.

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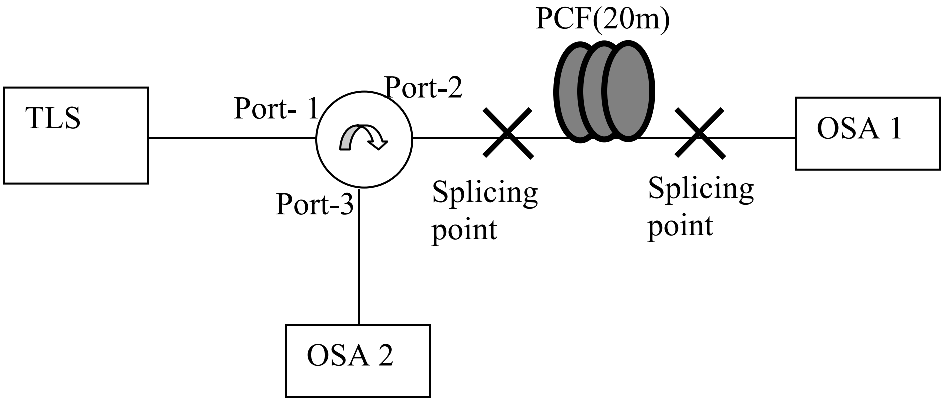

Figure 3.3: Experimental set-up to observe Brillouin shift in PCF

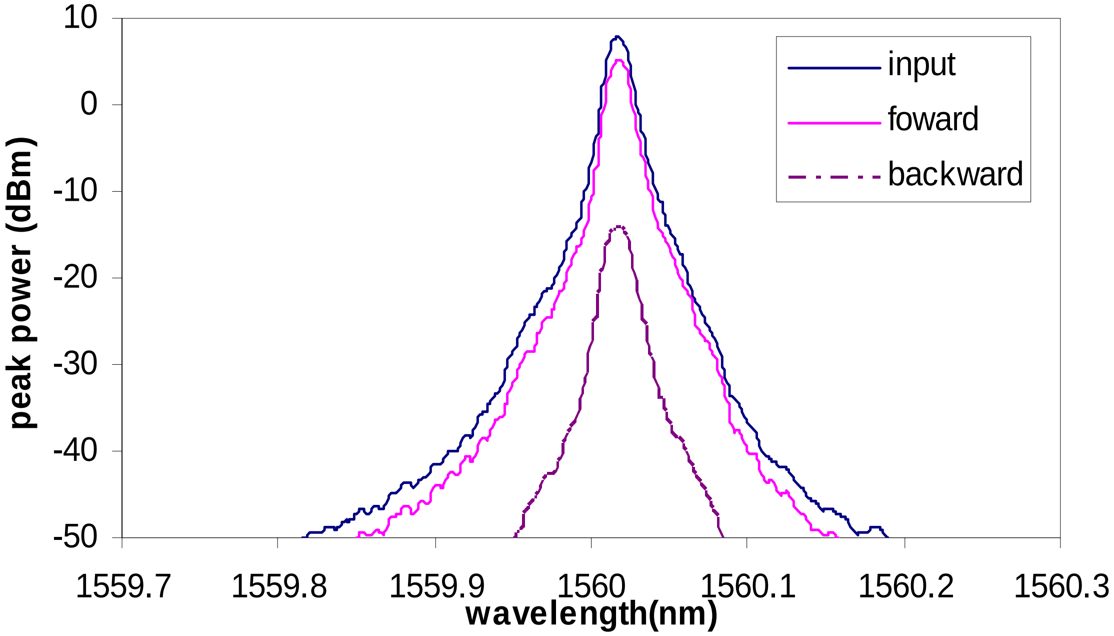

Figure 3.4: The output spectrum of the injected BP, transmitted and backscattered light from the PCF.

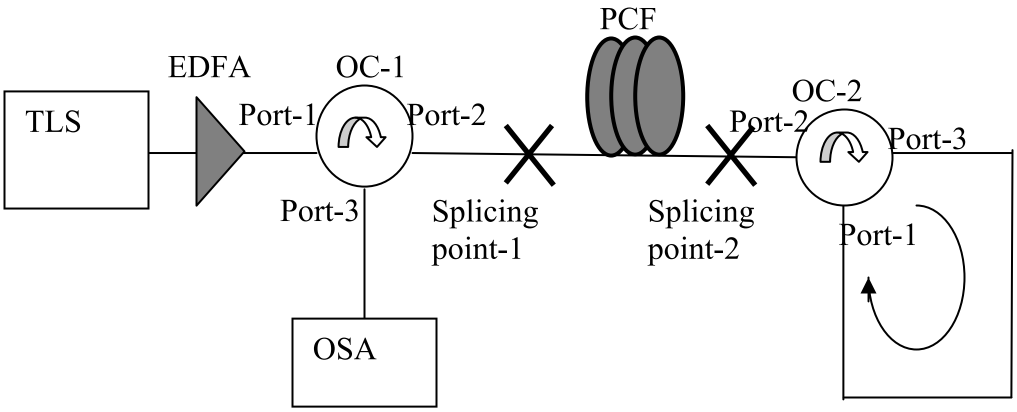

Figure 3.5: The modified experiment set-up to observe the SBS in a piece of PCF

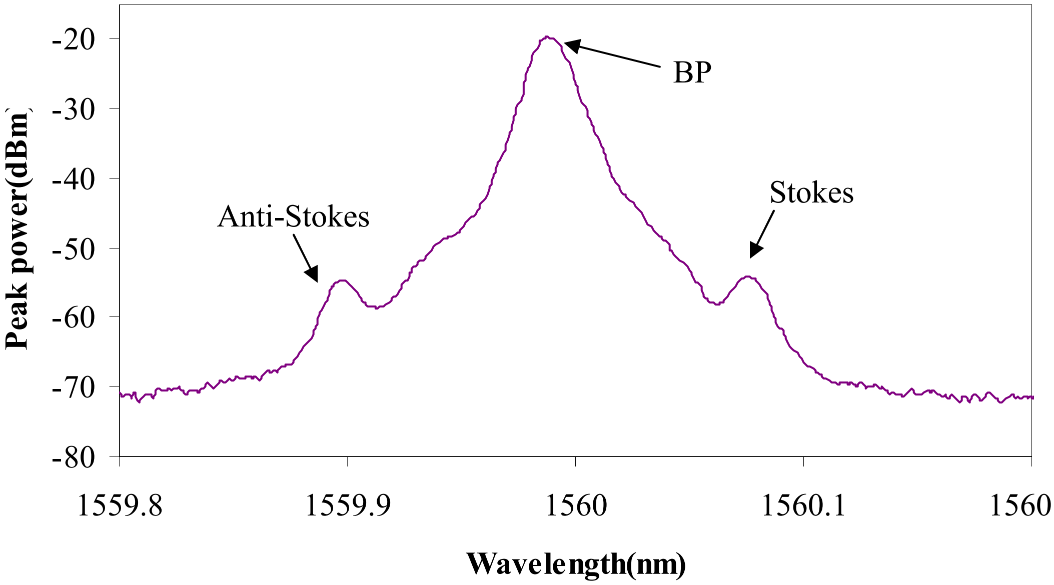

Figure 3.6: Single wavelength Brillouin spectra

In order to obtain Brillouin scattering by increasing the effective length of the PCF the previous configuration of figure 3.3 has been modified as shown in figure 3.5 At the right side of the PCF, an OC-2 is inserted that is used as a reflector where the end of the port-3 is connected with port-1 to allow the injected BP and Stokes propagate twice in the gain medium. An optical amplifier is incorporated into the set up to amplify the BP. This amplified BP is then injected into the cavity via OC-1 through port-1 to port-2 and then coupled into the PCF to generate the Stokes signal which propagates in the opposite direction of the BP signal. The light that is transmitted through the PCF is then reflected back into the gain medium. The double propagation of BP then generates Stokes and anti-Stokes in the backward direction which then routed into the OSA through OC-1. In this experiment, the effective length of PCF is doubled and the BP power is enhanced to 15dBm. However, the power of the booster is not enough to support the amplification of Stokes to generate many orders of Stokes. Therefore, at the end we only obtain a single wavelength Brillouin fiber laser with only one Stokes and one anti-Stokes generated as shown in figure 3.6.

3.4 Investigation of SBS Effect in the Closed Loop Resonator with PCF

The Brillouin effect in a closed cavity or resonator was investigated. The set up is shown in figure 3.7. The ring resonator consists of a circulator, a 20m-long PCF and a 10/90 coupler. The same PCF that is used in the previous study is used as the nonlinear gain medium. The amplifier signal from the TLS with an output power of 15dBm is used as the BP. The BP was injected into the PCF to generate a backscattered light and Stokes in the backward direction which oscillates in the ring cavity.

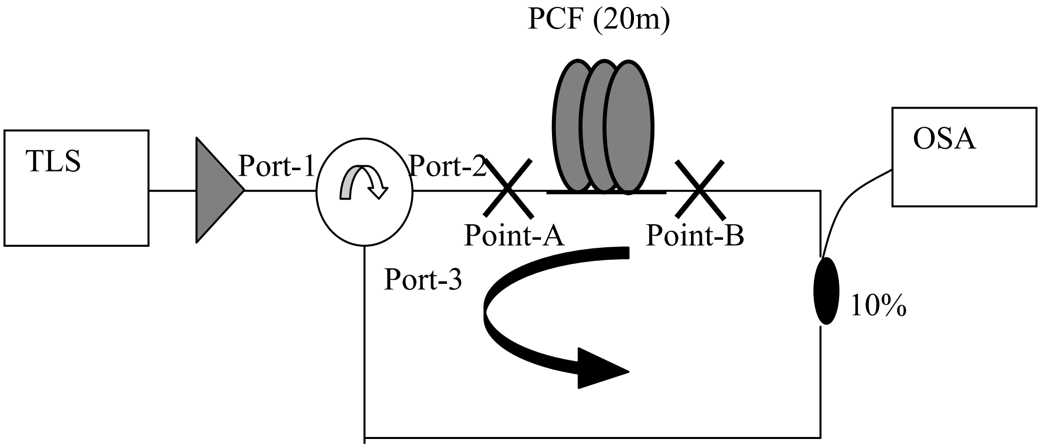

Figure 3.7: Experiment set up to investigate the Brillouin effect in a closed resonator

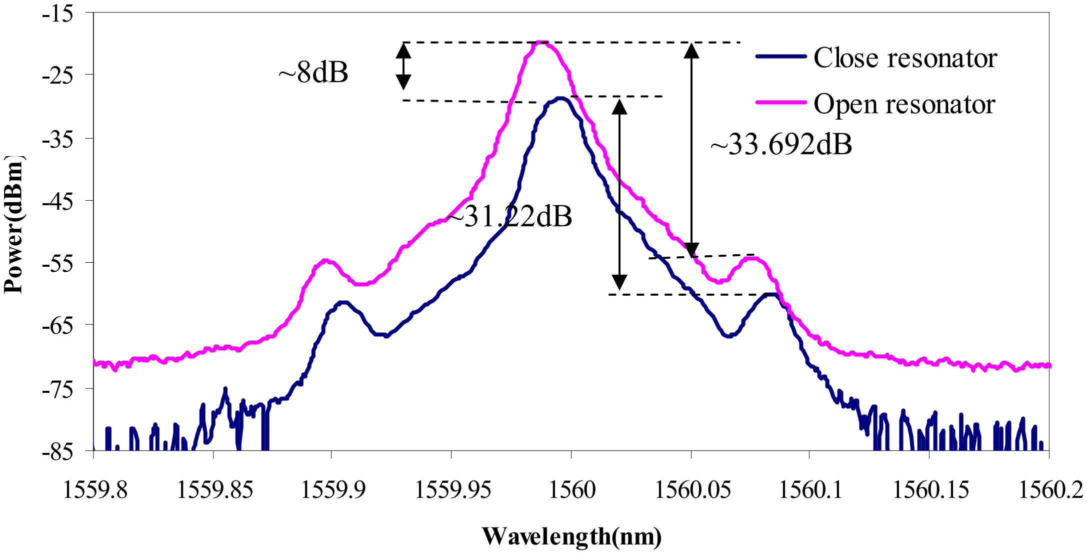

Figure 3.8: The generated Brillouin signal in closed and open resonator

Figure 3.8 shows the output spectrum of the Brillouin signal in an open and closed resonator. The open loop set-up is obtained by measured the output spectrum after the PCF. Both spectra are almost similar with the open resonator showing a higher power compared to the closed resonator. The leakage BP peak power for configuration of open and closed resonators is obtained at -19dBm and -27dBm respectively. However, the side mode suppression ratio(SMSR), which is difference top between the leakage BP peak power and Stokes peak power for the closed resonator was found to be lower than that on the open resonator. The SMSR of the closed and open resonator is obtained at 31.22dB and 33.692dB respectively. Thus shows that the Brillouin effect is stronger in the closed resonator as compared to the open resonator. This is attributed to the Brillouin gain, which amplifies the oscillating signal in the closed resonator set-up.

3.5 Introduction to Bismuth-based EDFA

Most optical amplifiers amplify incident light through stimulated emission, the same mechanism used by lasers. Gain is a measurement of an amplifier's ability to amplify the power level signals that signals can travel further in an optical fiber. Details of the frequency and intensity obtained from the optical gain is depends on the amplifier medium. Noise can be viewed as the random deviation of a physical parameter from the expected value. In the communication systems where electrical, radio or optical signals are transmitted, noise can be viewed as an impairment resulting in the degradation of the information contained in the signal [15]

In the recent years, extensive progress has been made in effort to develop high efficiency erbium doped fiber amplifiers (EDFAs) and they have attracted considerable interest as practicable element for application in optical fiber systems. Moreover, when a glass is doped with erbium ions as opposed to doping a crystal, the ions are incorporated into the amorphous SiO_2, producing an overall broadening of the transition spectrum. This makes possible approach as a laser medium with a broad bandwidth, is extremely valuable in practical terms when it is used as an optical amplifier or fiber laser. This effect can be promoted by co-doping the host glass with Al, Ge or Bi [14].

Recently, Bismuth glass-based hosts have shown increasing potential for use in highly doped EDFA applications due to their ability to accommodate more erbium ions in the glass matrix while at same time having good broadband properties [12,26,29]. It is suitable for applications such as wide-band amplifiers because of its high gain capability in a shorter length scales and wide amplification bandwidth. Bismuth-based glasses have the high nonlinearity property when compared to other glasses and have the advantage of requiring just a few meters length of fiber for effective wavelength amplifications [13,29]. The refractive index of bismuth-based glass is about 2.03 and it is much higher than that in silica which is 1.46. Compared to the silica-based EDF, it is higher gain coefficient, low up-conversion emission and lower cost by the use of cheaper, low power components [14]. More importantly, bismuth based fiber are easier to splice with conventional silica single-mode fibers as compared to other exotic fibers such as a gain medium with high nonlinearity. Bismuth ions are pumped by 1480nm pump laser to achieve population inversion that is similar to the Er^{3+} ion amplification using a two-level pumping scheme at room temperature.

3.5.1 High Power and Flat Gain EDFA

As mentioned in the previous chapter, there are few types of pumping schemes such as forward, backward and bi-directional pumping schemes are available for optical amplifiers. In simple terms, forward pumping is suitable for pre-amplifier applications, whilst backward pumping is appropriate for post-amplifiers (power amplifiers).

Bidirectional is an advantageous when an amplifier combining the characteristics of both set-ups is required.

In this work, to enhance the power of the amplifier, we demonstrate a hybrid silica and bismuth based erbium doped fiber amplifier (Bi-Si-EDFA) for the generation of a high gain wide-band amplifier ranging from 1520nm to 1620nm. The system combines forward pumping silica based EDFA (Si-EDFA) with another bidirectional configuration conventional Bismuth based EDFA (Bi-EDFA), where the forward pumping EDFA acts as a pre-amplifier to boost the signal before it enters the wider band Bi-EDFA. The advantage of this technique is that it allows for the use of lower powered and hence cheaper components to still generate a high gain which is a much sought-after pre-requisite by network system developers. The experimental set-up is to evaluate the amplification performance of the dual-amplifier is shown in figure 3.9(a). The performance of the proposed amplifier is compared with the conventional bi-directional Bi-EDFA of figure 3.9(b) which is obtained by removing the first-stage of the amplifier.

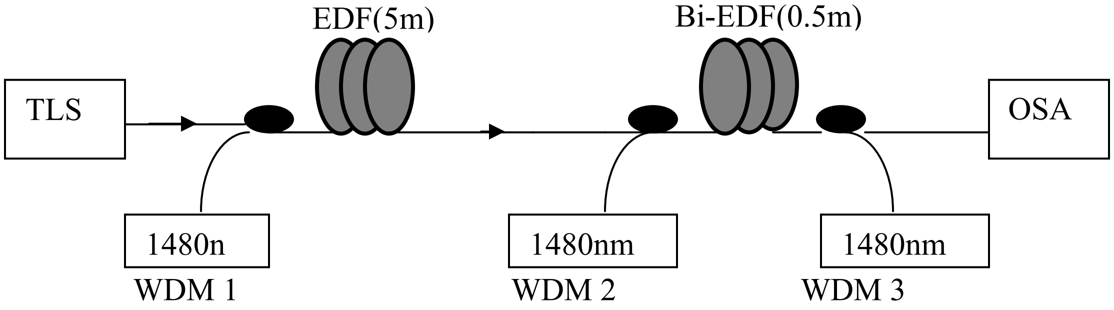

Figure 3.9(a): Proposed configuration of flat-gain amplifier

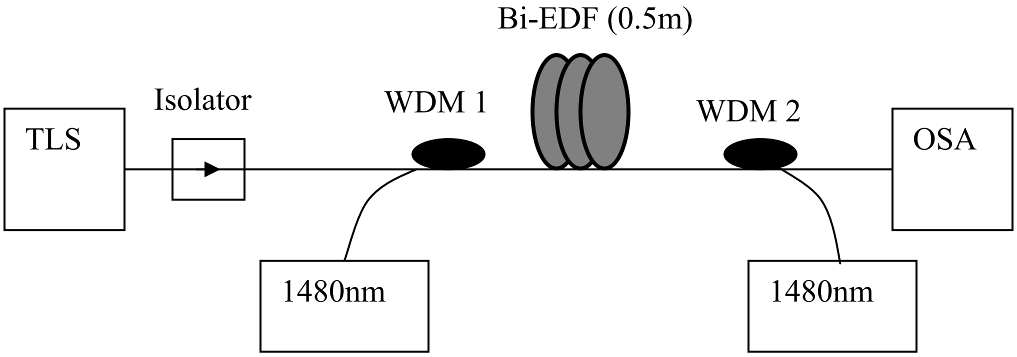

Figure 3.9(b): Conventional Bi-EDFA

The Si-EDFA and Bi-EDFA used in the setup has an erbium concentration of 960 ppm and 3250 ppm respectively. The Si-EDFA has an absorption coefficient value of 18.4 dB/km at 1531nm with a length of 5.0m while the Bi-EDFA has an absorption coefficient of 210 dB/m with a length of 0.49m. The NA of the Si-EDFA is 0.21 and of Bi-EDFA is 0.20. Si-EDFA in the first stage acts as a pre-amplifier and pumped uni-directionally first by a 1480nm laser diode in the forward direction with a pump power of 80mW. The Bi-EDF in the second stage is pumped in the bi-directional configuration by two 1480nm laser diodes with a total pump power of 270mW. Wavelength division multiplexing (WDM) coupler is used to combine the pump with the signal. TLS is used in conjunction with OSA to characterize gain and noise figure of the amplifier.

Pumping at 1480nm is essentially free of ESA and secondly because of the availability of high power laser diodes at this wavelength**.** It also presents the advantages of close proximity between pump and laser wavelength, which implies that the maximum possible laser slope efficiency is higher than that for 980nm pumping by a factor of 1.5. The gain efficiency of Er-doped fiber is generally smaller with 1480nm pumping than with 980-nm pumping. When pumping near 1480nm, stimulated emission at this wavelength is reduced and the required length of fiber is slightly increased [11].

Figure 3.10(a): ASE spectrum of Bi-EDFA

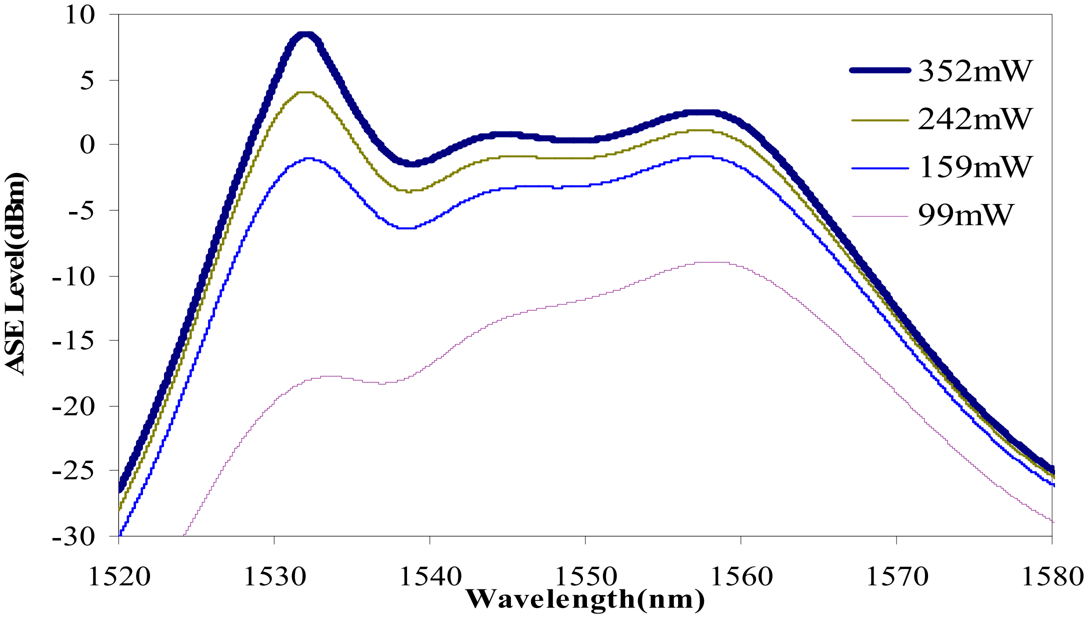

Figure 3.10(b): ASE spectrum for Bi-Si-EDFA

The gain bandwidth obtained from a direct amplifier correlates to the device's ability to amplify the whole spectral range that the light pulse possesses. This can be estimated directly from the spectral width of the amplified spontaneous emission (ASE). In an amplifier, the ASE bandwidth may be over 1 THz and therefore, excluding amplification of femtosecond (10^{-15}) pulses, this is not a cause for concern [14].

Figure 3.11 compares the measured forward ASE spectrum for the Bi-Si-EDFA with the bi-directional Bi-EDFA. ASE spectrum peaks at wavelength region from 1530 - 1570nm. As shown in figure 3.11, the proposed Bi-Si-EDFA shows a higher ASE level by more than 40dB compared to that of Bi-EDFA. This is attribute to the total 1480nm pump power used which is so much higher in hybrid Bi-Si-EDFA. The total erbium ions are also higher in the hybrid Bi-Si-EDFA, which increases the population inversion and thus increases the spontaneous emission in the amplifier.

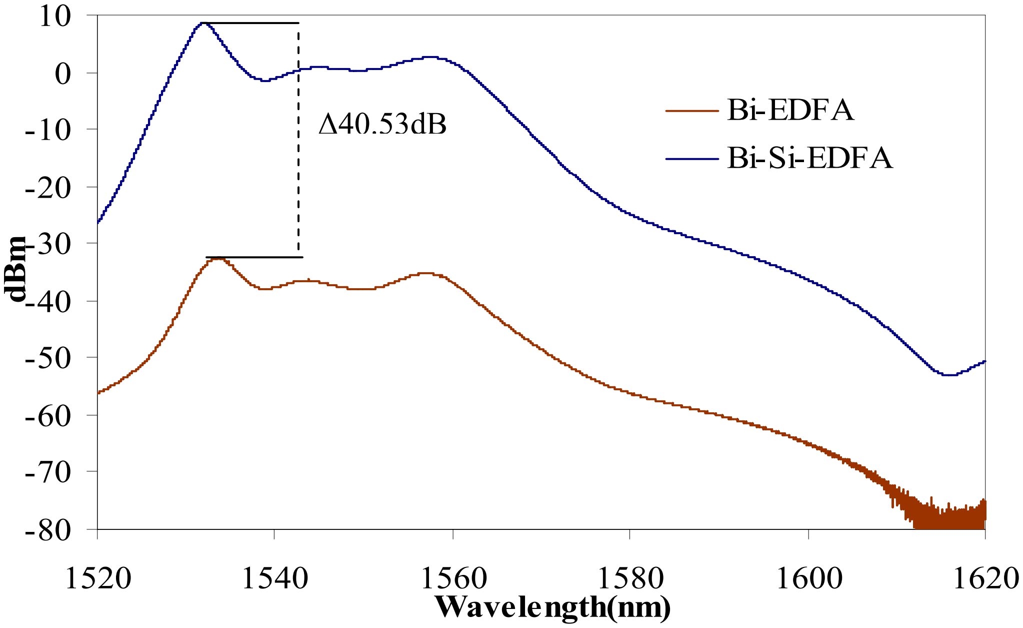

Figure 3.11: The generated ASE for Bi-EDFA and Bi-Si-EDFA

The gain for both amplifiers is then measured for different input signal powers and wavelengths. Gain is achieved in an EDFA due to population inversion of the dopant ions. The power of the pump wavelength and the power at the amplified wavelengths determine the inversion level of an EDFA. If the signal power increase or the pump power decrease, the inversion level will drop and therefore the gain of the amplifier will be reduced. This effect is known as gain saturation [14,17]. When the signal level increases, the amplifier saturates and cannot produce any more output power, and therefore the gain reduces.

The gain dependence with signal wavelength represents one of the most important optical amplifier characteristics. Figure 3.12 shows the Si-Bi-EDFA gain as a function of pump wavelength obtained from different input power signals. It shows that the variation of gain over the 76nm bandwidth. From the gain spectrum, we can see that the wavelength heads over long distances, the gain also increases until 1528nm and flattens out until a wavelength of 1568nm. Then, the gain spectrum starts to fall down from a maximum value of 27.79dB at 1568nm to the minimum value of 0.76dB value at a wavelength of 1596nm for a gain spectrum of lower input signal. For a 0dBm input signal, the gain increases with wavelength until 1528nm and flattens out until 1560nm. After this value of wavelength it falls down from maximum value of 19.71dB to the minimum value at 1592nm. The gain drops at around 1565nm to longer wavelengths but the stimulated emission at these wavelengths remains higher than the absorption. This produces a net gain as light travels along the fiber, so power increases along its length. The variation of gain bandwidth for both input signals is similar.

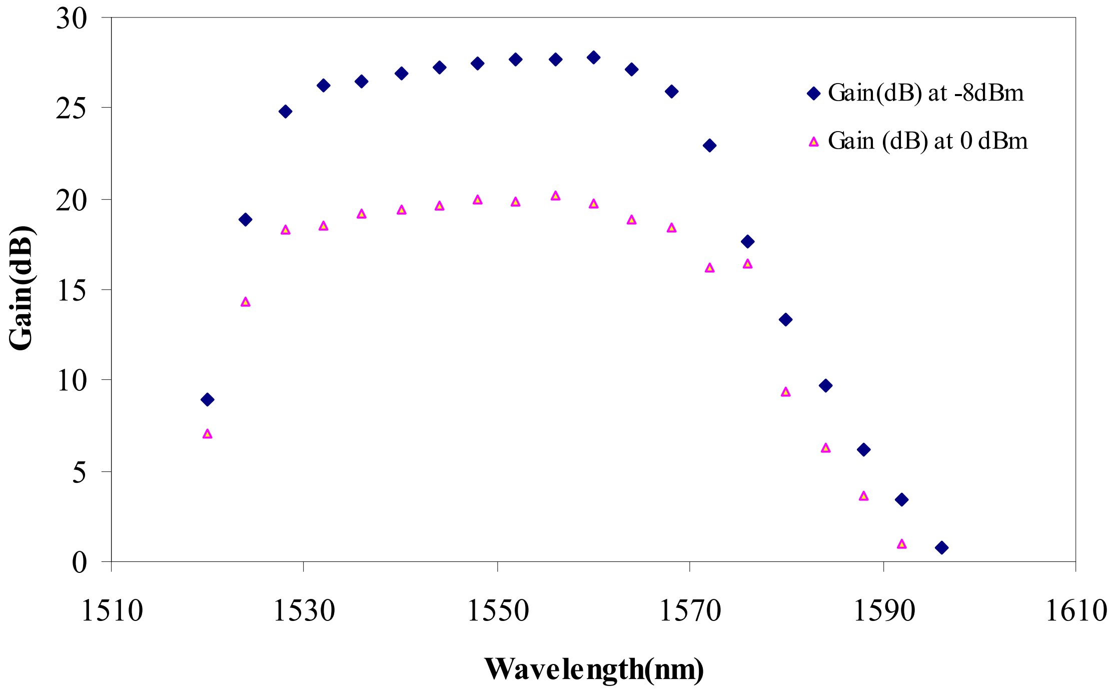

Figure 3.12: Gain spectrum of Bi-Si-EDFA

Gain is higher if the input signal is small. It is shown in this dissertation via the following: the gain at input powers of 0dBm and -8dBm input power are obtained at -19.71dB and 27.79dB respectively. The gain saturation is defined as the gain at 3dB gain compression from its unsaturated gain for a specific length of EDF and wavelength [27]. The bandwidth of 3dB down gain and nearly flat spectral region of 40nm from 1532nm until 1572nm for input power was 0dBm whereas the bandwidth of 3dB down gain and nearly flat spectral region of 40nm also from 1528nm up until 1568nm for input power -8dBm. The best wavelengths are from 1530nm to 1565nm.

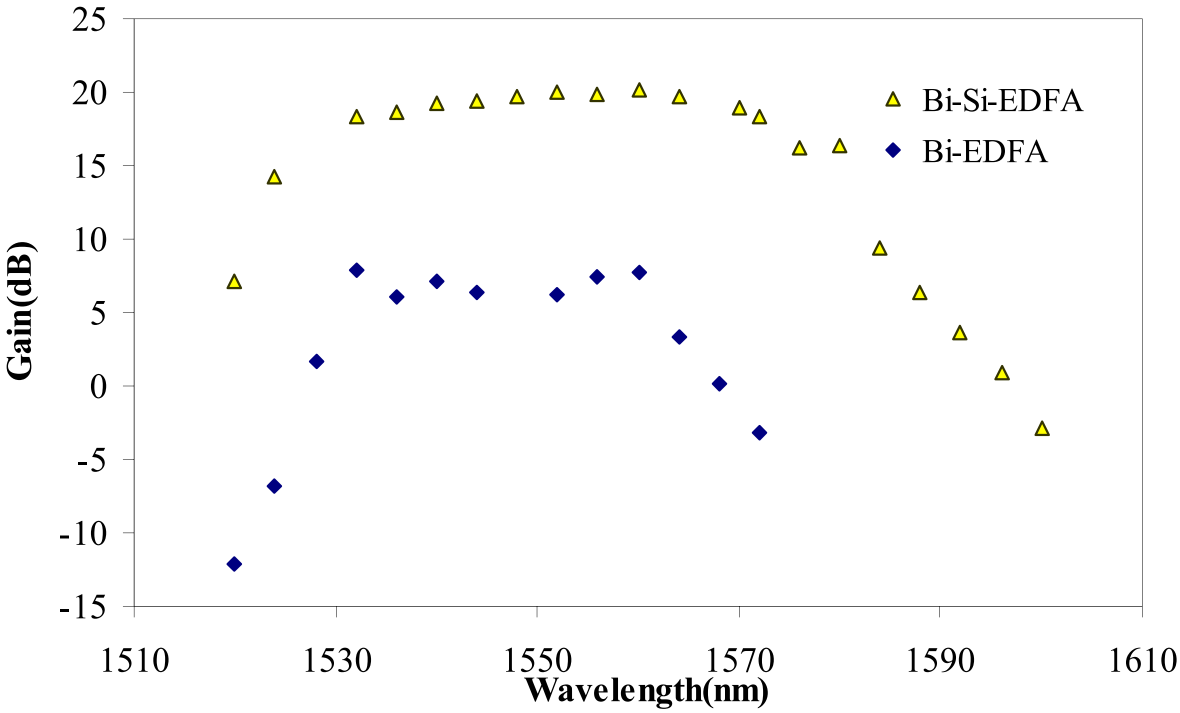

Figure 3.13: Gain comparison for between Bi-EDFA and Bi-Si-EDFA

Figure 3.13 compares the gain spectrum of the hybrid Bi-Si-EDFA with that of bi-directional Bi-EDFA with input signal fixed at 0dBm. The gain spectrum of the configuration with the double stage Bi-Si-EDFA is found to be flat with a bandwidth of 3dB down gain of 40nm from 1532nm until 1572nm with the highest achievable gain value of 20.14dB at 1556nm. On the other hand, the gain spectrum of the single stage bidirectional Bi-EDF configuration is found to be flat with a 3dB down gain of 28nm from 1532nm until 1560nm with the highest achievable gain value of 7.84dB. So the Bi-Si-EDFA gives a higher gain bandwidth than the Bi-EDFA gain bandwidth, a difference of 10dB. At this flat gain bandwidth, the maximum NF for a 0dBm input signal is 8.01dB at a wavelength of 1528nm. Through this gain bandwidth comparison between Bi-EDFA and Bi-Si-EDFA, the double stage configuration represents the better design for an amplifier in this dissertation.

The ASE power spectrum closely emulates the gain spectrum, so it provides useful information on the Bi-Si- EDFA operating characteristics in various signal power regimes. On the other hand, the ASE also contributes to the noise in the EDFA. The noise figure (NF) represents a measure of the signal to noise ratio (SNR) degradation from the input to the output of the amplifier [11]. The original formula of noise figure standardized by IEEE [11,14] is defined as

$$NF = \frac{SNR_{in}}{SNR_{out}} \tag{3.3}$$

Where SNR_{in} and SNR_{out} are the signal-to-noise ratio at the input and output ends of an amplifier respectively. Alternatively, noise figure may be defined in terms of dB units.

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \cdots + \frac{F_n - 1}{G_1 G_2 G_3 \cdots G_{n-1}}, \tag{3.4}$$

As the amplifier introduces noise, it is expected that $SNR_{out} < SNR_{in,}$ so the amplifier optical noise figure is always greater than or equal to unity[18]. A dual-stage configuration has been accepted as the design for low-noise and high-gain C-band amplifiers [30]. The first stage is pumped co-directionally pumped by a 1480nm LD and the second stage is a bi-directionally pumped with two 1480nm LDs. ASE utilize from the first stage as a pumping source for the second stage[30].

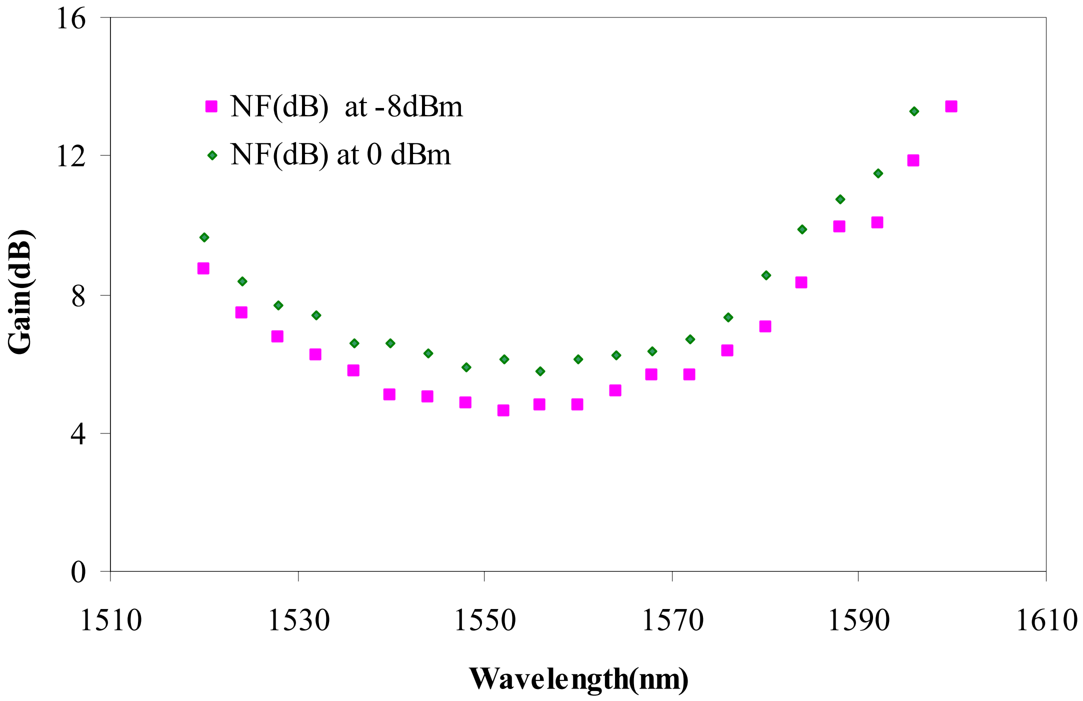

Figure 3.14: Noise Figure Distribution of Bi-Si-EDFA

Figure 3.14 shows the noise figure spectrum as a function of pump wavelength with two different input signals for the proposed hybrid Bi-Si-EDFA. The figure shows that the noise figure is declining slowly from 9.65dB at a shorter wavelength of 1520nm until 6.59dB at 1536nm. The NF readings are nearly constant in a small region from 1536nm to 1572nm. After this region, the NF increases until it exceeds the maximum value at longer wavelength, 1596nm. It is seen that the low input signal (-8dBm) give a lower spectral noise figure and the high input signal (0dBm) give a high spectral noise figure. However, a good EDFA design should give as high a gain and as low a noise figure as possible [27,28].

3.6 Summary

Characterizations of SBS on PCF fiber have been presented in this chapter. The performance of two types of resonators: Open and close resonators have been studied and we found that the closed resonator design is most suited for practical applications. Amplifier is a most important thing in supplying high power into the resonator. The high nonlinearity in the PCF (or any material that has high nonlinear characteristics), need for high power amplifier. Two types of amplifier which is Bi-EDFA and hybrid Bi-Si-EDFA have been demonstrated and characterized through ASE, gain and noise figure and we found that hybrid Bi-Si-EDFA give the good performance with give the large flat band of gain spectral, and high ASE level. A hybrid Bi-Si-EDFA shows the most promise as an amplifier with a gain reading of 10dB more than the single stage Bi-EDFA. It is practical to use cascade configurations for low-noise and high-gain amplifiers.

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