Simulation Analysis on Optimization of Optical Fiber Communication Based on L+ Band

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Abstract. Nowadays, L+ band (1600-1650 nm) is widely used in optical communication, however, the traditional fiber amplifiers for L+ band can no longer meet the increasing demand, and it is crucial to select more suitable materials and optimize the peak power of the output spectrum. In this work, we determine the rate equation and power propagation equation corresponding to the three-energy-level structure by Er3+ doping phosphate glass, and select the appropriate pumping wavelength and power, and calculate the variation of amplified spontaneous emission spectra with the length of the fiber and the doping concentration using MATLAB programming. Finally, on this basis, genetic algorithm is used to optimize the fiber length and doping concentration, and the parameter values to maximize the peak power of the output spectrum are successfully obtained, and the performance is compared with that of the traversing parameter method, which provides a reference for the design and optimization of fiber amplifiers.

Keywords: L+ band, fiber optic amplifier, Simulation, optimization.

1. Introduction

With the rapid development of information technology such as 5G and artificial intelligence, optical fiber communication plays a key role as one of the important means of information transmission [1]. However, how to find new materials and methods to break through the existing bottlenecks and develop wider bands is a practical need nowadays. Among them, the L+ band has an important position in optical fiber communication due to its lower fiber loss and smaller nonlinear effect [2]. Meanwhile, fiber optic amplifiers are the most important components in fiber optic communications and are the focus of today's research [3].

In this study, the optimization of the system is achieved by simulating the fiber-optic amplifier system in the L+ band through MATLAB. The author focuses on two aspects, performance optimization and parameter tuning. Firstly, Er3+ doped phosphate glass is chosen as the material, and the correlation formula for the three-energy level system is given [4-5]. Secondly, by targeting the optimization of parameters such as doping concentration and fiber length, the author explores how to maximize the signal transmission power and gain effect. Finally, a genetic algorithm is used to optimize the model in order to improve the stability and efficiency of the system. This study is of significance for the design, optimization, and performance enhancement of L+ band optical fiber communication system, which provides certain support and reference for the realization of future high-speed and high-bandwidth communication transmission.

2. Theoretical Analysis

2.1. Fiber optic amplifier

A fiber optic amplifier is a device that uses fiber doped with ytterbium-doped, erbium-doped, lutetium-doped, and other rare-earth ions to amplify optical signals. Fiber optic amplifiers are used for signal amplification, fiber optic communication system relaying, multi-wavelength optical signal merging, fiber Cross-Channel Conversion, switching and distribution of fiber optic signals, fiber optic

sensing, and so on. The principle of optical signal amplification is to inject external light energy into the optical fiber through the effect of stimulated radiation, so that the doped ions are excited, thus amplifying the transmitted optical signal, fiber amplifier in fiber optic communications in a wide range of applications [6].

Fiber optic amplifiers typically structure mainly consists of ytterbium-doped fiber, pump light source and coupler. When an optical signal passes through the ytterbium-doped fiber, the ytterbium-doped ions will absorb the energy provided by the pump light source and undergo stimulated radiation, generating an amplified optical signal with the same frequency as the input optical signal [7]. A coupler is used to efficiently couple the input optical signal and the pump light source into the ytterbium-doped fiber to ensure optimal amplification. The key to fiber amplifiers is the ability to amplify the input optical signal by excited radiation, and this amplification can be performed continuously.

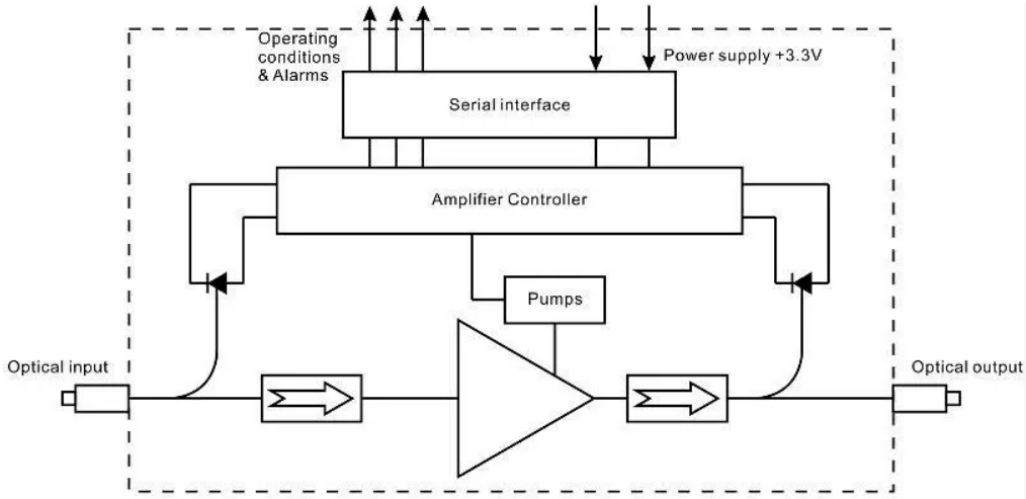


Figure 1. Structure of High-Power Fiber Amplifier (Photo/Picture credit: Original)

In the optical fiber, the light from the optical pump interacts with the fiber material and excites the electrons on the electronic energy level of the doped ions (e.g., erbium-doped, gallium-doped, etc.) in the optical fiber into an excited state through a nonlinear optical effect. The electrons in the excited state are spontaneously transferred to lower energy levels by radiation, releasing photons, and these photons interact with the input optical signal. This interaction causes the input optical signal to be amplified by the process of excited radiation and the output gets an enhanced optical signal.

2.2. Dopant material

In general, fiber optic amplifiers can be subdivided into semiconductor optical amplifiers (SOA), erbium-doped fiber amplifiers (EDFA), and Raman fiber amplifiers (FRA) [4]. Among them, EDFA has been applied for many years and is widely used in fiber optic communications [8]. However, with the continuous development of fiber optic communication, the traditional methods can no longer meet the demand for broadband emission at wavelengths above 1610nm (L+ band).

Starting from the perspective of dopant materials, there are many excellent ways to improve them. Among them, phosphate glass has many advantages, such as mature manufacturing technology, high transparency, high doping concentration, and large-scale adjustable composition. At the same time, the spectral properties of Er^{3+} in phosphate glass can be widely adjusted by changing the composition, which has a broad development prospect from a comprehensive point of view and is more suitable as an improved material [4-5]. Therefore, in this paper, Er^{3+}-doped phosphate glass is selected as the main material of fiber amplifiers for further research.

For fiber amplifiers in the L+ band, the materials selected in this paper should be designed using a three-energy level structure [4-5]. For a general erbium-doped fiber amplifier the three-energy level structure is shown in Fig. 2, which will be used as the basis for modeling.

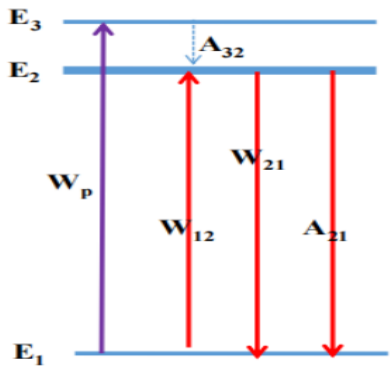


Figure 2. Three-energy structure diagram of a general erbium-doped fiber amplifier (Photo/Picture credit: Original)

3. Matlab-based simulation model study

3.1. Modeling

MATLAB is a powerful numerical computation and scientific programming environment used in a wide range of scientific, engineering, and technical applications. It provides a rich toolbox and library of functions that are often used for a variety of tasks such as data analysis, signal processing, image processing, control system design, optimization, etc. MATLAB features include an easy-to-use programming language, a rich set of mathematical and scientific functions, plotting and visualization capabilities, and the ability to integrate with other programming languages and tools [9].

In this paper, based on the above advantages, the model design of the L+ band fiber amplifier and the optimization of output spectral peak power will be realized through MATLAB simulation. By optimizing the spontaneous emission spectrum and the output spectral peak power, the performance and transmission capability of the fiber amplifier will be improved, and it tries to satisfy the requirements of the modern communication network for high-speed and high-quality signal transmission.

For the design of the fiber optic amplifier model, the basic parameters that need to be used for the relevant equations should be determined first. In the three-energy level structure, the variation of particle number in each energy level is given by the rate equation and the power propagation equation, and is used as the basis for the simulation code [10].

Here are the formulas for the rate equations used in the code:

$$\frac{\partial N_1}{\partial t} = -(W_{12} + W_{13}) \times N_1 + A_{21} \times N_2 + W_{21} \times N_2 \tag{1}$$

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

$$\frac{\partial N_3}{\partial t} = W_{13} \times N_1 - A_{32} \times N_3 \tag{3}$$

$$\frac{\partial N_3}{\partial t} = W_{13} \times N_1 - A_{32} \times N_3 \tag{4}$$

$$N = N_1(z) + N_2(z) + N_3(z) \tag{5}$$

Here are the formulas for the power propagation equation used in the code:

$$\frac{dP_p(z)}{dz} = \Gamma_p(-\sigma_p N_1(z) - \alpha_a)P_p(z) \tag{6}$$

$$\frac{dP_s(z)}{dz} = \Gamma_s[\sigma_{32} N_3(z) - \sigma_{23} N_2(z) - \alpha_s]P_s(z) \tag{7}$$

$$\frac{dP_{ase}(z)}{dz} = \Gamma_{ase}[\sigma_{32} N_3(z) - \sigma_{23} N_2(z) - \alpha_s]P_s(z) + \sigma_{32} N_3(z) h\nu\Delta\nu \tag{8}$$

In the above equations, N_1 means the total number of first energy level particles, N_2 means the total number of second energy level particles, N_3 means the total number of the highest energy level particles, σ_{32} means the emission cross-section, σ_{23} means the absorption cross-section, W_P means the pump optical absorption rate, W_{12} means the spontaneous emission light absorption rate, W_{21} means the spontaneous emission rate of photoexcited radiation, A_{32} means the radiation-free jump rate, A_{21} means the radiation forcing chance, P_p means the pump power, P_s means the signal optical power, P_{ase} means the stimulated emission power.

On this basis, the simulation code is designed, and the model is established by combining the rate equation and the power propagation equation. Combined with the experiments in the related papers, the results of the numerical setting of the related parameters in the model are shown in Table 1.

Table 1. Parameters in the rate equation and power propagation equation

Parameters	Numerical value	Parameters	Numerical value
Signal light wavelength λs (nm)	1625	Background wastage (db/m)	0.1
Pump light wavelength λp (nm)	976	Optical velocity c (m/s)	3*10^8
A_{21}(1/s)	100	Bait ion absorption cross section σa(m^2)	0.72*10^(-25)
A_{32}(1/s)	2010	Bait-ion emission cross-section σe(m^2)	0.122*10^(-25)

The parameters in Table 1 are important references for the design and optimization of fiber optic amplifiers, e.g. the signal light wavelength describes the wavelength of the signal to be amplified, and the pump light wavelength is the wavelength used to excite the erbium ions. The background loss indicates how much light is lost as it propagates through the fiber. The erbium ion absorption cross section and emission cross section reflect the erbium ion's ability to absorb and emit signal light. By analyzing these parameters, you can evaluate the performance of a fiber-optic amplifier, understand its gain characteristics and potential applications, and help select the appropriate wavelength configuration and adjust parameters to achieve the desired amplification.

3.2. Model analysis

The code defines the signal optical power, excited emitted power, and gain as follows:

$$Ps(int, count)=P(length(P),1)$$

$$Pase(int, count)=P(length(P),3) \quad (9)$$

$$G(int, count)=10*log10(P(length(P),1)./Ps_0)$$

The variation of Pase with respect to doping concentration and fiber length is firstly calculated through the double loop structure. The three-dimensional map of its spontaneous amplified emission spectrum is shown in Fig. 3:

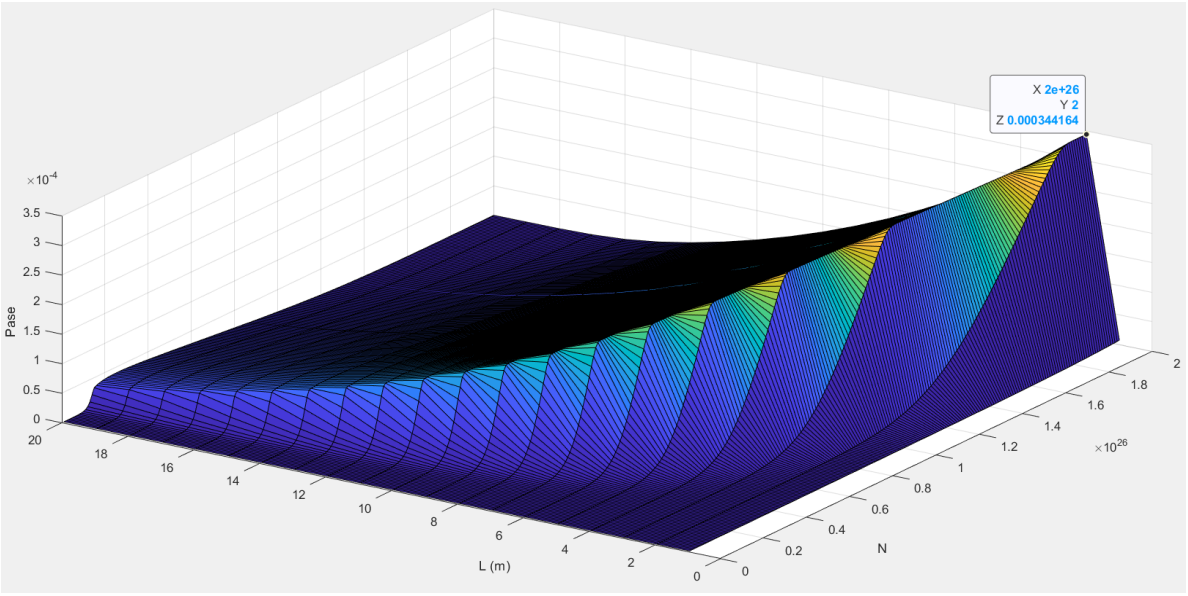


Figure 3. Spontaneous amplification of emission spectra (Photo/Picture credit: Original)

It can be noticed from the above figure that Matlab generates the results smoothly and verifies the accuracy of the model. Meanwhile, the overall trend of the spontaneous amplification emission spectrum shows a slope upward. The range of fiber length is set to 0-20m, and the range of doping concentration is set to 0-2*10^{26}, when the fiber length is 2m and the doping concentration is about 2*10^{26}, the power maximum value of 0.03*10^(-7)W is reached.

Next, the variation of gain with respect to doping concentration and fiber length is investigated and the gain spectrum is shown in Fig. 4.

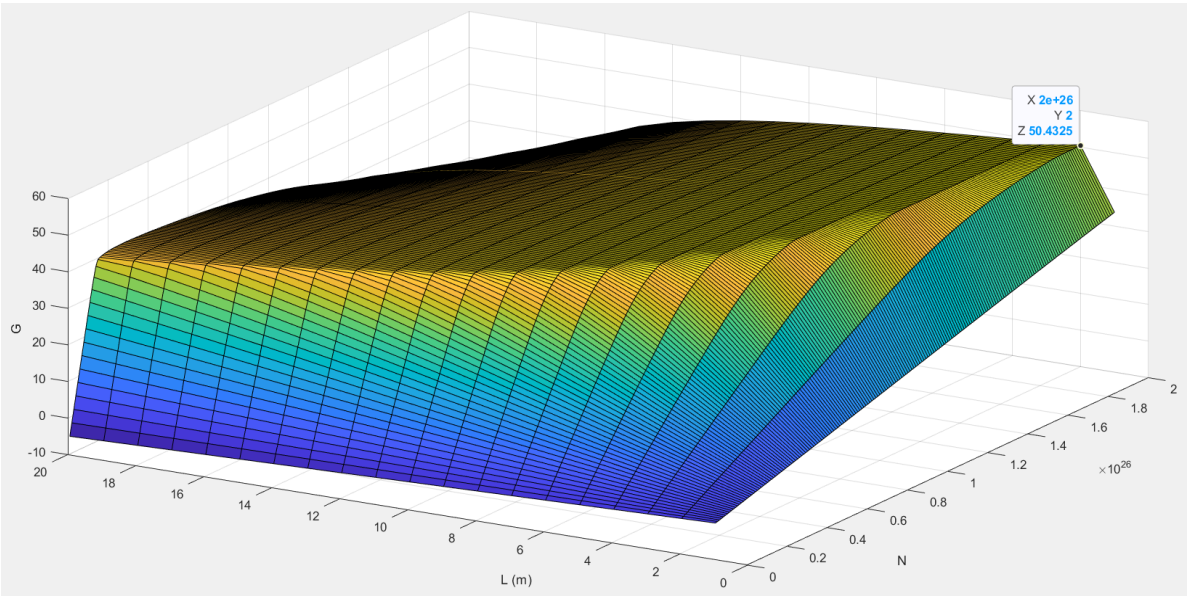


Figure 4. Gain spectrum (Photo/Picture credit: Original)

Similarly, it can be found that the 3D plot shows a smooth rising ridge. The gain maximum value of 50 is reached when the fiber length is 2m and the doping concentration is about 2*10^{26}.

3.3. Further optimization using genetic algorithms

Genetic algorithm, as one of the commonly used optimization algorithms in recent years, is of great significance for optimization models, capable of global search in complex solution spaces, adaptive and self-adaptive, able to deal with various types of optimization problems, and has advantages such as parallelization and scalability [11]. The design flowchart used in this paper is shown in Figure 5:

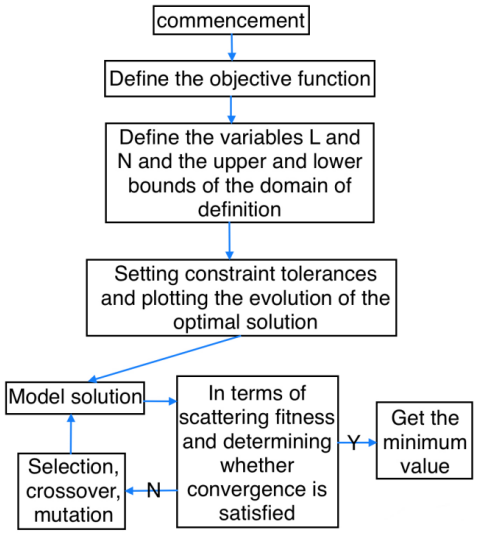


Figure 5. Flowchart of the design of the genetic algorithm (Photo/Picture credit: Original)

Throughout the process, constants were first defined, including the speed of light c and Planck's constant h. Input parameters were then extracted via the x-vector, including the length of the optical fiber L, the total concentration of erbium ions N. Next, the initial values of the signal power Ps0, the pump power Pp0, and the ASE power Pase0 at the input of the optical fiber (z = 0) were defined. After this the parameters of the fiber amplifier are defined, including the emission cross section sig21, absorption cross section sig12 (signal wavelength) and sig13 (pump wavelength) of the erbium ions, as well as the signal wavelength lams and the pump wavelength lamp. Next, the power transfer equation in the fiber optic amplifier was solved by calling ode45 function in the code calling oa fun function to get the variation of signal power, pump power and ASE power at different positions (z). Finally, the gain is calculated and the results are returned.

On this basis, the original code is modified to complete the optimization of the genetic algorithm, and the result is shown in Figure 6 and 7.

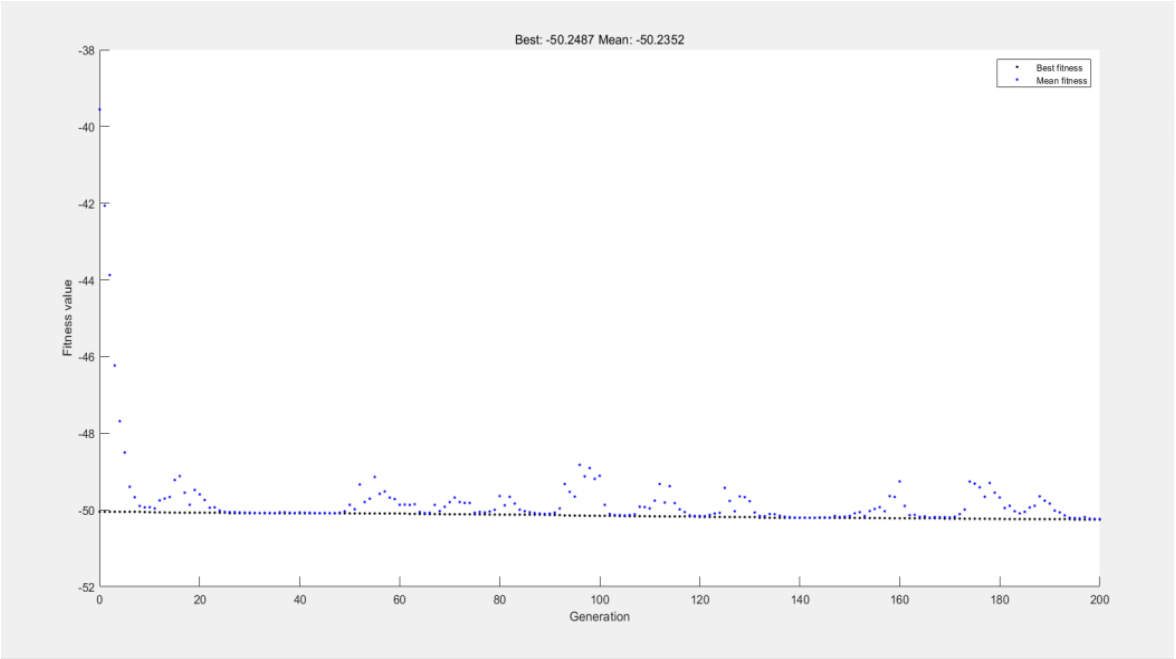


Figure 6. Optimization process of genetic algorithm (Photo/Picture credit: Original)

Figure 6 shows the optimization process of the genetic algorithm, and it can be seen that the gain stays around 50, which is consistent with the previous results and verifies the correctness of the algorithm.

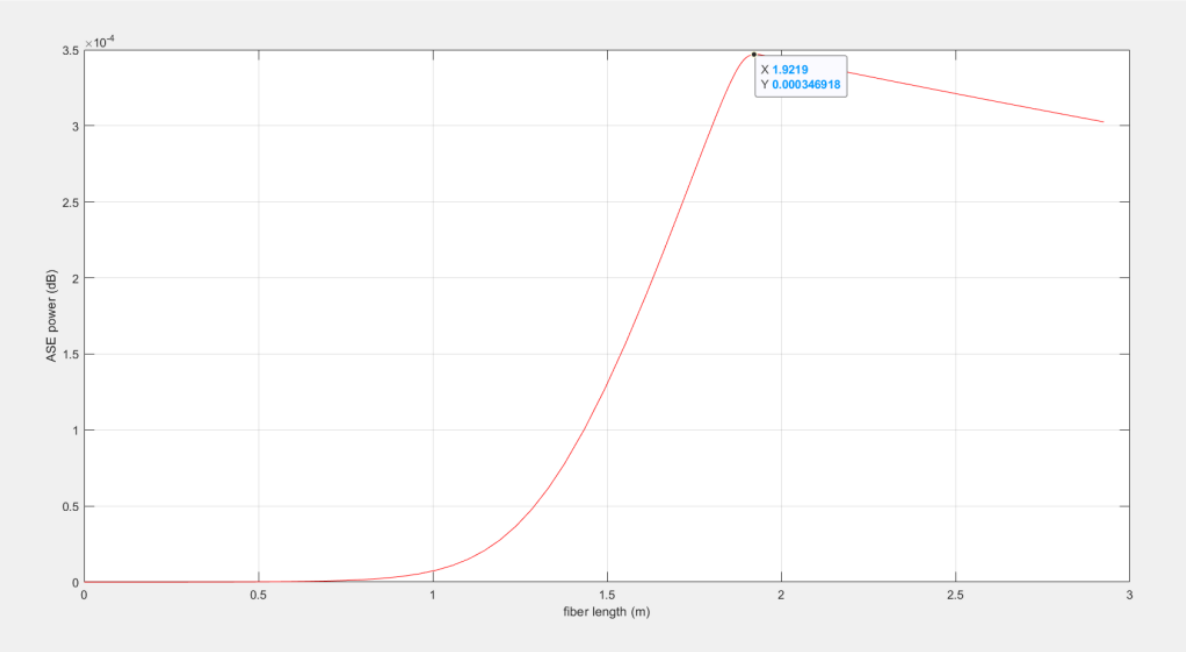


Figure 7. Maximum powering of the peak output spectrum from genetic algorithm optimization (Photo/Picture credit: Original)

As can be seen from Figure 7, the curve is relatively smooth before x=1, and shows an upward trend between x=1-2, and at x=1.9219, Y achieves the maximum value of about 0.03*10^(-7), which is basically in line with the traditional traversal algorithm, and slowly decreases after X=2. Comparison can be found that the genetic optimization algorithm is highly efficient, while the results are accurate, and have some significance for use.

4. Conclsuion

At present, L+ band (1600-1650nm) is widely used in optical communication, especially in the field of long-distance communication and high-capacity transmission. Through this study, we provide some support and contribution to the design and application of L+ band fiber amplifiers. We have successfully realized the study of Er^{3+} doped phosphate glass L+ band, and established the rate equation and power propagation equation according to the relevant parameters. The rate equations and power propagation equations were established based on the relevant parameters. The variation of the amplified spontaneous emission spectra with fiber length and doping concentration was calculated by MATLAB programming, and the fiber length and doping concentration were optimized by genetic algorithm to maximize the peak power of the output spectra at the point where L is about 2 m and N is about 2*10^26.

However, there are some shortcomings in this study that need to be further explored and improved. First, we have only considered the design and application of fiber amplifiers in the L+ band without an in-depth study of other bands. In the future, we can consider extending the design of fiber amplifiers to other bands to meet a wider range of communication needs. Second, although we utilized a genetic algorithm to optimize the fiber length and doping concentration, it is only a heuristic algorithm with some limitations. In further research, other optimization algorithms, such as particle swarm algorithm or simulated annealing algorithm, can be explored to obtain better optimization results. In the future, for the application of L+ band in optical communication, we can further study its integration in optical communication system, including the technology of fiber coupling, optical path selection and signal processing, in order to achieve higher speed and more reliable communication transmission.

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