Design and optimization of O-band and C-band fiber amplifier

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Abstract. In optical fiber transmission, the signal will weaken with the increase of distance, and it will also be affected by various factors such as attenuation, dispersion and so on, thereby reducing the quality of information transmission. Optical fiber amplifier is the key to realize long-distance signal transmission, among which O-band optical fiber amplifier and C-band optical fiber amplifier are two commonly used amplifiers. This paper establishes the rate equation based on the corresponding energy level structures of erbium and neodymium ions. The erbium-doped O-band optical fiber developer and neodymium-doped C-band optical fiber amplifier are optimized by the exhaustive search and genetic algorithm, respectively. The gain effect changes with fiber length and doping concentration are obtained. The final image shows that the gain effect of O-band fiber amplifier and C-band fiber amplifier constantly changes with the fiber length and doping concentration change and reaches the maximum gain effect at a certain point. These experimental results show that the gain effect of O+C band fiber amplifier can be maximized by controlling variables in practical application, or the maximum benefit can be achieved in combination with the material cost and the corresponding gain effect.

Keywords: Fiber amplifier, O-band, C-band.

1. Introduction

Over the past decade, the need for fiber optic communication has persisted due to the increasing popularity of human-machine communication such as the Internet, cloud computing, and the Internet of Things. [1] In optical fiber transmission, the signal will weaken with the increase of distance, and it will also be affected by various factors such as attenuation and dispersion, thus reducing the quality of information transmission. The invention of the Erbium-doped fiber amplifier (EDFA) in 1987 facilitated data transmission over long distances through silicon fibers and was a major improvement over electronic Repeaters that required conversion between optical and electronic signals. [2] Erbium-doped fiber amplifiers are widely used in optical communication and optical sensing. Besides the advantages of high gain and low noise, the output power and gain of Erbium-doped fiber amplifiers can be adjusted by changing the pumping wavelength and pumping power. However, in the early days, many fibers optic long-distance trunk, cable CATV and local area network systems used the cheaper and more reliable 1300nm semiconductor laser as a light source. To improve the system's information capacity and increase the transmission distance, people have explored 1300nm fiber amplifier [3]. At the same time, compared with inorganic host materials such as phosphate and silicate, neodymium-doped polymer material system has many advantages, such as easy adjustment of refractive index, low preparation cost, convenient rotation coating on various types of substrates, and easy integration with photonic devices. [4] Therefore, with people's efforts, neodymium-doped optical fiber amplifiers have also been invented and applied. Optical fiber amplifiers in the neodymium-doped band mainly operate in the wavelength of 1,060 nm to 1,080 nm. Compared with erbium-doped fiber amplifiers, optical fiber amplifiers in the neodymium-doped band have a narrower gain bandwidth, and are often used as the gain medium of various lasers, which are applied in material processing, liDAR and some scientific research. In previous studies, Qi Ying, Ren Yaoyao, Wang Lei et al have shown that under certain working conditions, O+ C-band fiber amplifiers can achieve high gain and low noise performance [5], and O+ C-band fiber amplifiers are showing a wide range of application prospects by their high performance and high efficiency. Zhang, X, Zhang, Y, and Chen, J. [6] introduced the implementation of high-power fiber amplifiers using different techniques, and discussed the design and optimization methods of wideband fiber amplifiers to achieve high gain and low noise performance over multiple wavelength ranges.

2. Design and optimization

2.1. Rate equation

Einstein [7] introduced the relationship between radiation and energy levels, laying the foundation of quantum theory. An energy level is a specific energy state in an energy level system. Each energy level has a specific energy value, usually identified by a quantum number. The transition between energy levels refers to the process of the system from one energy level to another, often accompanied by the absorption and release of energy and radiation and non-radiation processes. Different ions have different energy level structures. Constructing rate equation is a mathematical model to study the change of particle number between these energy levels with time. When constructing rate equation, it is necessary to consider the energy corresponding to energy levels, the transition rate between energy levels and the particle number density of energy levels. Then using the relationship between the transition rate between the energy levels and the population density, differential or difference equations can be established to describe the change in the population of particles over time, and these equations are the rate equations. By solving the rate equation analytically, the evolution of particle numbers with different energy levels in the system can be obtained. L. Su et al. introduced a modeling and simulation method for a four-level Erbium-doped fiber amplifier and analyzed the effects of its performance and parameters on the rate equation.[8] P. P. Bera et al. [9] analyzed the principle and performance of three-level fiber lasers using the rate equation and discussed optimising and controlling laser parameters. This paper uses erbium ion in three-level system and neodymium ion in four-level system, and Matlab establishes the rate equation and power propagation equation. The three-level structure diagram used is shown in Figure 1, and the four-level structure diagram is shown in Figure 2.

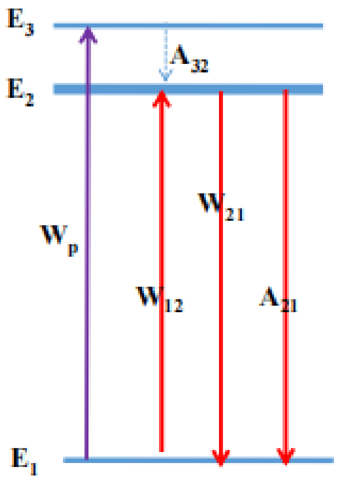

Figure 1. Lons in a three-level system

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

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

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

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

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

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

$$\pm\frac{dP_{ae}(z)}{dz} = \pm\Gamma_{ae}[\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_z]P_s(z) \pm 2\sigma_{21}N_2(z)h\nu\Delta\nu \tag{7}$$

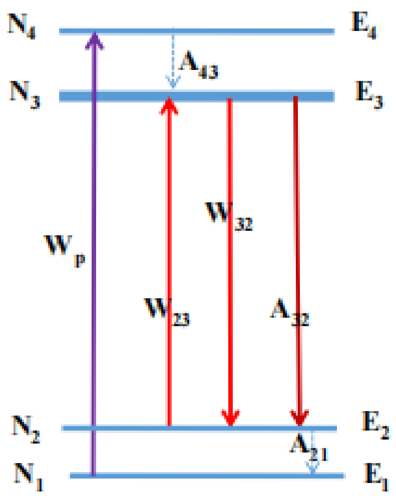

Figure 2. Lons in a four-level system.

$$\frac{\partial N_1(z)}{\partial t} = -W_p(z)N_1(z) + A_{21}N_2(z) \tag{8}$$

$$\frac{\partial N_2(z)}{\partial t} = -A_{21}N_2(z) - W_{23}(z)N_2(z) + W_{32}(z)N_3(z) + A_{32}N_3(z) \tag{9}$$

$$\frac{\partial N_3(z)}{\partial t} = W_{23}(z)N_2(z) - W_{32}(z)N_3(z) - A_{32}N_3(z) + A_{43}N_4(z) \tag{10}$$

$$\frac{\partial N_4(z)}{\partial t} = W_p(z)N_1(z) - A_{43}N_4(z) \tag{11}$$

$$N = N_1(z) + N_2(z) + N_3(z) + N_4(z) \tag{12}$$

$$\frac{dP_p(z)}{dz} = -\Gamma_p(\sigma_p N_1(z) + \alpha_a)P_p(z) \tag{13}$$

$$\frac{dP_s(z)}{dz} = \Gamma_s[\sigma_{32}N_s(z) - \sigma_{23}N_2(z) - \alpha_s]P_s(z) \tag{14}$$

$$\pm\frac{dP_{aae}(z)}{dz} = \pm\Gamma_{aas}[\sigma_{32}N_3(z) - \sigma_{z3}N_2(z) - \alpha_s]P_s(z) \pm 2\sigma_{s2}N_3(z)h\omega\Lambda\upsilon \tag{15}$$

The data used is shown in the Table 1.

Table 1. The data used in the simulation

Energy level / Representation letter	three-level	Pump light absorption rate
Wp	Pump light absorption rate	
W12	Signal light absorption rate	
W21	Stimulated emission rate of signal light	Non-radiative transition rate
A32	Non-radiative transition rate	Radiative transition probability
A21	Radiative transition probability	Optical fiber material loss coefficient
α	Optical fiber material loss coefficient	Frequency half high full width
Δu	Frequency half high full width	Signal light absorption rate
W23		Stimulated emission rate of signal light
W32		Non-radiative transition rate
A43		Pump light absorption rate

2.2. The analysis is combined with exhaustive method and genetic algorithm

Exhaustive search is a basic search method that considers all possibilities and finds a solution. In Matlab, the exhaustion method first defines the solution space by limiting the value range of variables. Then it generates the solution set according to the defined solution space, which can be realized by the loop method. Then check the solution set, check the generated solution set, if the conditions are met as a candidate solution, and finally seek the optimal solution according to the specific requirements of the problem. The exhaustive method is simple and intuitive, strong in completeness, and good at solving small-scale problems. However, when faced with large scale problems, the exhaustion rule is inefficient, and the exhaustion method needs to traverse all possible solutions. In the case of large solution space, the algorithm's time complexity will be very high. Therefore, for problems with large solution space, the exhaustive search will consume more time.

After using the exhaustive method, we optimize the fiber length and doping concentration of the fiber amplifier based on genetic algorithm to find the maximum gain point under changing the fiber length and doping concentration. Genetic algorithm (GA) is a search algorithm based on natural selection and genetic theory that combines the survival of the fittest rule in biological evolution with the random information exchange mechanism of chromosomes within a population [10]. Genetic algorithms, based on the principles of evolution and genetics, begin by creating an initial population, each representing a potential solution to a problem. The fitness function is used for each individual in the population to evaluate its superiority and inferiority in the solution space. Then, according to the fitness value of individuals, some individuals are selected as parents to produce offspring, among which individuals with higher fitness have higher selection probability. The process of selecting two or more entities from the selected parent entity for fragment-based exchange and combination is called crossover operation. Perform random genetic manipulation on newly generated individuals. Mutation operation randomly changes certain genes of individuals with a certain probability to introduce new variants. Through selection and mutation operation, new individuals are generated and the population is updated. These new individuals replaced some old individuals and formed a new population. The selection is then repeated until the stop condition is met. The final output finds the optimal solution. Genetic algorithm has a wide range of applicability, suitable for the optimization of various problems. It does not need the specific mathematical model of the problem. Only the definition of functions can be calculated. Genetic algorithm has a strong global search performance, to avoid falling into the local optimal solution, can maintain diversity in the search process to find the global optimal solution. The process is shown in Figure 3.

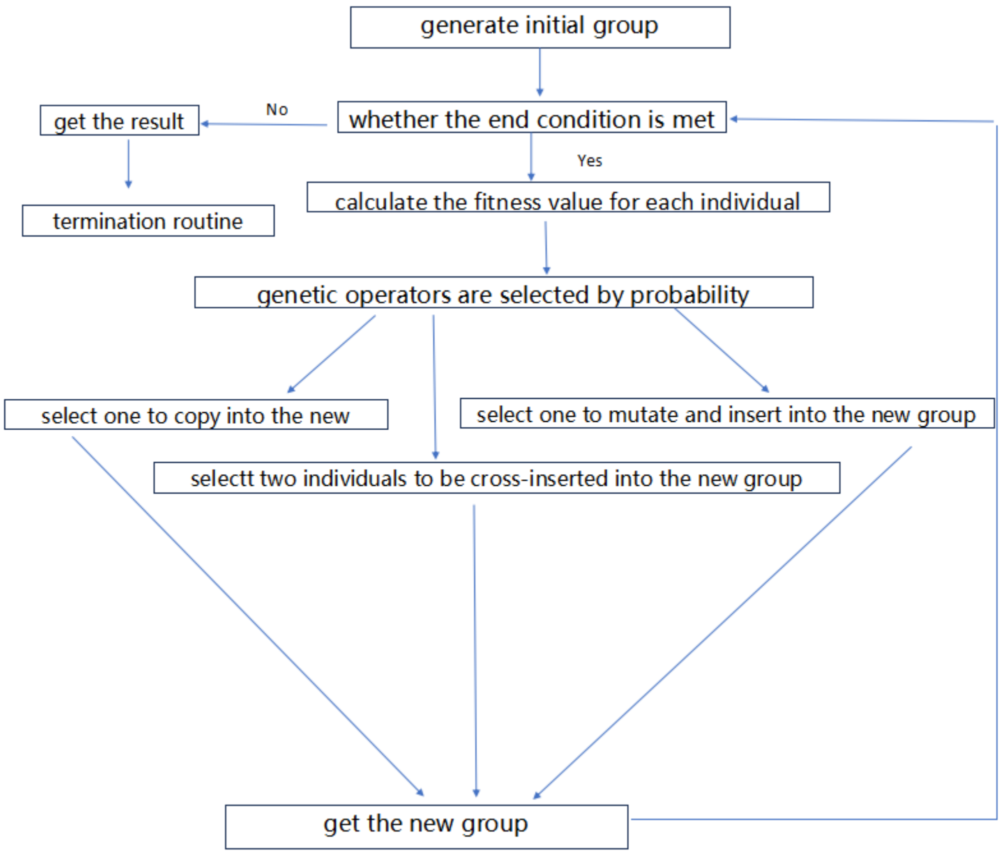

Figure 3. Genetic algorithm flow.

This study aims to optimize two kinds of optical fiber amplifiers by exhaustive search and genetic algorithm respectively, draw conclusions based on simulation images, and compare the simulation results and efficiency of the two methods. The simulation image of Neodymium-band fiber amplifier is shown in Figure 4. The simulation image of erbium-doped O-band fiber amplifier is shown in Figure 5.

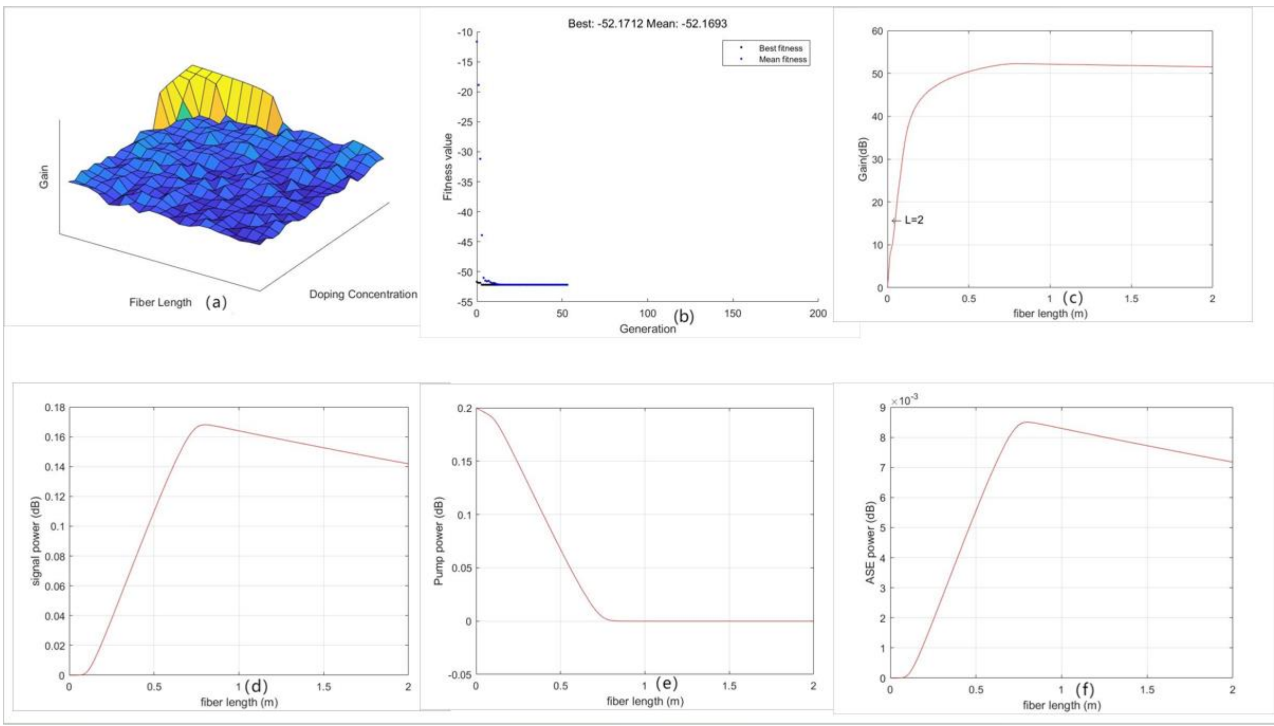

Figure 4. Simulation diagram of neodymium ion fiber amplifier.

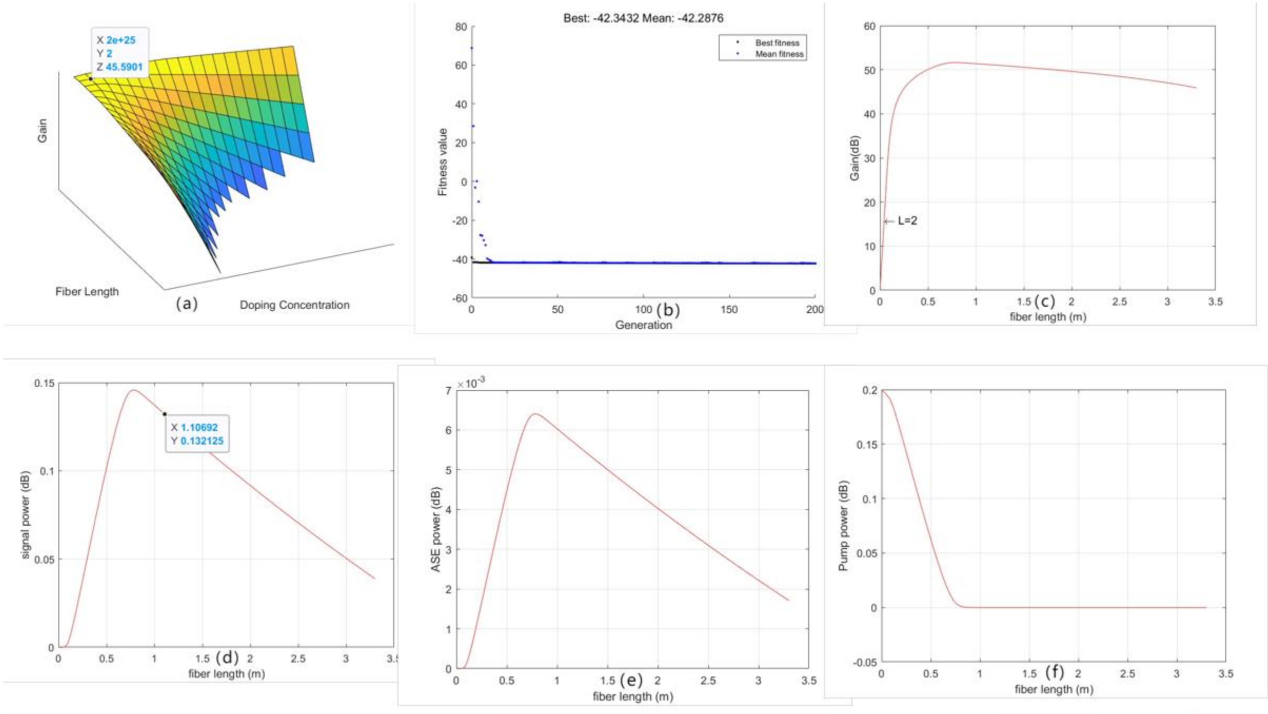

Figure 5. Simulation diagram of erbium ion fiber amplifier.

It can be seen from the figure that when the doping concentration is constant, the gain of erbium ion will increase rapidly with the increase of fiber length at the beginning, and then the growth rate will gradually decrease, reaching the highest value and then slowly decreasing. When the fiber length is constant, the initial gain of erbium increases rapidly with the increase of doping concentration, and then gradually becomes stable, with a slow decrease trend. The gain of neodymium ion increases rapidly with the increase of fiber length at a constant doping concentration, and then tends to be stable. When the fiber length is fixed, the initial gain of neodymium ion increases with the increase of doping concentration, and decreases rapidly when the doping concentration reaches a certain value, reaching a non-ideal state. In addition, we can also see that with the increase of fiber length, pump power gradually decreases and finally becomes stable, while ASE power increases rapidly at first, reaches its peak and then slowly decreases. single power also rapidly increases to a certain value and then slowly decreases. Overall, the results obtained by exhaustive search and genetic algorithm are roughly identical. For this study, genetic algorithm is faster and more efficient in dealing with large-scale problems, and the results are more intuitive.

2.3. The inadequacies and remaining problems of the research

The gain effects of Erbium-doped fiber amplifiers and neodymium-doped fiber amplifiers are analyzed by simulation under the doping concentration and fiber length change, respectively. However, the gain effects of Erbium-doped fiber amplifiers and neodymium-doped fiber amplifiers are also related to many other factors. Early P. C. Becker [11] et al. discussed the influence of dopant diffusion effect on gain. M. Laroche et al. [12] also studied the variation of the gain spectrum of neodymium-doped fiber amplifiers with temperature, and discussed the effect of temperature on gain. In addition, the selection of each parameter and the range of variables in this study also affect the experimental results. When the range of variables is set unreasonable, it is possible to ignore the subsequent changes in the gain effect, the resulting simulation results will be partially missing, and the conclusions drawn from the analysis are no longer complete.

3. Summary

This study optimized erbium-doped O-band fiber amplifier and neodymium-doped C-band fiber amplifier using the exhaustive search and genetic algorithm, and the simulation results were obtained. According to the images under the two algorithms, it can be concluded that the gain of Erbium-doped fiber amplifier and neodymium-doped fiber amplifier can be adjusted by changing the fiber length and doping concentration under the precondition of control variables. With the constant change of fiber length and doping concentration, the gain effect of the two kinds of fiber amplifiers has a certain regularity. In the actual production and application process, the gain effect can be changed by adjusting variables to get the desired gain size, combined with the actual cost to achieve the maximum benefit and reduce unnecessary waste of resources. Through investigation, we can know that many factors can affect the gain of fiber amplifier, such as excitation light power, fiber length, dopant diffusion effect, etc. In the production and application process, it is also necessary to consider the influence of various other factors such as temperature on the gain effect. Finally, this study also compares the efficiency of the exhaustive search and the genetic algorithm in solving this problem. It is found that the genetic algorithm takes less time to solve such a large-scale problem, while the exhaustive search takes several times more time. It is concluded that the genetic algorithm is more efficient in the face of large-scale problems, but other better algorithms are not ruled out. In the actual application process, we should adopt the appropriate algorithm to realize the optimal regulation of fiber optic amplifier and improve the performance and reliability of the amplifier. The research on single-band optical fiber amplifiers has gradually increased, but the research on dual-band parallel structure amplifiers is still relatively small. Compared with single-band optical fiber amplifiers, dual-band parallel structure optical fiber amplifiers have advantages of wide band amplification and high flexibility, which will be proposed in the subsequent research.

Authors Contribution

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

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