Modelling and numerical simulation optimization of output spectra of PbSe doped quantum dot fiber light source based on genetic algorithm

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Abstract. Optical fiber amplifiers mainly use rare earth elements as dopants. In the past 20 years, with the research on plastic optical fiber amplifiers doped with different natural elements (such as erbium and thulium), the performance of optical fiber amplifiers has been significantly improved. However, the application potential of natural elements has reached its limit. To improve optical communication, researchers are working on a fiber amplifier with a better flat gain and more intense light. In this paper, the quantum dot fiber amplifier is treated as a three-level structure, and a genetic algorithm is used to optimize the quantum dot fiber amplifier to maximize the total output power. In this study, by solving and analyzing the rate and power propagation equations of the numerical model, the gain spectrum of the amplifier at a wavelength of 1200~1700nm is obtained as a function of fiber length and doping concentration. Draw three-dimensional images based on fiber length, doping concentration, and ASE power axis to find the maximum power at the highest point of the image. Then, combined with the optimization results of the genetic algorithm, the maximum value of the total power is obtained.

Keywords: optical fiber amplifiers, genetic algorithm, quantum dot fiber amplifier.

1. Introduction

The study of fiber lasers began in the 1960s. Sniper first proposed the idea of using optical fibers in lasers and subsequently sparked a wave of research on fiber lasers. Compared with elemental doped lasers in nature, fiber lasers have many advantages, such as Good compatibility with optical devices and easy coupling with fiber transmission systems; Superior lasers provide a way; Fiber lasers use fiber as a substrate, and because the fiber has a higher "surface area and volume" and better heat dissipation, the optical conversion efficiency during transmission is higher; It can be used as an optical soliton source to provide a light source for soliton optical communication; Fiber lasers are small in size, flexible in structural design, and easy to transport. It is these advantages that make fiber lasers have broad application prospects in laser processing, high-precision sensing technology, optical data storage, biomedicine, and other fields, attracting the interest of many researchers and becoming the object of

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research.

Artificial semiconductor quantum dot materials have received considerable attention over the past several years. Because of the bonding of electrons and holes in quantum dots in three-dimensional space, various quantum effects are caused, such as quantum size effects, macroscopic quantum tunneling effects, surface effects, coulomb barrier effects, and so on [1]. It is these unique properties that make quantum dots have broad application prospects in single electron devices, memories, and various optoelectronic devices. Quantum dots have good fluorescence properties in the visible to the near-infrared range, and by changing the size of the quantum dots, quantum dots with different emission peak wavelengths can be obtained. Using Matlab to optimize fiber amplifiers is a bold and innovative method, which may be of great significance in further improving the gain flatness of fiber amplifiers.

This study is based on genetic algorithms to optimize quantum dot fiber amplifiers to maximize the total output power. In this study, we first understand the working principles of genetic algorithms and quantum dot fiber amplifiers. Secondly, by combining the particularity of Matlab, and using the Matlab genetic algorithm to optimize quantum dot fiber amplifiers, we successfully achieved the maximum total output power through several tests.

2. Development status and advantages and disadvantages analysis of quantum dot

In recent decades, quantum dots, or semiconductor nanocrystalline materials, have received extensive attention and research due to their special physical and chemical features (quantum size effects, surface effects, macroscopic quantum tunneling, Coulomb blocking effects, etc.). These studies have mainly focused on the applications of light-emitting diodes, solar cells, biomarkers, and other fields.

As the size of a quantum dot decreases, until its size is smaller than its Bohr radius, the energy levels of the quantum dot begin to separate, and its value is ultimately determined by its size. In the process of preparing quantum dots, their size can be controlled by controlling reaction time, temperature, and ligands, that is, the wavelength positions of their absorption and radiation peaks can be manually controlled. The PbSe quantum dots involved in this article are one of the more mature quantum dots in the preparation process.

In the past, optical fiber amplifiers were mainly doped with rare earth elements (such as erbium, thulium, ytterbium, etc.). The preparation process of related element materials was more mature than quantum dots, and the relevant research on various characteristic values was more abundant. At the same time, their optical fiber amplifiers also had the characteristics of high bandwidth and high gain. However, although natural element doping and various serial connection technologies have greatly improved the performance of fiber amplifiers, after decades of development, the potential of natural element doping seems to have been fully explored, and it is difficult to continue to improve. At this point, the advantages of quantum dots are reflected. We can create some desired characteristics through artificial means, adjust the wavelength positions of their absorption and radiation peaks, and the whole width at half height of the spectrum, to further optimize the performance of the optical fiber amplifier, and even move the absorption and radiation spectrum as a whole through different types of doping and other means, These outstanding characteristics are not possessed by natural elements such as rare earth ions [2].

3. Application principles of genetic algorithms

3.1. Principles of genetic algorithms

A genetic algorithm (GA) is an algorithm that simulates biological evolution and genetic processes. Each descendant undergoes some new changes in the process of inheriting the basic characteristics of its parent.

The genetic algorithm starts from a certain number of potential solution populations of the problem to be solved, and the population is constituted by a certain number of genetically coded individuals. Genetic algorithms mainly include selection, crossover, and mutation operators [3].

The basic principle and algorithm flow are as follows. Encoding style. Genetic algorithms cannot directly solve the parameters in the problem space. They must use coding methods to convert the

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parameters that need to be optimized to the form of gene strings, chromosomes, or individuals in a certain structural form [3].

Fitness function. The fitness function can indicate the ability of an individual to adapt to the environment and is used to assess the level of excellence of individuals in a group according to the objective function of the issue to be solved [3].

Selection, crossover, and mutation algorithms. The selection algorithm selects better individuals from a group, transfers the individuals with high fitness values directly to the next generation, and eliminates the individuals with low fitness values [3].

The crossover operator exchanges certain genes of two individuals within a population according to a given crossover rate, which greatly improves the searchability of genetic algorithms.

Mutation operators are used to changing certain genes of individuals based on a given mutation rate. Using mutation operators can accelerate convergence to the optimal solution, keep the population diverse, and prevent the occurrence of non-convergence in the algorithm [3].

3.2. Advantages and disadvantages of genetic algorithms

The advantages and disadvantages are as follows：

3.2.1. Advantage. First, the search starts from a group and has the potential for parallelism, allowing several individuals to be compared simultaneously. Second, the search is inspired by evaluation functions, and the process is straightforward. Third, iteration based on a probability mechanism is haphazard. Last, it is upgradeable and user-friendly in combination with other algorithms [4].

3.2.2. Disadvantage. First, the programming and implementation of genetic algorithms are relatively complex. First, it is necessary to encode the problem, find the optimal solution, and then decode the problem. Second, unable to utilize network feedback information on time, resulting in slow search speed and long time required. Third, the selection of parameters such as crossover rate, variability, and so on mostly relies on experience, which can easily affect the quality of the solution [5]. Last, the algorithm depends somewhat on the selection of the original population and can be improved by combining several heuristic algorithms. [6].

The genetic algorithm possesses a good global research capability, which can quickly search the solution space of all solutions without falling into the trap of rapidly descending locally optimal solutions; Distributed Computing accelerates the solution through the inherent parallelism. However, due to the poor local search ability of genetic algorithms, simple genetic algorithms are time-consuming and have low search efficiency in the later stages of evolution. In practical applications, genetic algorithms are prone to premature convergence problems.

4. Parameters and properties of PbSe quantum dot fiber amplifier

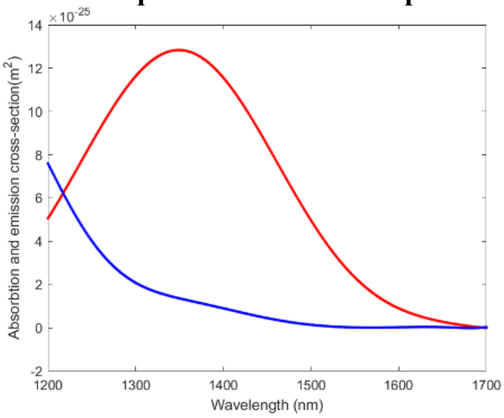

Figure 1. Absorption and emission cross sections as functions of wavelength.

Figure 1 shows the absorption and emission cross sections of PbSe quantum dots as a function of wavelength. In the figure, the absorption peak wavelength is about 1345 nm, and the emission cross section has no peak at the wavelength of 1200-1700 nm but continues to decrease and gradually flattens out at the wavelength of 1200-1700 nm.

Table 1. Table of relevant parameters [7].

Parameters	Value
Pump Wavelength /nm	980
Upper-level lifetime t/us	240
Pumping absorption cross-section sigma13 /m^2	3.4×10^{-24}
Pumping emission cross-section sigma31 /m^2	0.8×10^{-24}
Source absorption cross-section sigma12_0 /m^2	1.3×10^{-24}
Source emission cross-section sigma21_0 /m^2	1.3×10^{-24}
Fiber core radius r/m	2.5×10^{-6}
background lose alpha/m^{-1}	0.1
A_{32}	10^6

Table 1 shows the relevant settings of the PbSe doped quantum dot fiber amplifier selected in the experiment. After obtaining these parameters, we can use the following formula:

$$W_p(z) = \frac{\sigma_{13}P_p(z)}{hv_{13}A_{eff}} \quad W_p(z) = \frac{\sigma_{12}(v_{12})P_s(z)}{hv_{12}A_{eff}} \quad W_{21}(z) = \frac{\sigma_{21}(v_{21})P_s(z)}{hv_{21}A_{eff}} \quad A_{eff} = \pi r^2$$

To calculate the pump light absorption rate W_p, signal light absorption rate W_{12} signal light excited emission rate W_{21} non radiative transition rate A_{32} radiative transition probability A_{21}.And then bring these data into the numerical model built by the three-level system for debugging.

5. PbSe quantum dot fiber amplifier establishment of the mathematical model

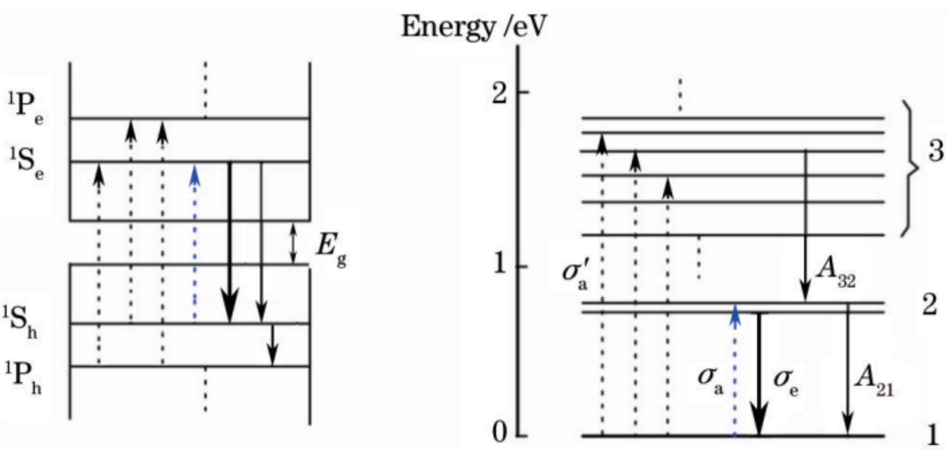

Figure 2. Schematic diagram of energy levels of PbSe quantum dots [8].

Three-level system: The lower energy level that generates the laser is the same as the ground state energy level.

(1) Under the excitation of an external excitation source (pump source), particles in the ground state are pumped to the pump energy level, with a pumping probability of W13.

(2) As shown in Figure 2, the lifetime of the E3 level is very short, which means that the pumped particles stay at the E3 level for a very short time.

(3) Between the E1 and E2 energy levels, that is, between the upper and lower laser levels that

generate the laser light.

Due to the metastable state of the E2 level that generates laser light, before the formation of a plum tree inversion, a small portion of the particles on the E2 level will return to the ground state in the form of spontaneous and house-signed radiation, with A_{21} and S_{21} being very small.

Three-level systems require higher threshold inversion particle counts and three-level systems share lower energy levels. Therefore, the number of ions at the upper level of the laser must be large. In a four-level system, due to the rapid evacuation of lower energy levels, only a small number of particles can achieve aggregation number inversion.

If the lower level of the laser is not a ground state level, it is a four-level level, otherwise, it is a three-level. In a four-level system, the lower laser level is almost not as high as the particle laser level, and the number of inversion particles is easy to increase. Therefore, the threshold value is low, and light is easy to emit.

The third level threshold is usually higher. For compounds in a general four-level system, the number of electrons in the third level tends to be saturated, while the number of electrons in the fourth level will normally have many vacancies.

This emission characteristic of quantum dots is caused by strong quantum well confinement. Therefore, a level 3 population is first excited by a nonradiative transition of probability A_{32} to level 2, and then by other radiative/nonradiative transitions to the ground state [9].

6. Result and discussion

6.1. Result

6.1.1. The gain of PbSe quantum dots varies with fiber length and doping concentration. The effects of fiber length and doping concentration on the gain of the quantum dot doped fiber amplifier are qualitatively studied by using the control variable method for the three-level system.

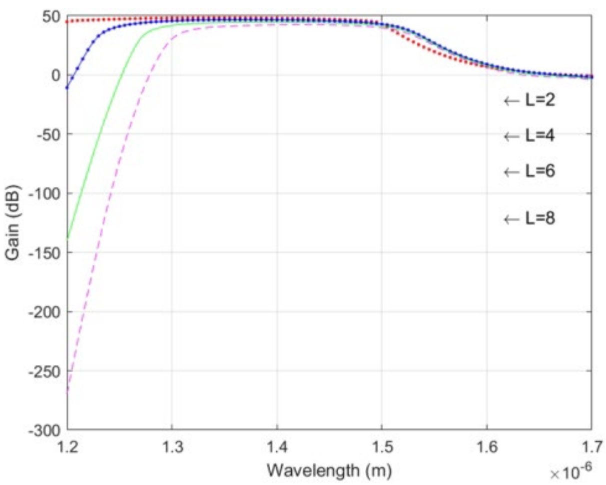

Figure 3. Set the wavelength of the pump to 980 nm, the pump power to 200 mW, the signal power to 10^{-3} mW, and the doping concentration to 1.7×10^{25} ions/m^3. Select four optical fiber lengths of 2 m, 4 m, 6 m, and 8 m.

First of all, set the wavelength of the pump to 980 nm, the pump power to 200 mW, the signal power to 10^{-3} mW, and the doping concentration to 1.7×10^{25} ions/m^3. Select four optical fiber lengths of 2 m, 4 m, 6 m, and 8 m to plot the gain versus wavelength graph, as shown in Figure 3. It can be seen that as the length of the optical fiber increases, the gain decreases, and the maximum gain is 50 dB.

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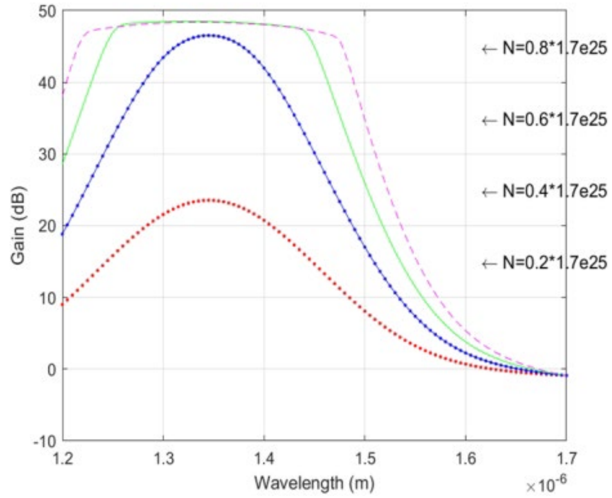

Figure 4. Set the wavelength of the pump to 980 nm, the pump power to 200 mW, the signal power to 10^{-3} mW, and the fiber length to 2 m. Select four doping concentrations of 3.4×10^{25} ions/m^3, 6.8×10^{25} ions/m^3, 1.02×10^{26} ions/m^3, and 13.6×10^{26} ions/m^3

Then, set the wavelength of the pump to 980 nm, the power of the pump to 200 mW, the signal power to 10^{-3} mW, and the fiber length to 2 m. Select four doping concentrations of 3.4×10^{25} ions/m^3, 6.8×10^{25} ions/m^3, 1.02×10^{26} ions/m^3, and 13.6×10^{26} ions/m^3 to draw a graph of gain versus wavelength. As illustrated in Figure 4, the gain can be seen to rise as the doping concentration increases, and the maximum gain is 50 dB.

6.2. Optimize doping concentration and fiber length to maximize total power. This study draws three-dimensional images based on the fiber length, doping concentration, and ASE power axes, respectively, and searches for the maximum power when the highest point position of the image is L=1.15 m, N=4.93×10^{-25} ions/m^3. Then, as shown in Figure 5 and Figure 6, combining the optimization results of the genetic algorithm, the maximum value of the total power is found to be 3.44×10^{-39} W. The power value in the figure is negative because only the minimum value can be obtained during the optimization process using genetic algorithms. Therefore, negative values of power are taken to obtain the minimum value before obtaining the maximum value.

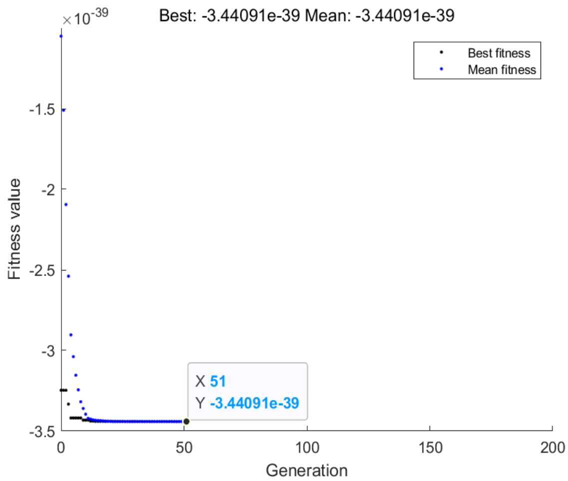

Figure 5. Optimization results of the genetic algorithm.

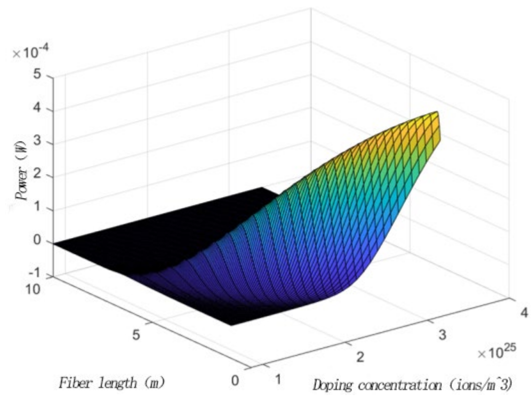

Figure 6. Three-dimensional images based on the fiber length, doping concentration, and ASE power axes.

6.3. Discussion

As a result of the impact of quantum containment, the electron energy levels are split from continuous states into discrete levels. However, due to the different sizes and particle size distributions of doped quantum dots, the fluorescence wavelength distribution radiated by quantum dots is relatively wide [9].

In the experimental results, we found that no matter how the fiber length is shortened, and the doping concentration is increased, the maximum gain is 50 dB. According to other relevant studies, the maximum gain is affected by other factors such as temperature. Therefore, when optimizing, other environmental factors should be fixed for research, without blindly pursuing a reduction in the fiber length value and an increase in the doping concentration. In addition, these two variables will have a certain impact on each other, and due to the size effect and quantum constraint effect of quantum dots, it is speculated that this is due to the diameter of the quantum dots themselves. Finally, considering the two variables simultaneously for optimization, the optimal result of obtaining the maximum total power was obtained [9,10].

This research helps to break through the current bottleneck of bandwidth constraints in fiber amplifiers.

7. Conclusion

In this study, a numerical model of the energy level and transition configuration of a quantum dot- doped fiber amplifier is proposed using a three-level system model. After solving and analyzing the rate and power propagation equations of the numerical model, the gain spectrum of the amplifier at wavelengths of 1200-1700 nm is obtained as a function of fiber length and doping concentration. When the power of the pump is 200 mW, the gain decreases as the fiber length increases, and increases as the doping concentration increases, with a maximum gain of 50 dB.

Then, Combining the genetic algorithm and three-dimensional graph, it is concluded that the maximum total power is 3.44×10^{-39} W when the fiber length is L=1.15 m and $N=4.93\times10^{-25}$ ions/m^3.

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