Design and Optimization of S-band Fiber Amplifier (1450-1530nm)

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Abstract. In the current era of rapid development of information technology, people need larger capacity and faster ways to improve communication transmission efficiency. In order to seek more efficient transmission rates, people began to study the optical transmission of signals. Thulium doped fiber amplifiers are an important research topic in the field of communication. Presently, L-band and C-band TM-doped optical amplifier have been developed into commercial applications. The S-band approaches the common C band. So it is very important to study S band Ti-doped Fibre Amplifier in order to enlarge the bandwidth and increase the communication capability. By utilizing 1400 nm single-wavelength pumping technique, the gain for the wideband S-band (1450-1530 nm) in thulium-doped fluor tellurite glass fiber has been optimized. Genetic algorithms have been employed to analyze and optimize the parameters of fiber length and doping concentration for thulium-doped fluoride tellurite glass fiber. It is shown that the maximal gain can be obtained when the dopant concentration is high enough. Therefore, thulium-doped fluoride tellurite glass fiber is a promising and potential gain medium that can be used for constructing efficient wideband S-band fiber amplifiers.

Keywords: S-band, Thulium-Doped Fiber Amplifiers, Gain, Genetic algorithm.

1. Introduction

As scientific and technological progress continues to improve, the increasing demand for transmission system capacity has put the current data servers under immense pressure. The existing transmission communication capacity is insufficient to meet the needs of people, and ordinary metallic media can not accommodate a large amount of information. Subsequently, it was discovered that optical communication offers faster rates and greater capacity than previous metallic methods. Consequently, research has been conducted in optical fibers and semiconductor communication over the past decades to achieve higher gains in thulium-doped fiber amplifiers. In order to study the maximal FM-TDF (Fiber Mode-TDMA Filtering) (Fiber Mode-TDMA Filtering) [1] with various pumping modes and strengths, some researchers have used Super Gauss Thd Doped Optical Fibre Amplifiers for multi-mode multiplex in S Band. Later, it was proposed that thulium-doped fiber amplifiers hold the greatest potential in the S-band. It was found that using a dual-wavelength pumping technique (1400-1570 nm) in thulium-doped Tm*-fluoride tellurite glass fiber amplifiers (TDFTFs) can provide better optical amplification performance for the S-band (1480-1530 nm). As early as the 1960s, a good understanding of the spectroscopic properties of thulium (Z=69) in crystals had been achieved[2]. The TDFA (Thulium-Doped Fiber Amplifier), known for its high performance and practicality, was selected as the research basis for matrix materials. Subsequently, TDFTFs were discovered to offer modularity, extra bandwidth, higher pumping efficiency, lower degradation of nonlinear signals, and higher gains for the S-band. The length and doping concentration of TDFTFs are crucial parameters determining the achievable gain. At present, the R&D of Thallium Doped Amplifier (TDFA) for S and Gain Shift Thallium (GS-TDFA) has become a hotspot in the field of fibre communication [3, 4].

This paper provides a detailed description of the optimization of TDFA gain using rate equations as well as power propagation equations, along with the implementation of genetic algorithms and three-dimensional plotting.

2. Theory of the TDFTFs

This paper provides a detailed exploration of the optimization of gain in TDFTFs (Thulium-Doped Fiber Amplifiers), Potential gain medium for building effective broadband S-band fiber amplifiers. The combination of S-band fiber amplifiers using TDFTFs with developed L-band (1565-1625 nm) and C-band (1530-1565 nm) erbium-doped fiber amplifiers (EDFAs) has attracted significant attention due to its potential to expand transmission capacity and raise the number of channels in long-haul photon networks employing wavelength-division multiplexing (WDM) transmission. Various technologies have been employed for the amplification of S band, such as Tm* Doped Fibre Amplifier (TDFA), Semi-Conductor Optics Amplifier, EDFA, Raman Fibre Amplifier and BDFA (BDFA) [1-12]. TDFA has been applied extensively in S band due to its outstanding power transmission properties. The S-band amplifying source is subjected to a stimulated emission transition from $_3H^4$ to $_3F^4$. Due to the high phonon energy of silicon glass, Tm^{3+} is not suitable for constructing efficient S band optical amplifiers [11,12]. At present, the S-band TDFA is mainly concerned with the Tm*-doped fluoro-glass fibre with relatively low phonon energy [1-5]. In 1995, Komukai et al reported that a Tm^{3+} doped fluoro-glass-fibre amplifier, which had been pumped at 1064 nm. and obtained a gain above 10 dB in the 1440 to 1510 nm range. [1]. To improve the gain capability of the system and to make it more widely used in S band, a new type of high - thulium density doping and double wavelength pumping technique has been developed [3-5]. In 2002, Kasamatsu et al showed that the TDFTFs, which were pumped with 1400 nm and 1560 nm laser diodes, had a maximum output of 21.5 dBm and an efficiency of 29.3 percent [4]. The influence of Tm^{3+}doping density upon the gain bandwidth of S-band TDFA was systematically studied in 2007 by Aozasa et al. . Their gain was 26 dB, and the noise value was less than 7 dB at a wavelength of 1480 to 1510 nm with a Tm^{3+}density of 4000 ppm. [5]. Although advances have been made in this area, the gain bandwidth for a single fluoro fiber based TDFA is still very narrow (-40 nm). Unlike fluorio glass, it has a higher stability and broader gain properties, suggesting that Tm * -doped tellurite glass fibers are suitable to build broadband S-band amplifiers. Composed of fluoro tellurite glass, these fibers possess advantages such as large transmission window, excellent thermal and chemical stability, high solubility of REE, and wide stimulated emission cross-section.

3. Theory of the Genetic algorithm

The impact of genetic algorithms on the amplifier performance, along with other factors, was explored. The analysis included the effect of fiber length and doping concentration parameters on the bandwidth and amplifier gain, which were incorporated into the optimization process of genetic algorithms.

In the context of genetic algorithms, the problem was first clearly defined in this research project, including optimization objectives, constraints, and adjustable parameters. The goal was to maximize the gain and bandwidth of the fiber amplifier while establishing reasonable range limitations. A fitness function was developed in MATLAB to evaluate the performance of individual chromosomes. This function took a chromosome as input and returned a fitness value reflecting its quality concerning the objectives[5].

A function for generating random numbers was used to initialize an initial population of multiple chromosomes, each representing a set of potential parameter combinations. Through a series of genetic algorithm operations such as selection, crossover, and mutation, the chromosomes in the population were gradually optimized through multiple generations of iterations. In each generation,

chromosomes were evaluated based on the fitness function, and superior individuals were selected for reproduction and evolution based on their fitness values.

Appropriate termination conditions were set, such as reaching the maximum number of iterations, convergence of fitness values, or meeting specific threshold criteria. Once the termination conditions were met, the algorithm stopped and returned the best chromosome as the optimization result.

After the optimization process, the obtained best chromosome was analyzed and validated. The resulting parameter configuration for the fiber amplifier was applied, and the optimized results from the genetic algorithm were verified using cross-validation methods. By comparing the optimized amplifier model with the three-dimensional simulated S-band signal, it was confirmed that the optimized amplifier indeed exhibited improved performance.

4. Computing Method

Figure 1 illustrates the analysis of a three-level system, specifically the energy levels of Tm^{3+} in fluoro tellurite fibers. The emission and absorption transitions of TDFTFs at a pumping wavelength of 1400nm are shown in Figure 2(a) and (b). In the S-band amplification, the primary transition occurs from the $_3H^4$ level to the $_3F^4$ level. Within the 1400nm range, electronic excitation to higher energy states is achieved via excited state absorption (ESA) on the $_3F^4$ level. On the other side, to populate the $_3H^5$ level from the state $_3H^6$ via non-radiative relaxation, the ground state absorption (GSA) on the $_3H^6$ level must be non-zero, considering 1400nm as the main excitation source. Raising the input signal power further populates the state 3F4, as the pump power exceeds the threshold, promoting the excited ions from the lower level ($_3H^4$) to the higher level ($_3H^4$). The pumping transition to the $_3F^4$ level involves the energy levels $_3F^3$ and $_3F^2$,which seem quite close and could be approximated as a single level for simplicity. Therefore, the excited ions at the $_3F^4$ level are re-excited to the $_3F^2$ level and undergo non-radiative decay to the $_3H^4$ level via excited-state absorption [12,13].

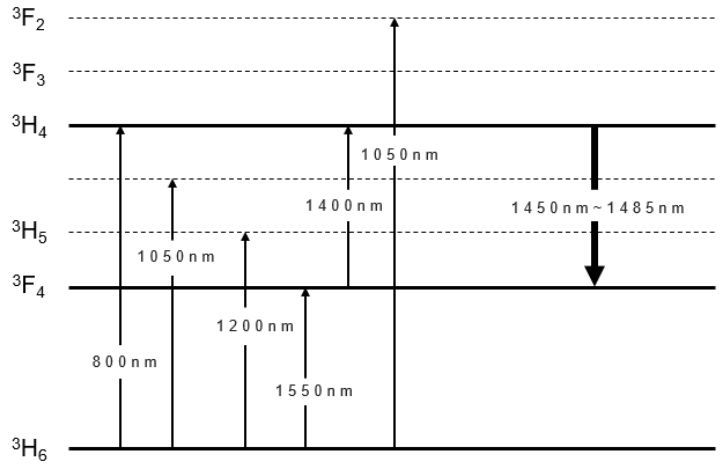


Figure 1. Energy levels with pumping mechanism 1400 nm of Tm^{3+} in fluoro glass.

The power propagation equation and rate equation for calculating the gain are given as follows [3]:

$$\frac{\partial N_1(z)}{\partial t} = -[W_p(z) + W_{12}(z)]N_1(z) + A_{21}N_2(z) + W_{21}(z)N_2(z) \tag{1}$$

$$\frac{\partial N_2(z)}{\partial t} = W_{12}(z)N_1(z) - W_{21}(z)N_2(z) - A_{21}N_2(z) + A_{32}N_3(z) \tag{2}$$

$$\frac{\partial N_3(z)}{\partial t} = W_p(z)N_1(z) - A_{32}N_3(z) \tag{3}$$

$$N = N_1(z) + N_2(z) + N_3(z) \tag{4}$$

W_P, W_12 , W_21, A_32, A_21 are respective rates, pumping light absorption rate, the spontaneous emission light absorption rate, the stimulated emission rate, the non-radiative transition rate, and the radiative transition probability. (in units of s-1)

$$\frac{dP_p(z)}{dz} = (-\sigma_p N_1(z) - \alpha_a) P_p(z) \tag{5}$$

$$\frac{dP_s(z)}{dz} = [\sigma_{21} N_2(z) - \sigma_{12} N_1(z) - \alpha_s] P_s(z) \tag{6}$$

$$\frac{dP_{ase}(z)}{dz} = [\sigma_{21} N_2(z) - \sigma_{12} N_1(z) - \alpha_s] P_{ase}(z) + \sigma_{21} N_2(z) h\upsilon \Delta\upsilon \tag{7}$$

$$P_s(z) = f(P_p(0), P_s(0), N, z) \tag{8}$$

α represents the fiber material's loss coefficient (/m), while Δv represents the frequency half-width at half-maximum (Hz).

5. Results and Discussions

The S-band range for this system is 1450 ~ 1530 nm. Table 1 are the parameters which is used in the simulation.

Table 1. The parameters used in the simulation. [4]

Parameter	**Value**	**Units**
Doping concentration	$1.6x10^{24}$- $2x10^{\wedge 25}$	
Fiber length	1-10	m
Signal light emission cross-section	$1x10^{-24}$	m^3
Signal light absorption cross-section(m^3)	$1x10^{-24}$	m^3
Spontaneous emission rate from $_3H^5$ to $_3F^4$	515.76	S^{-1}
Spontaneous emission rate from $_3H^4$ to $_3H^5$	2496.10	S^{-1}
Pump stimulated emission cross-section	$4.05x10^{-21}$	cm^3
Pump absorption cross-section	$3.34x10^{-21}$	cm^3
Pump wavelength	1400	nm
Signal light wavelength	1480	nm
Pump power	200mw	mw
Signal power	-30	dBm

The genetic algorithm results as shown in Figure 2-4.

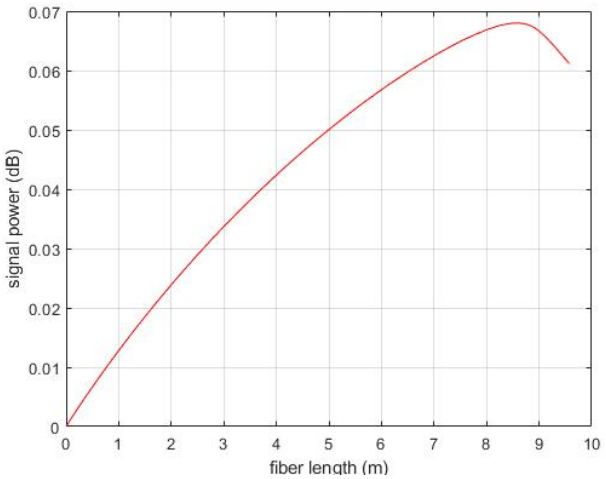


Figure 2. Signal optical power and fiber length genetic algorithm mapping.

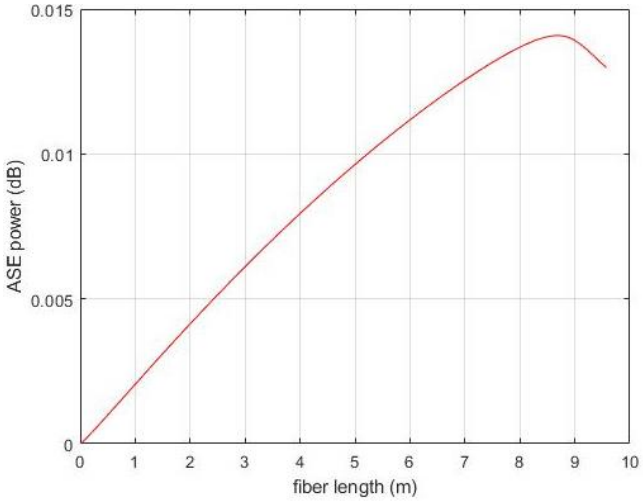


Figure 3. ASE optical power and fiber length genetic algorithm mapping.

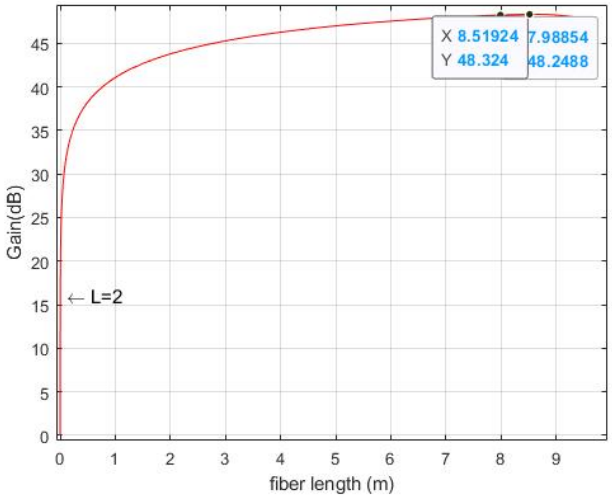


Figure 4. Gain and fiber length genetic algorithm mapping.

When the signal light passes through the fiber amplifier, the doped material within it absorbs the signal light, amplifies it, and emits it. The amplifier's gain depends on the concentration of the doping material and the fiber's length. Along with the growth of fibre length, the gain of the amplifier is also increased. However, as the fiber length increases, the gain starts to decrease. When the fiber length is less than 8.5722m, the gain increases with the length of the fiber, reaching 48.244dB at 8.5722m. When the fiber length is more than 8.5772m, however, the gain decreases with the fiber length.

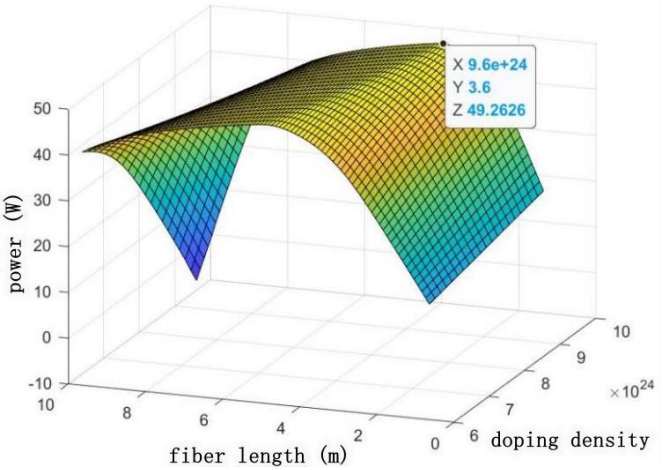


Figure 5. 3D plot of gain versus fiber length and concentration

Assuming a pump power of 200mW, the gain spectrum can be calculated using MATLAB, considering the variation in fiber length and doping concentration. The 3D drawing results are shown in Figure 5. When the values are L = m and N = 9.6 x 10^24 m^(-3), the peak gain is 39.1294dB. The results obtained from the genetic algorithm optimization were validated using cross-validation. By comparing the optimized amplifier model with the three-dimensional simulated S-band signal, the optimized amplifier indeed exhibits improved performance. The results indicate that the optimal values for achieving the maximum gain are a fiber length of 8.5722m and a doping concentration of 9.6 x 10^24 m^(-3).

6. Conclusion

This paper provides a detailed description of the relationship between the pump power at 1400nm and the length and doping concentration of the thulium-doped fluoride tellurite fiber (TDFTFs) in single-pass TDFTFs systems. The gain of TDFTFs is determined based on rate and power propagation equations. It was found through optimization using a genetic algorithm that the best performance is achieved when the TDFTFs length is 8.5722m and the doping concentration is 9.6x10^24m-3.

Thulium-doped fluoride tellurite fiber amplifiers can achieve good signal gains for the S-band (1460-1530nm) in fiber-optic communication. Considering factors such as stability, these amplifiers have the potential for future commercial use. This research provides valuable insights for further developments in optical communication and is expected to play an important role in fiber-optic communication systems.

In conclusion, our research results demonstrate that thulium-doped fluoride tellurite glass fibers are promising materials with excellent gain characteristics for constructing efficient S-band fiber amplifiers. However, there are limitations in the current study, such as the lack of physical contact with the materials, as it was only a theoretical verification. Future research should focus on exploring these materials in practical applications.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

References

[1] NKONDE Sampa, JIANG Chun J. Shanghai Jiao Tong Univ. (Sci.), 2018, 23(3): 352-359.

[2] T. Komukai, T. Yamamoto, T. Sugawa, and Y. Miyajima, IEEE J.Quantum Electron. 31, 1880 ,1995. W.J. Minisecalo, J . Lightwave, Technol. 9,234 1991.

[3] Muzhi Cai, Yu Lu, Ruijie Cao, Ying Tian, Shiqing Xu, Junjie Zhang, Optical Materials,2016, 236-242.

[4] F. Roy, D. Bayart, C. Heerdt, A. L. Sauze, and P. Baniel, Opt. Lett. 27, 10 ,2002.

[5] S. Aozasa, H. Masuda, M. Shimizu, and M. Yamada, J. Lightwave Technol. 25, 2108 ,2007.

[6] E. M. Dianov, Light: Sci. Appl. 1, e12 ,2012.

[7] A. Donodin, V. Dvoyrin, E. Manuylovich, L. Krzczanowicz, W. Forysiak, M. Melkumov, V. Mashinsky, and S. Turitsyn, Opt. Mater. Express 11, 127 ,2021.

[8] H. Ahmad, M. Z. Zulkifli, N. A. Hassan, A. A. Latif, and S. W. Harun, Laser Phys. 21, 1208 ,2011.

[9] M. N. Islam, IEEE J. Sel. Top. Quantum Electron. 8, 548 ,2002.

[10] G. Qin, R. Jose, and Y. Ohishi, J. Lightwave Technol. 25, 2727 ,2007.

[11] P. R. Watekar, S. Ju, and W.-T. Han, IEEE Photonics Technol. Lett. 18, 2035 ,2006.

[12] P. R. Watekar, S. Ju, and W.-T. Han, J. Lightwave Technol. 25, 1045 ,2007.

[13] M. Naftaly, S. Shen, and A. Jha, Appl. Opt. 39, 4979 ,2000.