# Design and Optimisation of S-band fibre optic amplifier

Juncen Li *

College of Computer Science and Electronic Engineering, Hunan University, Changsha, China

* Corresponding author: ljc20030405@hnu.edu.cn

**Abstract.** S-TDFA (S-band thulium-doped fibre amplifier) is a device that uses thulium-doped fibre to achieve the enhancement of optical signals in the S-band (1450-1530 nm), which is of great significance in long-distance optical communication systems, providing high gain, low noise and a wide range of wavelengths. Nowadays, thulium-doped fibre amplifier is one of the research hotspots of fibre-optic communication devices, and how to obtain high signal gain is also of great significance and value.In this paper, based on the energy level structure of thulium ion, the electron jump process, and the characteristics of tellurite glass medium, two physical models, namely, the rate equation of thulium ion's three energy level structure and the power propagation equation, are established.Under the power of 793 nm pump light, 1470 nm signal light and 200 mW pump light, the maximum signal gain of thulium-doped tellurite is 48 dB when the length of the optical fibre is 1.42 m and the thulium-doped ion concentration is $\mathbf{1.7 * 10^{26}}$ ions per square metre, combined with the numerical solution in MATLAB and optimized peak value using a genetic algorithm.

**Keywords:** S-band, Thulium-doped, Tellurite fibres, Fibre length.

## 1. Introduction

With the development of optical fibre communication technology, the demand for S-band (1450 nm~1530 nm) optical amplification is increasing, and there are energy level transitions in the energy level structure of $Tm^{3+}$that satisfy S-band optical amplification. Meanwhile, the study of S-band fibre-optic amplifiers is beneficial to expand the communication bandwidth and increase the communication capacity. However, China's thulium-doped fibre amplifier started late compared with foreign countries, but thulium-doped fibre amplifier (TDFA) is one of the most promising laser amplifiers in S-band, which is of great significance and value for the expansion of the communication window of the fibre optic communication system to S-band. In S-band applications, S-band fibre optic amplifiers have high noise figure requirements. Various parameters of the fibre optic amplifier have a great influence on the signal gain, and the study of the signal gain of the fibre optic amplifier under different conditions allows for continuous optimization of the amplifier. In recent years, people have been exploring and optimizing S-band fibre optic signal amplifiers from various aspects, such as amplifier structure, noise figure, signal gain, output stability, pumping efficiency, and so on. Therefore, a thulium-doped fibre amplifier is one of the research hotspots of fibre optic communication devices.2021 Rajandeep Singh and Maninder Lal Singh [1] investigated thulium-based S-band optical amplification optical amplifier to observe the effect of change in doping radius and doping concentration on gain. In 2022, S.H. Kazemi [2] et al. investigated the effect of different parameters of fibre optic amplifiers on the signal gain by the establishment of rate equation and power propagation equation. Therefore, in this paper, according to the S-band signal wavelength range, thulium-doped tellurite glass medium ($75TeO_2 02: 10ZnO: 15Na2Na_2O$), the energy level structure and the electron jump process design the pump wavelength of 793 nm, the signal light wavelength of 1470 nm, the establishment of rate equations and power propagation equations. The variation of the gain spectrum with fibre length and doping concentration is calculated using MATLAB programming at a pump power of 200mW, and genetic algorithm is used to optimize the fibre length and doping concentration to maximise the peak gain.

## 2. Models and Methods

Fibre optic amplifier is an optical signal amplifier using rare earth ion doped optical fibre as a gain medium, and the basic theory of thulium-doped fibre amplifier is also applicable to fibre optic amplifiers. The gain of thulium-doped fibre amplifiers has a very important relationship with the pumping mode of the amplifier, the choice of substrate, the length of the fibre and the spectral properties of thulium ions. To achieve efficient amplification of communication laser signal output, a fiber amplifier must make the gain medium in the particle number inversion state. Therefore, to achieve the particle number inversion, the gain medium must provide external energy as a pump source so that the dopant ions in the gain medium absorb the external pump energy from the low energy level jump to a higher energy level.

According to the energy level structure of the doped ions in the optical fibre and the different wavelengths of the pump light, the optical fibre amplifiers can be mainly classified into two-energy level systems, three-energy level systems and four-energy level systems, etc. The three-energy level system of thulium ions as shown in Figure 1 is utilized here. The particles in the ground state energy level E1 absorb the pump light energy and then jump to the high energy level E3. At the same time, the particles in the E3 energy level will be rapidly transferred to the substable E2 energy level by spontaneous radiative jump. Due to the longer particle lifetime of the E2 energy level, the particles in the ground state energy level continuously jump to the E2 energy level under the action of the pumping source so that the number of particles on the E2 energy level continues to accumulate, and ultimately realize the number of particles between the E2 energy level and the lower energy level of the E1 inversion. Finally, the signal light passing through the amplifier is effectively amplified. Trivalent thulium ions can absorb many different wavelengths of pump light to make the ions undergo excitation, which results in the excitation of different wavelengths of stimulated radiation. Among them, the laser wavelengths radiated by the excited transitions from $3H_4$to$3F_4$are in the range of 1450 nm-1530 nm, which can exactly cover the optical signals in the S-band.

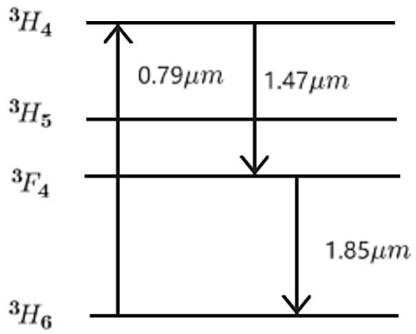



**Figure 1.** $Tm^{3+}$ energy level diagram

Three energy level rate equations:

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

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

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

$$N = N_1(z) + N_2(z) + N_3(z) \quad (4)$$

Three energy level power propagation equations:

$$\frac{dP_p(z)}{dz} = -\Gamma_p(\sigma_p N_1(z) + \alpha_a)P_P(z) \quad (5)$$

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

Specific parameters are explained in Table 1.

**Table 1**. Description of the parameters of the rate equation and power propagation equation

| parametric | Parameter description |
|---|---|
| $W_P$ | Pump light absorption rate |
| $W_{12}$ | Signal light absorption rate |
| $W_{21}$ | Signal light stimulated emission rate |
| $N_1$ | Particle number density in the first energy level |
| $N_2$ | Particle number density in the second energy level |
| $N_3$ | Particle number density in the third energy level |
| $N$ | Total particle number density |
| $A_{21}$ | Radiation jump rate |
| $A_{32}$ | Spontaneous radiation jump rate |
| α | Loss factor of fibre optic materials |
| $\Gamma_p, \Gamma_s$ | Overlapping factor |

A review of the literature [3] shows that in thulium-doped tellurite fibre amplifiers, the absorption cross-section of the pump light is $\sigma_p = 0.89 * 10^{-24} m^2$ and the emission cross-section of the signal light is $\sigma_1 = 0.36 * 10^{-24} m^2$.

Calculation of the absorption cross section from the emission cross section of the signal light:

$$v = \frac{c \times l \times 10^9}{1470} \quad (7)$$

$$\sigma_2(v) = \sigma_1(v) \exp(\frac{\varepsilon_0 - hv}{KT}) \quad (8)$$

The absorbing cross-sectional area is calculated to be $\sigma_2 = 0.36 * 10^{-24} m^2$

So far, the energy level structure of thulium ions, the rate equation, and the power propagation equation are combined as the propagation model of the optical fibre amplifier, and the tellurite ($75TeO_2 O2: 10ZnO: 15Na2Na_2O$) is used as the substrate, and the 793 nm pump light and the 1470 nm signal light are selected as the light sources. The required parameters are calculated and then MATLAB is used to numerically solve for the maximum gain of the signal at the length of the fibre and the concentration of dopant ions respectively. Since this method is time-consuming and not precise enough, a genetic algorithm is used in this study to optimise the fibre length and dopant concentration to maximise the peak gain.

## 3. Literature References

### 3.1. Solve using matlab loop

The 3D image of signal gain variation with fibre length and dopant ion concentration is shown as Figure 2:

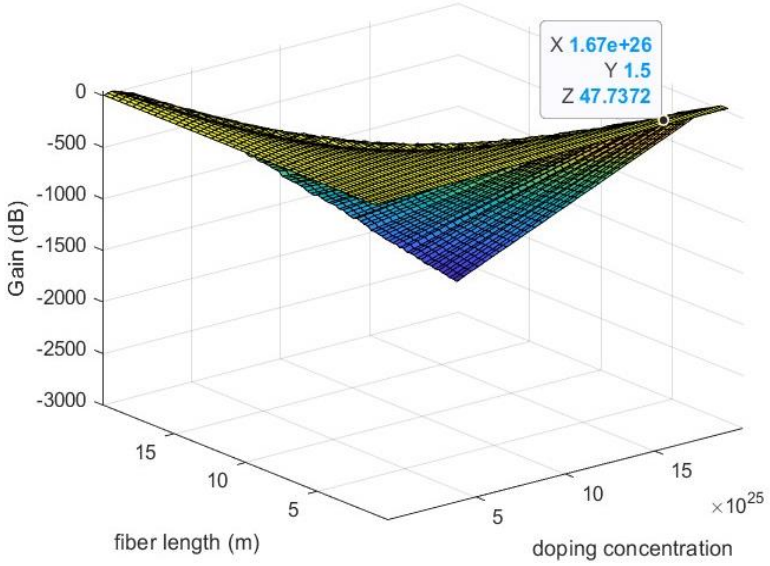



**Figure 2.** Signal Gain 3D Graph

A three-dimensional view of the signal gain with the fibre length and dopant ion concentration is obtained, in which the fibre length is varied at an interval of 0.1. The gain of the fibre amplifier is enhanced with the increase of both the length of the light ray and the concentration of the ion-dopant ions, with a certain length of the fibre, the gain grows positively with the dopant concentration, and no longer grows when it reaches a certain saturation value; and with a certain concentration of the dopant ions, the gain grows positively with the length of the fibre. The gain grows positively with the doping concentration for a certain fibre length and stops growing when it reaches a certain saturation value. Analysis of the images and data shows that the signal gain peaks at about 47.7 dB at a fibre length of 1.5 m and a thulium ion doping concentration of $1.67 * 10^{26}$ ions per square metre. However, this method takes a long time to run and is not accurate enough, so it is optimised using a genetic algorithm.

### 3.2. Optimisation using genetic algorithms

The signal gain image is shown as Figure 3:

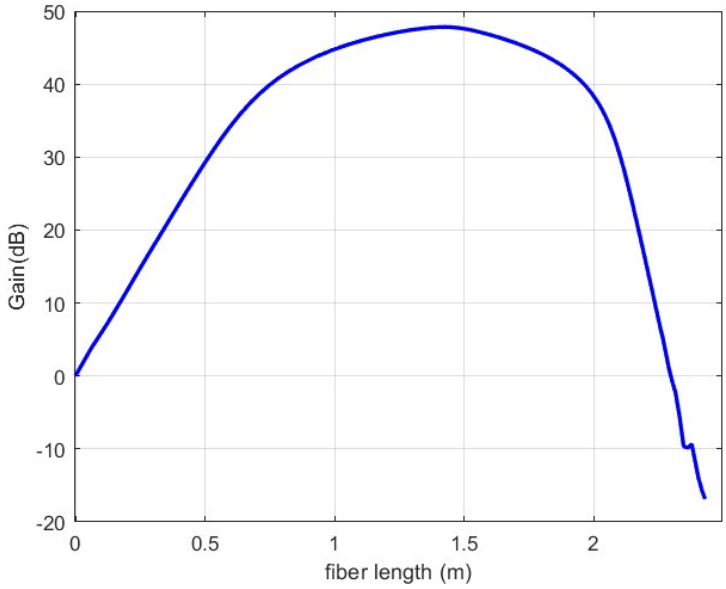



**Figure 3.** Signal gain optimisation results graph

The signal gain firstly increases with the increase of fibre length and ion concentration, but when the fibre length and ion concentration reach a certain level respectively, the signal gain stops increasing to saturation and then decreases with the increase of fibre length and ion concentration.

So, by using MATLAB as well as image solving it is obtained that the maximum signal gain is 48dB when the length of the fibre is 1.43m and the concentration of dopant ions is $\mathbf{1.7 * 10^{26}}$ ions per square metre. Comparison of the results is similar to those of the three dimensional images.

## 4. Conclusion

In this paper, the rate equation and power propagation equation of thulium-doped tellurite fiber amplifier under pump light and signal light are established by studying and analyzing the spectral properties and energy level structure characteristics of thulium ions and the structural characteristics of thulium-doped tellurite fiber amplifier, the rate equation and the power propagation equation are solved, and the optimization of the peak gain using genetic algorithms obtains the following results: when the length of the fiber is 1.43 m, the thulium-ion doping concentration is $1.7 * 10^{26}$ ions per square meter the signal gain reaches the maximum, and the signal gain at this time is 48 dB.

S-TDFA still has great potential in the future. With the continuous development of optical communication technology, the demand for higher speed and longer distance transmission will continue to increase. S-TDFA needs to improve gain, reduce noise, and extend the wavelength range to suit different applications. In addition, introducing new materials and technologies will provide new opportunities and challenges for developing S-TDFA. For example, research based on synthetic thulium-doped fibres and photonic crystal fibres may improve the performance of S-TDFA and open up new application areas. Overall, the importance of S-TDFA in optical communications and other optical applications will continue to grow and be further advanced in future development and research.

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