

## Simulation of dual stage thulium-doped fiber amplifier using pump power distribution technique

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### ABSTRACT

This paper shows dual stage thulium-doped fiber amplifiers (TDFAs) that use a pump power distribution technique. Simulations were done with signals ranging from 1975 nm to 2000 nm using the OptiSystem v.13 software. The results required were gathered from the software. The results of gain, noise figure, optical signal-to-noise ratio (OSNR) and output power were obtained. The highest gain and lowest noise figure results were achieved for the double pass dual stage TDFA configuration with values of 19.85 dB and 5.58 dB respectively, followed by the single pass dual stage TDFA. The OSNR and output power performances were also better for the double pass dual stage TDFA, obtaining 57.12 dB and 19.55 dBm respectively. This study shows that thulium can be used in the 2  $\mu\text{m}$  region as an active gain medium and the dual stage architecture and distributed pumping technique proves to be effective techniques to obtain the desired results. Experimental work will be done in the future with the simulated results used as a reference.

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## 1. INTRODUCTION

The development of a new and improved access system is one of the advancements in the community of photonics as it satisfies the needs of higher bandwidth particularly the existing 1.55  $\mu\text{m}$  system [1]. Nowadays, there is a need for a vast amount of information measure to enable high speed network services. Therefore, erbium-doped fiber amplifiers (EDFAs) are used greatly in wavelength division multiplexing (WDM) technology that increases the potential of high speed optical network [2] due to their advantages. This results to countless researches being done in previous years.

The rapidly increasing enhancements in communication technology and the requests for wide bandwidth opts for another region of wavelength [3] which is the 2000 nm or 2  $\mu\text{m}$  region [4-5] with thulium-doped fiber lasers (TDFLs) being the suitable candidate [6-8]. Researches are motivated to focus on thulium-doped fibers (TDFs) as numerous applications are done at the 1700-2100 nm region [6, 9-10]. Thulium-doped fiber amplifiers (TDFAs) are being introduced recently due to the limitation capacity [11-14] to operate in a wider waveband as compared to EDFAs, thus garnering a broader gain spectrum [15] and possibly going beyond the conventional 1550 nm region [16-17]. This larger waveband requires higher gain and lower noise figure. The output end of the thulium-doped fiber (TDF) being underpumped causes low population inversion [18] which is a key component in obtaining high gain [19]. The amplified spontaneous emission (ASE) also builds up [20] and not only cause low gain but high noise figure.

In order to obtain sufficient power to excite the thulium ions, dual stage architecture and distributed pumping techniques are implemented. The whole TDF can be pumped more efficiently and therefore reducing the length of underpumped fiber. This way, a large amount of ASE at the middle point of the fiber can be eliminated [21], increasing gain and lowering noise figure.

With regards to the current issues, realising the 2  $\mu\text{m}$  optical communication system can be done with TDFA [22] as it has been proven that it is a good contender to do so. El-Nahal and Husein [23] reported obtaining gain and noise figure values of 15 dB and 2.9 dB respectively using their numerical model. Li et al. reported on their experimental work which have a gain (>35 dB) and noise figure as low as 5 dB when employing a dual stage TDFA [22]. In this research, the OptiSystem v.13 is used to design the TDFA. The gain, noise figure, optical signal-to-noise ratio (OSNR) and output power performances are observed for the whole simulation of a single stage TDFA, single pass (SP) dual stage and double pass (DP) dual stage TDFA's that both use distributed pumping.

## 2. RESEARCH METHOD

Figure 1 shows the single stage configuration. It is used as a reference to compare the other two dual stage with pump distribution configurations. It consists of a continuous wave (CW) laser with an input signal of 0 dBm and an operating wavelength set from 1975 nm to 2000 nm. A 0 dBm signal power is chosen as it corresponds to the channels in dense wavelength division multiplexing (DWDM) system of 40 channels with -16 dBm signal power for each channel. This is to ensure a signal ranging from 1975 nm to 2000 nm is provided for the whole simulation.

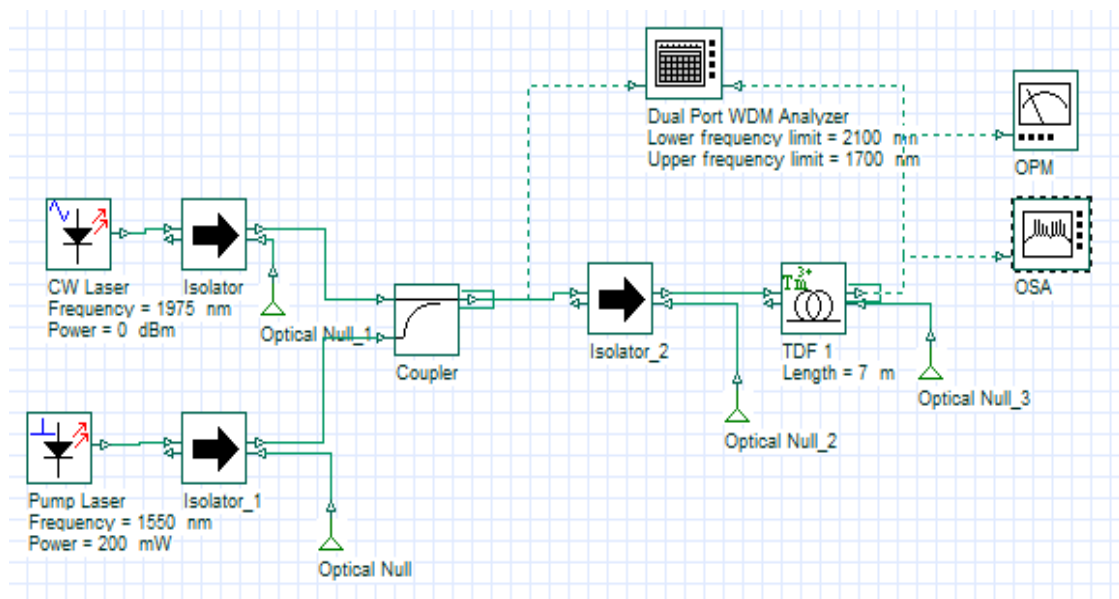


Figure 1. Single stage TDFA

A 1550 nm pump laser pumps the input signal with a pump power of 200 mW. A coupler is used to combine the two signals and pass through to the gain medium. The TDF has a core numerical aperture (NA) of 0.15 and a core/cladding diameter of 9/125  $\mu\text{m}$ . It also has a predicted mode field diameter of 10.5  $\mu\text{m}$  at 2000 nm. All the isolators are used to ensure that the signals are moving in a unidirectional manner. The signal then goes through the active gain medium. 7 meters of thulium-doped fiber (TDF) is used. An optical spectrum analyser (OSA) is connected to the output port of the TDF in order to measure the absorption spectrum of the TDF. An optical power meter (OPM) is also connected to monitor the output power. A dual port wavelength division multiplexer (WDM) analyser is also used in this simulation to monitor the gain, noise figure, OSNR and output power for the whole configuration. The components' setting is set as near as possible to real components. A distributed pumping technique is implemented on two other configurations where in Figure 2 is a SP dual stage TDFA.

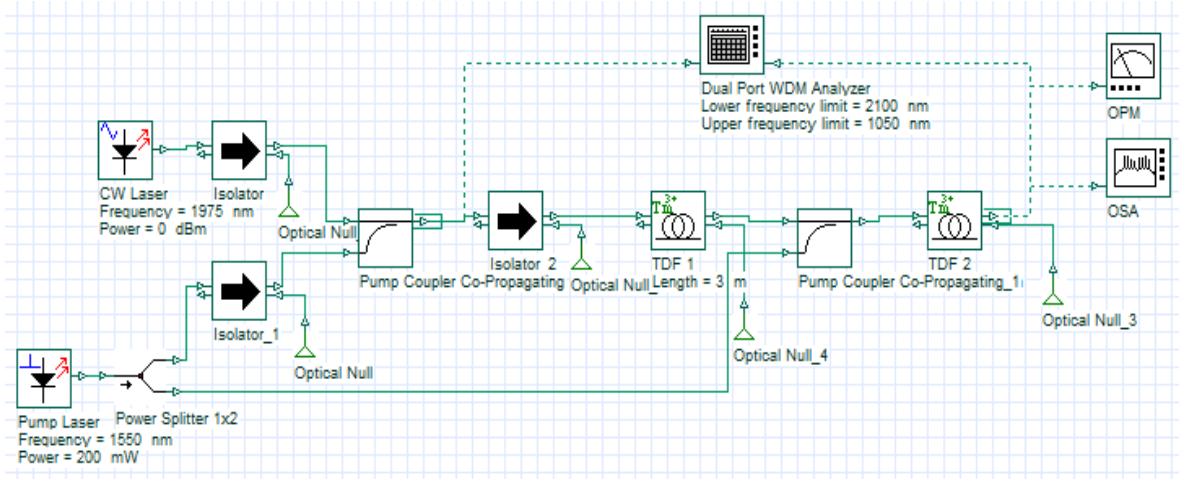


Figure 2. SP dual stage TDF

In Figure 2, the TDF is split into two stages. The first stage consists of a 3 m TDF while the second stage has 4 m of TDF. This way, the setup still has 7 m of TDF. The pump laser is distributed into two where 50% pump power is propagated into the first stage. The other 50% is distributed into the second stage and coupled with the signal from the first stage. Figure 3 depicts a DP dual stage TDF.

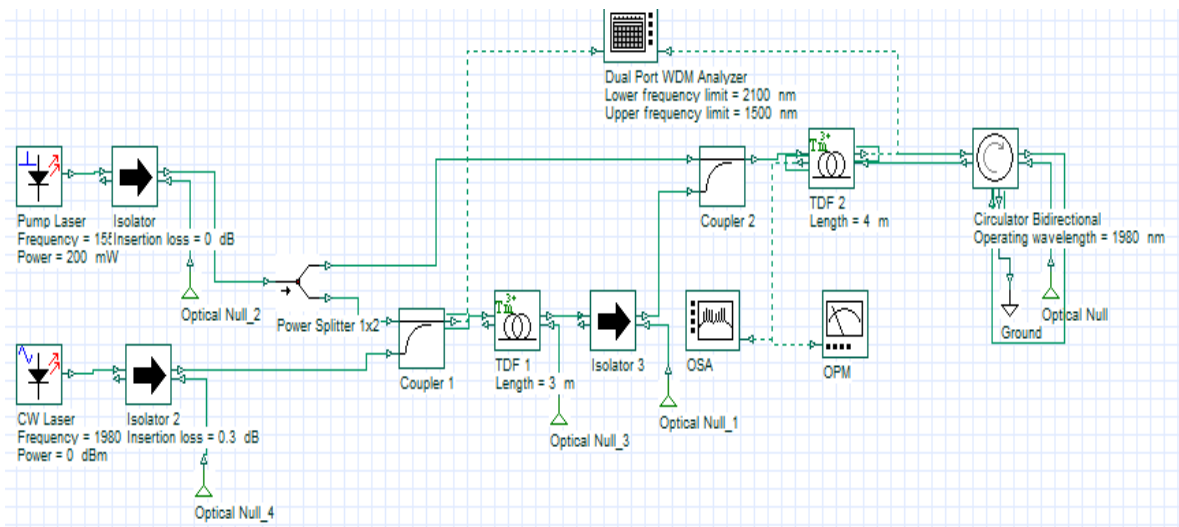


Figure 3. DP dual stage TDF

The DP dual stage TDF is similar to the SP dual stage TDF. However, a circulator is added at the output end of the TDF. In this DP dual stage configuration, the signal to be amplified passes the gain region twice. The circulator routes the signal to the OSA. Using a circulator can prevent backward amplified spontaneous emission (ASE) [24] and amplified signal from propagating into the TDF. The stability of the amplifier is also increased as the circulator suppresses parasitic lasing [25]. The population inversion at the input portion is barely affected by intense lights and therefore keeping the noise figure low [26].

### 3. RESULTS AND ANALYSIS

#### 3.1. Absorption Spectrum

The absorption spectrum of TDF obtained from the simulation is shown in Figure 4. It can be seen that the absorption is at its peak at around 1800-1850 nm.

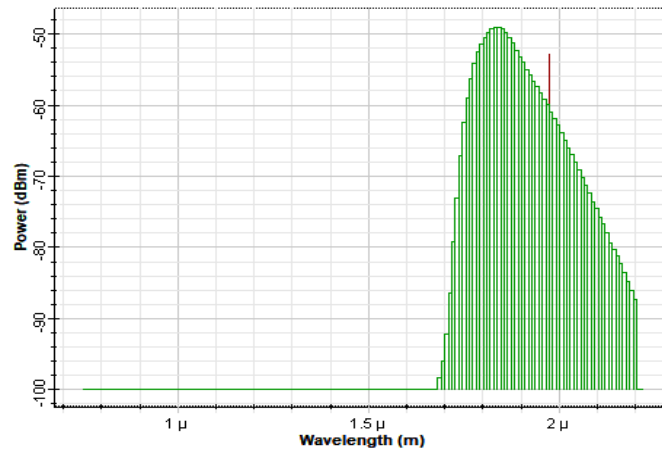


Figure 4. Absorption spectrum of TDF

The dopant ( $\text{Tm}^{3+}$  ions) and the host material, which in this case is silica, affects the absorption and emission responses of the TDFA. The  $\text{Tm}^{3+}$  ions have been absorbed in the host material in this simulation. Being pumped at a wavelength of approximately 1550 nm, the  $\text{Tm}^{3+}$  ions get excited and transition to a higher energy level from the ground state level. This transition from a lower to higher level is called population inversion. The laser is emitted at the higher level. The  $\text{Tm}^{3+}$  ions can be pumped at a wavelength of ~1550 nm due to the ions' transition from the ground level to a higher level and the emission is around the 2  $\mu\text{m}$  region where amplification occurs.

### 3.2. Optimisation

#### 3.2.1 Pump Power

Figure 5 depicts the gain obtained using a single stage TDFA at various pump powers ranging from 100-1000 mW. At the lowest pump power of 100 mW, the maximum gain obtained is 17.53 dB. As the pump power increases, so does the gain. The highest gain is obtained at the maximum pump power of 1000 mW with a value of 29.03 dB. At higher ends of the wavelengths, the gain starts to decrease slightly. This due to the gain becoming saturated. Gain saturation occurs when the full absorption of the pump power happens in that region. The pump is unable to restore the amount of excited ions as quick as the depletion of the ions. Absorption occurs rather than amplification. At the higher ends of the wavelength, the pump photons have been used up for the input portion of the fiber. Hence, the unpumped region. 200 mW is chosen as the pump power since it has the best gain flatness compared to the other pump powers.

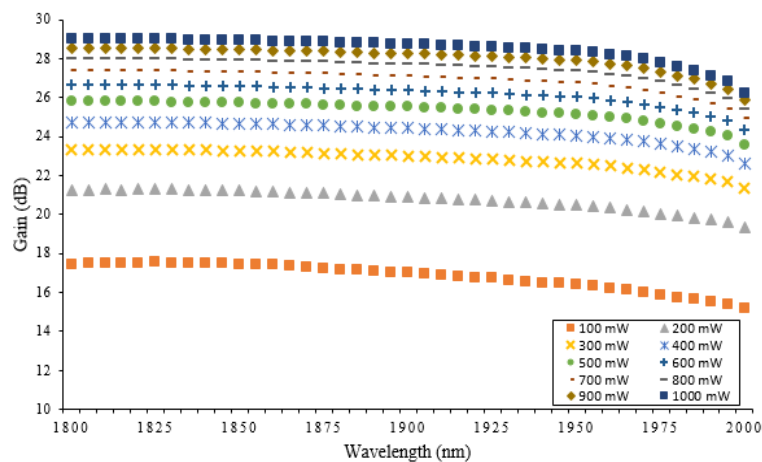


Figure 5. Gain at various pump powers

**3.3. Gain**

The gain performance of the three configurations is depicted in Figure 6. The figure is a plot of gain against wavelength and the values are observed from a signal of 1975 nm to 2000 nm using a 0 dBm input signal. The DP dual stage TDFA obtained the highest gain for the whole signal. At 1975 nm, the maximum gain is 19.85 dB. The gain decreases gradually to its minimum value of 19.14 dB at 2000 nm. The SP pass dual stage TDFA has the next highest value at 1975 nm with 19.55 dB and achieving a minimum of 18.82 dB at 2000 nm. The single stage TDFA has the lowest maximum gain value of the three configurations which is 19.27 dB at 1975 nm and a minimum value of 18.40 dB at 2000 nm. The highest average gain is obtained by the DP dual stage TDFA configuration with 19.54 dB followed by SP dual stage and single stage TDFAs at 19.23 dB and 18.89 dB respectively.

The population inversion is high at the 1975 nm wavelength. The decrease of it is caused by inadequate pump photons to excite the thulium ions. The pump power loses energy over time which causes the number of pump photons to decrease and therefore causing less thulium ions to be excited. The long length of TDF in the single stage TDFA causes some portion of the fiber to be unpumped. The distributed pump power helps to decrease the unpumped region, thus giving higher gain for the dual stage configurations.

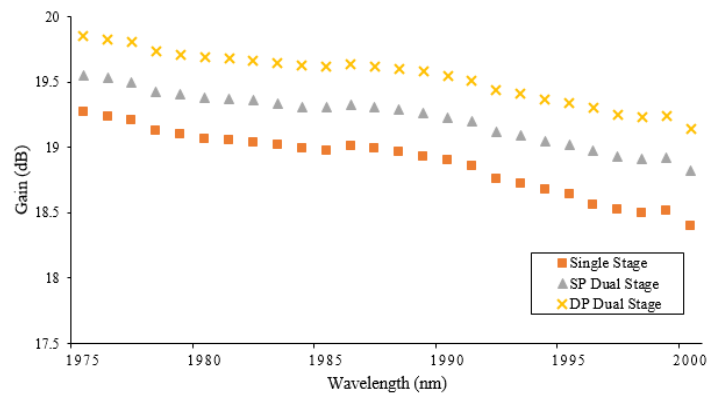


Figure 6. Gain performance of the three configurations

**3.3.1 Gain Saturation**

Based on Figure 7, all three configurations decline in gain from 26 dB to 19 dB when the input signal is varied from -30 dBm to 0 dBm at a wavelength of 1987.5 nm. Unsaturated gain, referring to slight gain variations, occurs at low input signal which in this case varies from -30 dBm to -5 dBm. A saturated point is where a gain reduction of 3 dB (50%) occurs. It is at that point where the gain decreases drastically. As previously mentioned, the inability for the pump to restore excited state ions that are quickly depleting with the addition of more signal photons being applied to the amplifier contributes to gain saturation. By referring to that definition, the input saturation point for all three configurations is noticed to be at approximately -6 dBm.

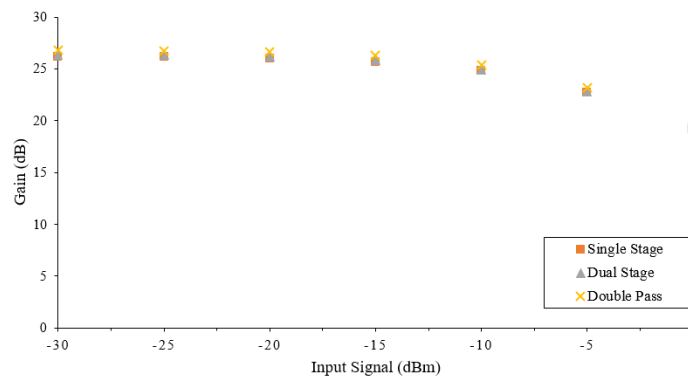


Figure 7. Gain performance at varying input signal

### 3.4. Noise Figure

The noise figure performance of the three configurations is depicted in Figure 8. The figure is a plot of normalised noise figure values against wavelength and the values are observed from a signal of 1975 nm to 2000 nm. The input signal was set at 0 dBm. Among the three configurations, the DP dual stage TDFA obtained the lowest average noise figure for the whole signal which is 5.94 dB. The SP dual stage TDFA has the next lowest average noise figure with a value of 6.21 dB. The highest noise figure is obtained by the single stage TDFA setup with a value of 6.40 dB. It can be concluded that less noise is generated in the two dual stage configurations as compared to the single stage TDFA and the DP dual stage has the lowest average noise figure.

The back end of the TDF in the single stage TDFA configuration is unpumped due to insufficient pump photons which causes minimal population inversion and therefore results in high noise figure readings. In the SP dual stage TDFA setup, the noise figure reduces as the pump power is distributed into the two stages, preventing an unpumped region in the middle of the TDF and unlike the single stage TDFA. For the DP dual stage TDFA, using a circulator can prevent backward amplified spontaneous emission (ASE) and amplified signal from propagating into the TDF. The population inversion at the input portion is barely affected by intense lights and therefore keeping the noise figure low.

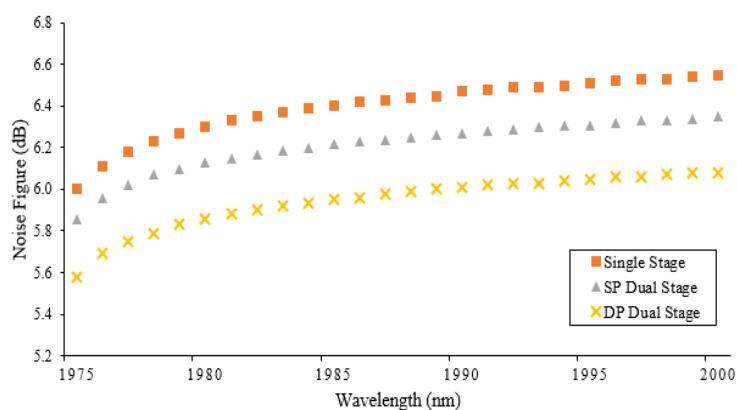


Figure 8. Normalised noise figure performance of the three configurations

### 3.5. Optical Signal-to-Noise Ratio (OSNR)

The OSNR performance of the three configurations is shown in Figure 9 which is a plot of normalised OSNR against wavelength ranging from 1975 nm to 2000 nm. 0 dBm is used as the signal input. The DP dual stage TDFA has a higher peak and average OSNR with a values of 57.12 dB and 56.81 dB respectively. The single stage TDFA has the lowest peak and average OSNR with 56.71 dB and 56.36 dB respectively. The SP dual stage has a peak OSNR value of 56.85 dB and an average of 56.54 dB. The OSNR for all three configurations decreases gradually from 1975 nm to 2000 nm.

The OSNR decreases till it reaches longer wavelengths. The highest OSNR value is obtained when sufficient pump photons are supplied. As the wavelength increases, the number of pump photons decreases as due to insufficient pump power at the longer wavelengths. Furthermore, the noise figure correlates with the decrease of OSNR as the ASE accumulates in the amplifier.

Decreasing the amount of signal photons will cause the peak power-to-noise floor ratio to be reduced. The conversion of pump-to-ASE rate is reduced when higher amount of signal photons is generated. This will result into high output power and low noise floor. On the other hand, the gain keeps decreasing as a result from saturation effect as the signal power increases.

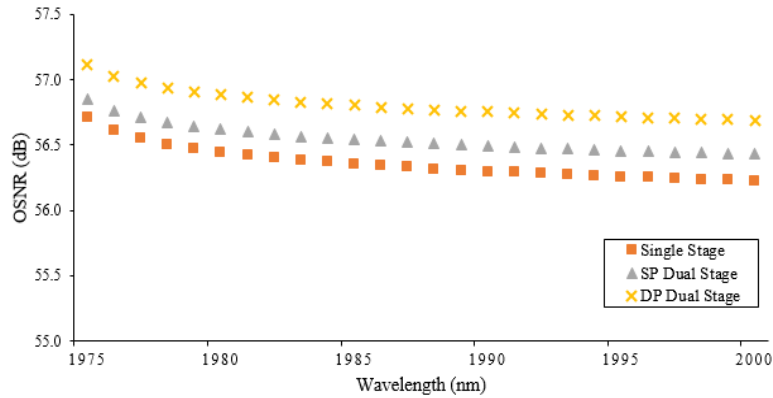


Figure 9. Normalised OSNR performance of the three configurations

**3.6. Output Power**

Figure 10 illustrates the output power performance of the three configurations. It is a plot of output power against wavelength that has a range of 1975 nm to 2000 nm. The input signal is also 0 dBm. The highest output power is obtained by the DP dual stage TDFA with 19.55 dBm followed by the SP dual stage and single stage TDFAs with their respective values of 19.25 dBm and 18.97 dBm. It is shown here that a dual stage setup gives a higher output power as compared to a single stage arrangement.

The output power decreases as it reaches longer wavelengths. It could be predicted that gain saturation occurs and the TDFA performance can be affected. This also indicates that increasing the pumping power will not only unable to increase the output power but also the gain.

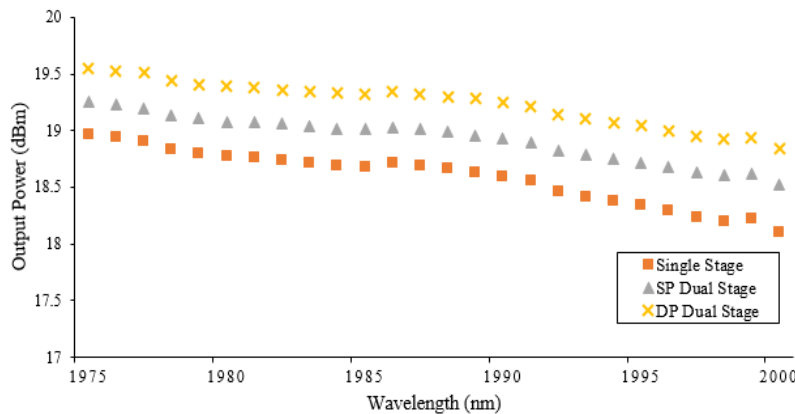


Figure 10. Output power performance of the three configurations

**4. CONCLUSION**

A single stage TDFA and dual stage TDFAs with pump distribution technique at 2 μm over a signal wavelength ranging from 1975 nm to 2000 nm were simulated using OptiSystem v.13. The dual stage TDFAs with pump distributed technique was done using a SP and DP architecture. The dual stage configurations produced good results in terms of gain, noise figure, OSNR and output power. The DP dual stage TDFA configuration yielded high average gain and low noise figure with 19.85 dB and 5.58 dB respectively, which are highly desirable in an amplifier. The simulation also obtained high OSNR and output power from the DP dual stage TDFA setup with values of 57.12 dB and 19.55 dBm respectively. This research indicates that thulium can be used as an active gain medium in the 2 μm wavelength region. A dual stage architecture and distributed pumping technique also contribute in achieving high gain and low noise figure. The results from the simulations in this paper will be compared to experimental works that will be done in the future.

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## REFERENCES

- [1] N. M. Sharif *et al.*, “Thulium-Doped Fiber Amplifier at Near 2000 nm with Different Pumping Scheme,” *Advanced Science Letters*, vol. 23, pp. 5260-5263, 2017.
- [2] U. J. Sindhi *et al.*, “Gain Optimization of EDFA for WDM System,” *Communication and Signal Processing, 2017. ICCSP 2017*. Available from: IEEE.
- [3] N. Simakov *et al.*, “Holmium Doped Fiber Amplifier for Optical Communications at 2.05 - 2.13  $\mu\text{m}$ ”, *Optical Fiber Communication Conference, 2015. OFC, 2015*. Available from: Optical Society of America.
- [4] M. A. Khamis and K. Ennsner, “Gain control dynamics of thulium-doped fiber amplifier at 2  $\mu\text{m}$ ”, *Optical Components, and Materials XIII*, 2016, vol. 9744, pp. 974419. Available from: International Society for Optics and Photonics.
- [5] Z. Liu *et al.*, “High-capacity directly modulated optical transmitter for 2- $\mu\text{m}$  spectral region”, *Journal of Lightwave Technology*, vol. 33(7), pp. 1373-1379, 2015.
- [6] D. J. Richardson *et al.*, “High power Fiber Lasers: Current Status and Future Perspectives,” *Journal of the Optics Society of America B*, vol. 27, B63-B92, 2010.
- [7] J. Wang *et al.*, “Broadband Silica-based Thulium Doped Fiber Amplifier Employing Multi-wavelength Pumping,” *Optics Express*, vol. 24, pp. 23001-23008, 2016.
- [8] D. Hanna *et al.*, “Efficient and Tunable Operation of a Tm-doped Fibre Laser,” *Optics Communications*, vol. 75, pp. 283-286, 1990.
- [9] S. D. Emami *et al.*, “1700 nm and 1800 nm band tunable thulium doped mode-locked fiber lasers”, *Scientific reports*, vol. 7(1), pp. 12747, 2017.
- [10] A. M. Heidt, Z. Li, and D. J. Richardson, “100kW peak power picosecond thulium-doped fiber amplifier system seeded by a gain-switched diode laser at 2 $\mu\text{m}$ ”, *Optics Letters*, vol. 38(10), pp. 1615-1617, 2013.
- [11] M. Heidt, Z. Li and D. J. Richardson. “High Power Diode-Seeded Fiber Amplifiers at 2  $\mu\text{m}$ -From Architectures to Applications”, *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 20(5), pp. 525-536, 2014.
- [12] Z. Li *et al.*, Jung, “Extreme Short Wavelength Operation (1.65 - 1.7  $\mu\text{m}$ ) of Silica-Based Thulium-Doped Fiber Amplifier”, *Optical Fiber Communication Conference, 2015. OFC 2015*. Available from: Optical Society of America.
- [13] H. Zhang *et al.*, “100 Gbit/s WDM transmission at 2  $\mu\text{m}$ : transmission studies in both low-loss hollow core photonic bandgap fiber and solid core fiber”, *Optics Express*, vol. 23(4): pp. 4946-4951, 2015.
- [14] M. Yamada, H. Ono, and J. Ono, “1.7  $\mu\text{m}$  band optical fiber amplifier”, *Optical Fiber Communication Conference, 2014*. Available from: Optical Society of America.
- [15] Z. Li *et al.*, “Diode-Pumped Wideband Thulium-Doped Fiber Amplifiers for Optical Communications in the 1800 – 2050 nm Window,” *Optics Express*, vol. 21, pp. 26450-26455, 2013
- [16] H. Fatehi *et al.*, “Analytical model for broadband thulium-bismuth-doped fiber amplifier”, *IEEE Journal of Quantum Electronics*, vol. 48(8), pp. 1052-1058, 2012.
- [17] S. D. Emami *et al.*, “Thulium doped fiber laser utilizing a photonic crystal fiber-based optical low-pass filter with application in 1.7  $\mu\text{m}$  and 1.8  $\mu\text{m}$  band”, *Optics Express*, vol. 23(15), pp. 19681-19688, 2015.
- [18] N. M. Yusoff *et al.*, “Dual-stage L-band erbium-doped fiber amplifier with distributed pumping from single pump laser,” *Optics Communications*, vol. 285, pp. 1383-1386, 2012.
- [19] Y. Jung *et al.*, “Silica-based thulium doped fiber amplifiers for wavelengths beyond the L-band,” *Optical Fiber Communications Conference and Exhibition, 2016. OFC 2016*. Available from: IEEE.
- [20] N. M. Yusoff *et al.*, “Bidirectional-pumped L-band erbium-doped fiber amplifier with pump distribution technique,” *Laser Physics*, vol. 22, pp. 1252-1256, 2012.
- [21] P. C. Becker, A. A. Olsson, and J. R. Simpson, “*Erbium-Doped Fiber Amplifiers, Fundamentals and Technology*”. Academic Press. 1999.
- [22] Z. Li *et al.*, “Thulium-doped Fiber Amplifier for Optical Communications at 2  $\mu\text{m}$ ,” *Optics Express*, vol. 21, pp. 9289-9297, 2013.
- [23] F. I. El-Nahal and A. H. M. Husein, “Thulium Doped Fiber Amplifier (TDFA) for S-band WDM Systems”, *Open Journal of Applied Sciences*, vol. 2(4), pp. 5, 2013.
- [24] A. M. Markom *et al.*, “Performance comparison of enhanced Erbium–Zirconia–Yttria–Aluminum co-doped conventional erbium-doped fiber amplifiers”, *Optik-International Journal for Light and Electron Optics*, vol. 132, pp. 75-79, 2017.
- [25] Z. Li *et al.*, “Extreme short wavelength operation (1.65-1.7  $\mu\text{m}$ ) of silica-based thulium-doped fiber amplifier”, *Optical Fiber Communication Conference, 2015. OFC 2015*. Available from: Optical Society of America.
- [26] S. W. Harun, N. M. Samsuri, H. Ahmad, “Gain-clamping techniques in two-stage double-pass L-band EDFA”, *Pramana*, vol. 6(3), pp. 539-545, 2006.



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