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Performance of Gallium-Erbium Fiber Amplifier in a Double-Pass Configuration

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Abstract

In a previous amplifier setup, a Gallium co-doped Erbium fiber (Ga-EDF) with a length of 2 m has been used as a gain medium. The amplifier which was designed as a single-pass configuration, achieving a highest gain of 22.45 dB. In this paper, the Ga-EDF amplifier is designed as a double-pass setup. The gain and noise figure at the input signal's wavelength of 1520 nm - 1580 nm is investigated at various input powers, which are from -30 dBm to 0 dBm. This study compares the performance of the amplifiers as it is pumped by a laser signal at the wavelength of 980 nm and 1480 nm, with a power of 140 mW. The amplifier obtained the highest gain of 36.62 dB and 35.77 dB for the pump wavelength of 980 nm and 1480 nm, respectively. The corresponding noise figures are 3.48 dB and 5.01 dB, which occurs at the input signal's wavelength of 1555 nm. The results indicate that the double-pass Ga-EDF amplifier pumped at 1480 nm outperforms the single pass Ga-EDF amplifier by 15.08 dB, with a comparable noise figure. The results also show that the double-pass Ga-EDF's performance are comparable at both pump wavelengths.

1. Introduction

Erbium-doped fiber amplifiers (EDFAs) are critical components in optical communication systems as they provide efficient and high-gain amplification for optical signals transported through fiber optic cables. Amplification using EDFAs provides a long-distance optical signal transmission with minimal degradation by using erbium ions introduced within the fiber core, making them crucial for the evolution of modern telecommunications. In an EDFA, erbium ions are responsible for the amplification of optical signals. However, the clustering of erbium ions in EDFAs affects its performance. When erbium ions cluster together, their energy levels can be affected, leading to a reduced amplification efficiency. Clustering restricts the number of erbium ions available for signal amplification, resulting in a decrease in the gain of the EDFA. Improving gain and decreasing noise figure in an EDFA is critical as it has a direct impact on the general performance and reliability of fiber optic communication systems. The ability to obtain both a high gain and a low noise figure is critical for maximizing an EDFA's efficiency and reliability in a variety of applications, including telecommunication networks and high-speed data transfer.

The clustering of erbium ions is due to the increased concentration of erbium ions within the fiber core[1]. When the erbium ion concentration is increased beyond a certain level, the erbium ions tend to cluster together in the fiber core instead of being uniformly distributed. These clusters can form due to the limited solubility of erbium ions in the fiber core material or the presence of impurities. To mitigate the clustering effect and maintain optimal performance in EDFAs, researchers suggest that co-doping the fiber core with rare earth ions, such as gallium, ytterbium or thulium helps reduce the clustering effect [6]. Gallium ions can reduce the clustering of erbium ions, promoting a more uniform distribution. The implementation of highly doped Ga-EDF allows a significant gain over reduced fiber length. This subsequently permits a decrease in the amplifier cavity length, thus enhancing system compactness.

The pump wavelengths that are typically used by EDFAs are 980 nm and 1480 nm due to the high absorption efficiency of fiber at both wavelengths. Erbium ions have a relatively high absorption cross-section at 980 nm and 1480 nm which leads to effective population inversion and allows for efficient amplification of the input signal [7]. With the increasing number of research studies on EDFAs, there are various configurations of EDFAs that can be implemented based on different research objectives. To address the limitations of EDFAs, researchers have turned their attention to the alternative amplifier configuration, which is the double-pass configuration. This configuration offers the potential for improved amplification performance, making it a compelling area of study. The double-pass configuration refers to reflecting the amplified signal back through the erbium-doped fiber for a second round of amplification. In a traditional single-pass EDFA, the signal is amplified once it travels through the fiber. A double-pass EDFA, on the other hand, reflects the amplified signal back into the fiber, allowing for a second amplification stage.

A few studies have been conducted to compare the performance of single- and double-pass EDFAs. Experimental results reported in [8] show that the double-pass configuration offered more gain than the single-pass configuration, especially at low input powers. The small-signal gain of the double-pass amplifier is higher the single-pass amplifier by 14 dB at the input signal wavelength of 1500 nm, with a 0.9 dB higher noise figure than a single-pass configuration. This enhancement was attributed to the increased gain acquired from the second pass through the doped fiber. The double-pass amplifier was also proven to have a larger flat gain bandwidth and a lower noise figure than the single-pass amplifier [5]. In summary, the comparison of gain and noise figure performance in single-pass and double-pass EDFA emphasizes the trade-offs between these parameters. While double-pass EDFA may have a higher gain due to the additional pass over the doped fiber, they have a larger noise figure. Single-pass EDFAs, on the other hand, have lower noise figures but may have limited gain performance. The ideal configuration is determined by the optical communication system's specific requirements, and optimization techniques can be used to improve the performance of both configurations. Early works on double-pass amplifiers used a common EDF as the gain medium. [1] used 7 m length EDF as the gain medium, focusing on extending it for a multi-channel application. The work in [3] used three EDFs with the lengths of 4 m, 50 m and 50 m, focusing on enhancing noise figure performance. The work in [8] utilized a 15 m depressed cladding single mode fiber (SMF) as the gain medium in their double-pass amplifier. Meanwhile, researchers in [5] used a high concentration EDF in two stages configuration with the gain medium length of 1.5 m and 9 m. The performance of a double-pass amplifier with a Ga-EDF of 2 m length is investigated in this paper, which was a different gain medium from the previous work done using a double-pass configuration.

The performance of a Ga-EDF amplifier in a single-pass setup, pumped at 1480 nm and 980 nm was analyzed in our recent study [4]. The single-pass Ga-EDF amplifier, pumped at 980 nm achieved the highest gain of 22.45 dB and a corresponding noise figure of 5.71 dB. In this paper, the same length of 2 m Ga-EDF gain medium is used in a double-pass setup to improve the capability of the Ga-EDF amplifier. This paper investigates the influence of the pump wavelengths on the gain and noise figure of the double-pass Ga-EDF amplifier. Two typical laser pumps at 980 nm and 1480 nm were used, enabling signal amplification at various input power. The significance of the double-pass configuration is demonstrated by comparing its performance with the single-pass configuration from the previous study. The scope of this paper includes evaluating the proposed amplifier's performance under various operating conditions to improve gain and minimize noise figure simultaneously.

2. Methodology

Before measuring the amplifier's performance, the laser pump power with respect to the driver current was characterized to determine the highest achievable pump power. After that, the amplified spontaneous emission (ASE) spectrum of the Ga-EDF in a double-pass configuration was obtained using the experimental setup, as shown in Fig. 1.

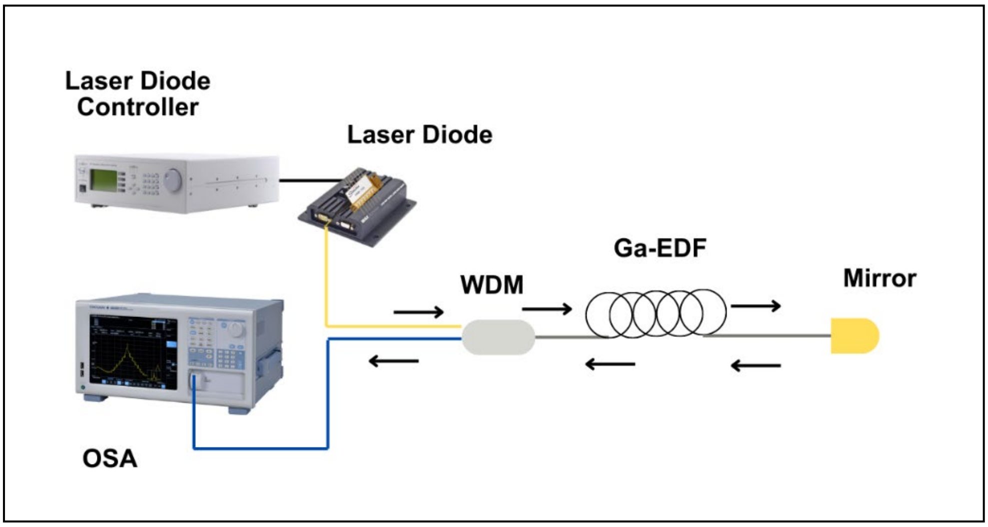

Fig. 1 *The experimental setup for characterizing the ASE spectrum of a double-pass Ga-EDF amplifier*

A laser diode controller, 'Newport Model 8000' powered a 14-pin butterfly laser diode 980 nm 'Lumics'. The laser diode was tuned to provide a pump power of 140 mW. The laser diode was connected to the 980/1550 nm wavelength division multiplexing (WDM) module, which was coupled to the 2 m of Ga-EDF and an optical mirror. The WDM was also connected to the optical spectrum analyzer (OSA) 'YOKOGAWA AQ6370C' with a 0.2 nm resolution to measure the output signal. The experiment was conducted again with a 14-pin butterfly laser diode 1480 nm 'Anritsu' and a WDM module 1480/1550 nm.

The performance of the double-pass Ga-EDF amplifier was evaluated in terms of the gain and the noise figure. The gain of an amplifier indicates the amplification factor that the amplifier provides to the input optical signal. Meanwhile, the noise figure indicates the loss of the signal-to-noise ratio (SNR) as the input signal passed through the amplifier. It shows how much more noise the amplifier makes when compared to an ideal noiseless amplifier. The initial step to characterize the performance of a Ga-EDF amplifier is to set the input signal power. The input power that was needed to be achieved was -30, -20, -10 or 0 dBm, depending on the requirement of the design. The experimental setup to set the input signal power is shown in Fig. 2.

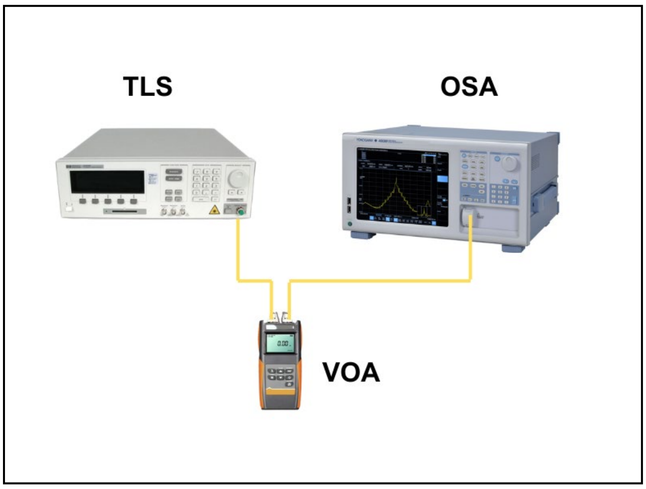

Fig. 2 *Experimental setup to set the input signal power*

A tunable laser source (TLS) 'ANDO AQ4321D' supplies the input signal at a specific wavelength, ranging from 1520 to 1580 nm. The output signal was observed at the the optical spectrum analyzer (OSA) 'YOKOGAWA AQ6370C' and the signal was attenuated by the variable optical attenuator (VOA) simultaneously. As the signal was attenuated to the required power level, the attenuation value was recorded. The output signal that was measured by the OSA was saved as it is needed to be used in the upcoming step. The experimental setup to measure the gain and the noise figure of the double-pass Ga-EDF amplifier is shown in Fig. 3.

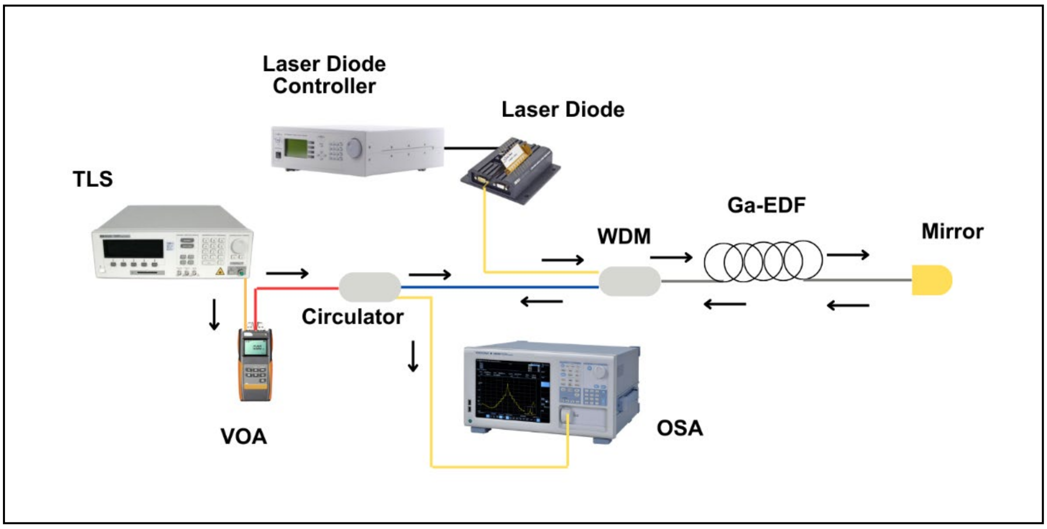

Fig. 3 *Experimental setup for characterizing the double-pass Ga-EDF amplifier*

A TLS provides the input signal between 1520 and 1580 nm wavelengths. VOA attenuates the input signal to the desired values, between -30 to 0 dB. To stop the reflected signal from affecting the TLS, an optical isolator was added between the VOA, WDM and OSA. The Ga-EDF was connected to a 14-pin butterfly laser diode through a WDM. The laser diode was powered by a modular controller, 'Newport model 8000'. It acts as a laser pump to provide the energy required to create population inversion, excite erbium ions and enable the amplification of the optical signal. The Erbium-Gallium doped fiber used was from the fabrication by [2]. The fiber was subsequently connected to an optical mirror, which serves to bounce the signal back into the fiber and consequently twice the amplification. The signal from the output of the fiber was then passed to the OSA 'Yokogawa AQ6370D' through WDM and circulator. The amplified signal was measured using OSA with 0.05 nm resolution in the wavelengths ranging from 1520 nm to 1580 nm. Table 1 provides a summary of the experiment's parameters.

Table 1 *Parameters used in the experiment*

Parameter	Value
Laser pump wavelength	980 nm and 1480 nm
Gallium-erbium doped fiber length	2 m
Pump power	140 mW
Input signal power	-30 dB, -20dB, -10 dB and 0 dB
Input signal wavelength	1520 nm to 1580 nm
OSA resolution	0.05 nm

3. Results and Discussion

Fig. 4 shows the ASE spectrum for the double-pass Ga-EDF amplifier at the pump wavelengths of 980 nm and 1480 nm. At 1533 nm, the ASE amplitude is higher when the 1480 nm pump is used, which is the first peak of the spectrum with an amplitude difference of 2.302 dBm. At 1552 nm, which is the second peak of the spectrum, the ASE amplitude is also slightly higher when it is pumped at 1480 nm, with an amplitude difference of 0.835 dBm. Overall, there was no significant difference between the amplifiers, as the ASE spectrum was slightly higher when the 1480 nm pump was used than the 980 nm pump. Contrarily, the ASE was significantly higher for the single-pass Ga-EDF amplifier when the 980 nm pump was used than the 1480 nm pump. It was due to the higher absorption at 980 nm, as reported by [4]. The result is the opposite for the case of the double-pass Ga-EDF amplifier, which might be due to the higher reabsorption of the 980 nm signal at the second pass.

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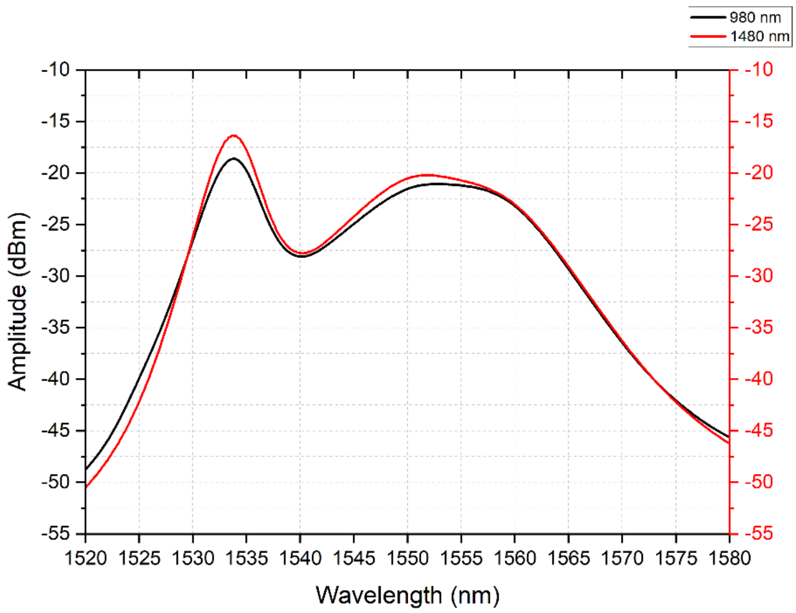


Fig. 4 *ASE Spectrum of the double-pass Ga-EDF amplifier, pumped at 980 nm and 1480 nm*

Fig. 5 shows the comparison on the performance of the single-pass and double-pass Ga-EDF amplifiers pumped at 1480 nm. The single-pass Ga-EDF amplifier was reported in our previous work [4]. The comparison was made for the input signal power of -30 dBm. The result shows that the overall gain for the double-pass Ga-EDF amplifier was higher than the single-pass Ga-EDF amplifier. The maximum gain for the double-pass Ga-EDF amplifier is 35.91 dB at 1555 nm, while the single-pass Ga-EDF amplifier obtained a gain of 20.83 dB at 1550 nm. The maximum gain difference is 15.08 dB, which is very remarkable. On the other hand, the noise figures for both configurations do not have a significant difference. Overall, the double-pass Ga-EDF amplifier performs better than the single-pass Ga-EDF amplifier, indicated by the significantly higher gain with minimal differences of the noise figure. The double-pass setup caused the input signal to pass through the gain medium twice, which resulted in a higher gain than a single-pass configuration. The repeated excitations of erbium ions from the ground energy level to the higher excitation energy level and then to the lower excitation energy level contribute to the higher population inversion than the single-pass configuration [6]. Also, another significant finding in this study is that the double-pass amplifier has better flat gain in the wavelength range of 1550 to 1560 nm in comparison to a single-pass amplifier. This might be due to the compensation for gain tilt. Gain tilt is the term for a variation in gain over an EDFA's amplification bandwidth [9]. It might happen as a result of the pump power distribution or the erbium-doped fiber's natural properties. The gain tilt is noticeable in a single-pass amplifier, producing a gain profile that is not uniform. However, the second pass of the signal in a double-pass amplifier may slightly compensate for this gain tilt, producing a flatter gain response over the amplification bandwidth.

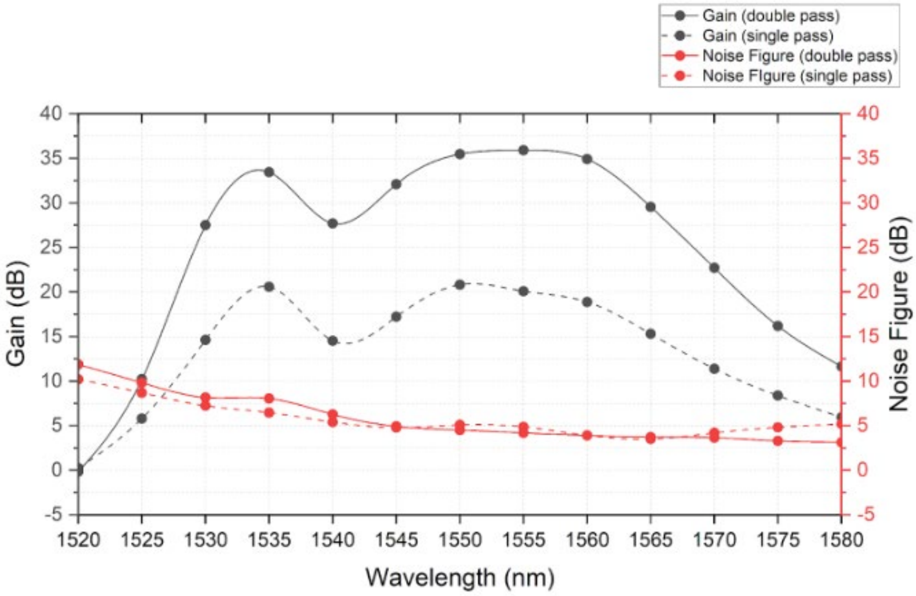
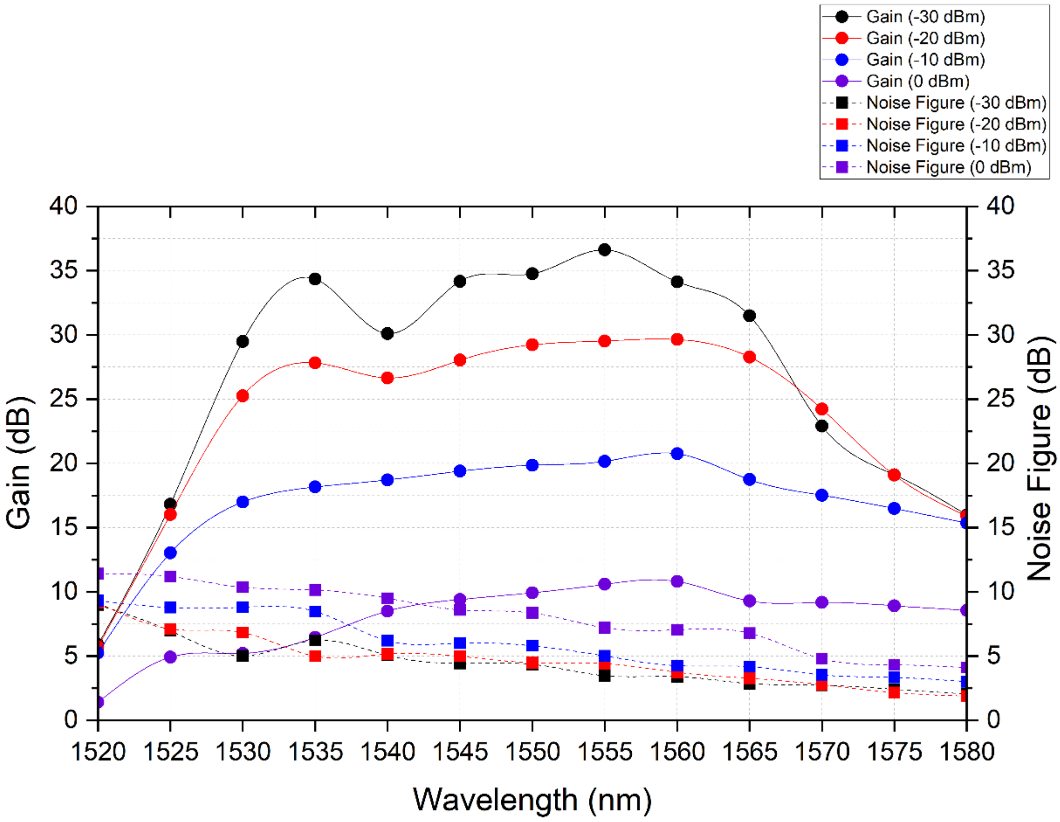
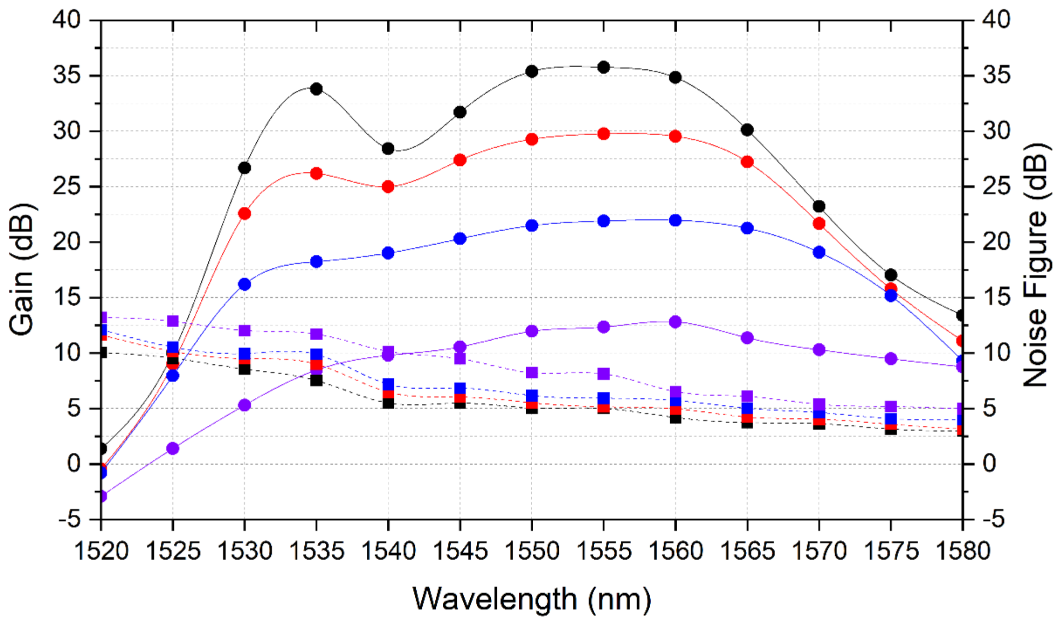


Fig. 5 *Comparison between the double-pass and single-pass Ga-EDF amplifiers, pumped at 1480 nm*



(a)



(b)

Fig. 6 *Performance of the double-pass Ga-EDF amplifier at various input power, (a) pumped at 980 nm, and (b) pumped at 1480 nm*

The Ga-EDF amplifier's performance when pumped at 980 nm was characterized for the input power levels of -30, -20, -10 and 0 dBm, as illustrated in Fig. 6 (a). The highest gain was achieved at the smallest input power, as expected. At the -30 dBm input power, the maximum gain was 36.62 dB at 1555 nm, and the minimum noise figure was 2.04 dB at 1580 nm. The pattern of the gain spectrum follows the pattern of its ASE spectrum. The noise figure rises as the input power rises, with a trend of lower noise at a higher input signal wavelength. The gain and noise figure for the Ga-EDF amplifier pumped at 1480 nm was shown in Fig. 6 (b). The overall trend was the same with the 1480 nm-pumped Ga-EDF amplifier. At the input power of -30 dBm, the amplifier achieved the highest gain of 35.77 dB at 1555 nm. Meanwhile, the minimum noise figure was 2.98 dB at 1580 nm. The performance of Ga-EDF at the 0 dBm input power was low as it was limited by its gain saturation level. The Ga-EDF functions on the concept of stimulated emission, where erbium ions absorb pump photons, exciting them to higher energy levels. At a large input signal such as 0 dBm input power, erbium ions approached their maximum absorption capacity and affected their absorption effectiveness. Thus, the high input power leads to reduced absorption of pump photons and reduced population inversion. As the population inversion was limited due to saturation, the gain also decreased. This means that the amplification of the large input signal was not as effective as it was at lower input power levels. Comparing Fig. 6 (a) and Fig. 6 (b), it was also observed that the amplifier's performance does not differ much for the two pump wavelengths (980 nm and 1480 nm), which was as expected from the ASE spectra.

The findings in this paper show that the new double-pass Ga-EDF amplifier can be used in the current optical fiber communication system, which typically carries a 1550 nm signal. It can amplify a -30 dBm telecommunication signal with a gain of 35 dB using either 980 nm or 1480 nm pump laser. However, a 980 nm pump is a better choice if noise is a big concern since 1480 nm causes a slightly higher noise figure.

4. Conclusion

In this research, the gain and noise figure characteristics of a Ga-EDF amplifier in a double-pass configuration were analyzed. The pump wavelengths that are used in this study were 980 nm and 1480 nm. When single-pass and double-pass Ga-EDF amplifiers performance were compared, the overall gain indicated that the double-pass Ga-EDF amplifier performed significantly better than single-pass. The gain was improved by 15.08 dB, while the noise figures are comparable. The capability of the double-pass Ga-EDF amplifier with various input signal power were analyzed. At the -30 dBm input signal power, the 980 nm-pumped double-pass Ga-EDF amplifier achieved the maximum gain of 36.62 dB and the minimum noise figure is 2.04 dB. Overall, the results show that the double-pass configuration has improved the performance significantly, especially for small signal input. It was also observed that the performance at the pump wavelengths of 980 nm and 1480 nm are comparable. In this study, the role of the gallium as the co-dopant in the gain medium is not fully understood because there is no fiber sample without the gallium co-dopant with the same erbium concentration available. This study limits the length of the gain medium to 2 m. A study to determine the optimum fiber length for the amplifier will be conducted in the future.

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Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Siti Azlida Ibrahim, Syafiq Irfan Samsudin, Amilia Mansoor;* ***data collection:*** *Syafiq Irfan Samsudin, Siti Musliha Aishah Musa, Amilia Mansoor;* ***analysis and interpretation of results:*** *Siti Azlida Ibrahim, Amilia Mansoor, Nelidya Md. Yusoff, Syafiq Irfan Samsudin, Katrina D. Dambul, Hairul Azhar Abdul Rashid;* ***draft manuscript preparation:*** *Syafiq Irfan Samsudin, Amilia Mansoor, Siti Azlida Ibrahim. All authors reviewed the results and approved the final version of the manuscript.*

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