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Gain maximization of BDFA between the wavelength of 1700nm to 1800nm

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Abstract. Fiber optic communication technology is becoming increasingly important in various fields, and high-speed, large-capacity fiber optic transmission systems are urgently needed. The design of fiber amplifiers is influenced by both fiber length and doping concentration. Although the Erbium-doped fiber amplifier (EDFA) is one of the most widely used components in fiber optic communication systems, its working area cannot meet the growing demand for network traffic.This paper presents a new fiber amplifier operating in the spectral region of 1700-1800 nm, pumped by commercially available laser diodes, highlighting the potential benefits of developing optical amplifiers for new spectral regions.This paper constructs a model to optimize gain at the central wavelength by finding relevant parameters, fitting a binary function of gain as a function of doping concentration and fiber length using Matlab, and optimizing the maximum gain using a simulated annealing algorithm. The proposed fiber amplifier has potential applications in telecommunications, sensing, and spectroscopy. The design of the amplifier has been optimized to achieve high gain and low noise figures, which are crucial for practical applications. Furthermore, the amplifier can be easily integrated into existing fiber optic networks, making it a promising candidate for future optical communication systems.

Keywords: BDFA, bismuth soped fiber, simulated annealing algorithm.

1. Introduction

A fiber amplifier is an indispensable device in an optical fiber communication system. To study the fiber amplifier with better performance, it is necessary to understand the influence of different variables on its gain [1].

Since the invention of the first ruby laser by the American scientist Meyman in 1960, the search for and fabrication of new active laser materials has attracted a lot of attention from researchers. This made it feasible to improve the performance of existing lasers or to invent new ones, and in 1966, the British-Chinese scientist Charles Kao and his collaborator Hockham proposed a new term, transmission medium, and they thought that low-loss optical fiber suitable for long-distance communication use could be

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manufactured by purifying raw materials [2]. Since then, optical information transmission technology has entered a phase of rapid development. In 2008, Dianov first built a bismuth-doped fiber amplifier (BDFA). In 2009, a maximum gain of 24.5 dB at 1320 nm was achieved. In 2016, Firstov et al. obtained a BDFA with a working wavelength in the range of 1640-1770 nm by using a self-made light source with a signal less than 20 dBm, a 1550 nm LD, and a 150mW double-end pump. The maximum gain is 23 dB at 1710 nm, and the gain efficiency is 0.1 dB/mW. In 2020, Dvoyrin et al. use a self-made Tm-doped fiber ASE light source as a signal source, a 1330nm / 1550nm RFL as a pump, and a maximum gain of 27.9dB at 1445nm at 2W pump power [3].

As people have higher requirements for the capacity and speed of optical fiber transmission systems, it is necessary to fully increase the bandwidth. Modern fiber amplifiers only cover a small part of the fiber low-loss transmission window, and many bands have not been developed and utilized. Bismuth ion doped fiber covers the ultra-wideband near-infrared fluorescence in the range of 1000-1800 nm, which has a good prospect for studying ultra-large capacity fiber. To optimize the performance of BDFA, we use the simulated annealing algorithm to find the maximum gain of the BDFA with the doping concentration and fiber length as variables. It is of great significance for the future design of advanced BDFA.

2. Simulated annealing algorithm

2.1. Principle of the simulated annealing algorithm

The word simulated annealing was invented by Kirkpatrick et al. who got inspiration from Metropolis et al.'s Monte Carlo simulation. To solve the combination problem and discover the optimal solution, they use the simulated annealing approach. Finding the ideal solution to the issue is comparable to discovering the system's minimal energy, which is similar to the object annealing process. As a result, the energy gradually decreases as the system cools. The problem's solution falls to its lowest potential value in a similar manner. Each stage of the updating process in this process has a length that is proportional to the temperature represented by the associated parameters. The temperature is initially raised very high in a bid to accelerate minimization and is then gradually lowered to stabilize.Figure 1 shows the process diagram of the physical annealing.

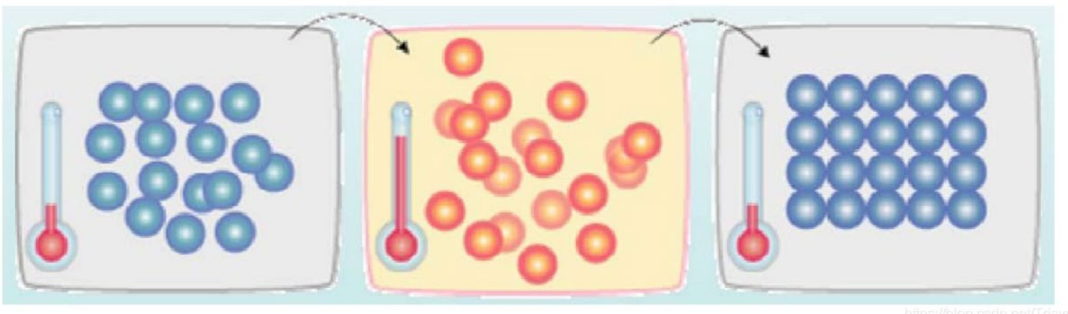

Figure 1. Process of physical annealing [4].

The solid annealing principle is the ancestor of the simulated annealing algorithm. It is commonly known that the internal particles of a solid would initially become disordered and then finally become ordered, achieving equilibrium at all temperature levels, when heated to a high temperature and then gradually cooled. The internal energy is decreased to its lowest feasible level when it ultimately achieves the ground state at ambient temperature [5]. The likelihood of particles tending to be balanced at temperature T, based on the Metropolis criterion, is given by the expression $e^{(-\Delta E/\kappa T)}$, where E is the temperature's internal energy and κ is the Boltzmann constant. The combinatorial optimization issue is simulated using solid annealing. The internal energy E is simulated as the objective function value f, and the temperature T is developed as the control parameter t. The combinatorial optimization problem is solved using the simulated annealing algorithm: Starting from the original solution i and the first value of the control parameter t, repeat create a new solution to calculate the target function's difference to adopt or abandon, moreover build down the value of t, the present solution at the final stage of the procedure is roughly the ideal solution [6].

Table 1. Comparing the process of physical annealing and simulated annealing.

Physical annealing	**Simulated annealing**
Particle state	Solution
Lowest energy state	Optimal solution
Melting process	Setting initial temperature
Isothermal process	Metropolis sampling process
Cooling	Control parameters falling
Lowest energy state	Objective function

2.2. Advantages of the simulated annealing algorithm

The simulated annealing algorithm has many advantages over other algorithms. First, it can break through the limitations of the hill-climbing algorithm which can solve the global optimum. Since the initial solution and the final solution are randomly selected, the simulated annealing algorithm has very good robustness which represents its ability to resist external unstable factors. Normally the number of iterations k has an impact on the optimal solution. The search time is longer, and the result is more reliable if the value of k is larger; the search time is shorter which may lead to the skip of the optimal solution if the value of k is too small, so it is of great importance to choose the appropriate value of k. The temperature cooling rate also has an influence on the simulated annealing procedure. Longer search times are associated with slower cooling rates.

As in this work, fiber length and doping concentration of Bi are the two variables affecting the gain of the optical fiber amplifier, with the simulated annealing algorithm the optimal fiber length and doping concentration of Bi leading to the maximum gain can be calculated.

3. Theoretical foundations and model equations

3.1. Energy level structure of bismuth ions

To optimize the system parameters in the experimental design, such as the optical fiber length, concentration, and pumping power, the establishment of the theoretical model is very important. Although the near-infrared ultra-broadband luminescence of bismuth-doped materials has attracted the attention of many researchers, and the rapid development of corresponding materials and devices, the mechanism of bismuth-related NIR luminescence is still unclear. The energy level of bismuth ions is complicated. In this work, the viewpoint that the luminescence center is derived from Bi + is adopted, and the energy band diagram is constructed according to the measured data. Then the three-level transition model is used to obtain the rate equation and power transfer equation in the steady state. In simplified cases, according to its spectral characteristics, the bismuth ion has a three-level structure between 1700-1800nm. The rate equation and power propagation equation of the three-level structure are given below [7].

3.2. Rate equations for the three-level structure

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

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

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

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

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$$W_p(z) = \frac{\sigma_{13} P_p(z)}{h v_{13} A_{eff}} \tag{5}$$

$$W_{12}(z) = \frac{\sigma_{12}(v_{12}) P_s(z)}{h v_{12} A_{eff}} \tag{6}$$

$$W_{21}(z) = \frac{\sigma_{21}(v_{21}) P_s(z)}{h v_{21} A_{eff}} \tag{7}$$

Where N_1, N_2, and N_3 are the particle number densities of the ground, metastable, and excited states, respectively, and N is the total particle number density. A_{21} is the spontaneous radiation transition chance and W_{32} is the chance of non-radiative transition from an excited to a metastable state. Because A_{21} and W_{32} occupy a large proportion, the non-radiative transition from the metastable state to the ground state is neglected [8]. Figure 2 illustrates the flow of the simulated annealing algorithm.

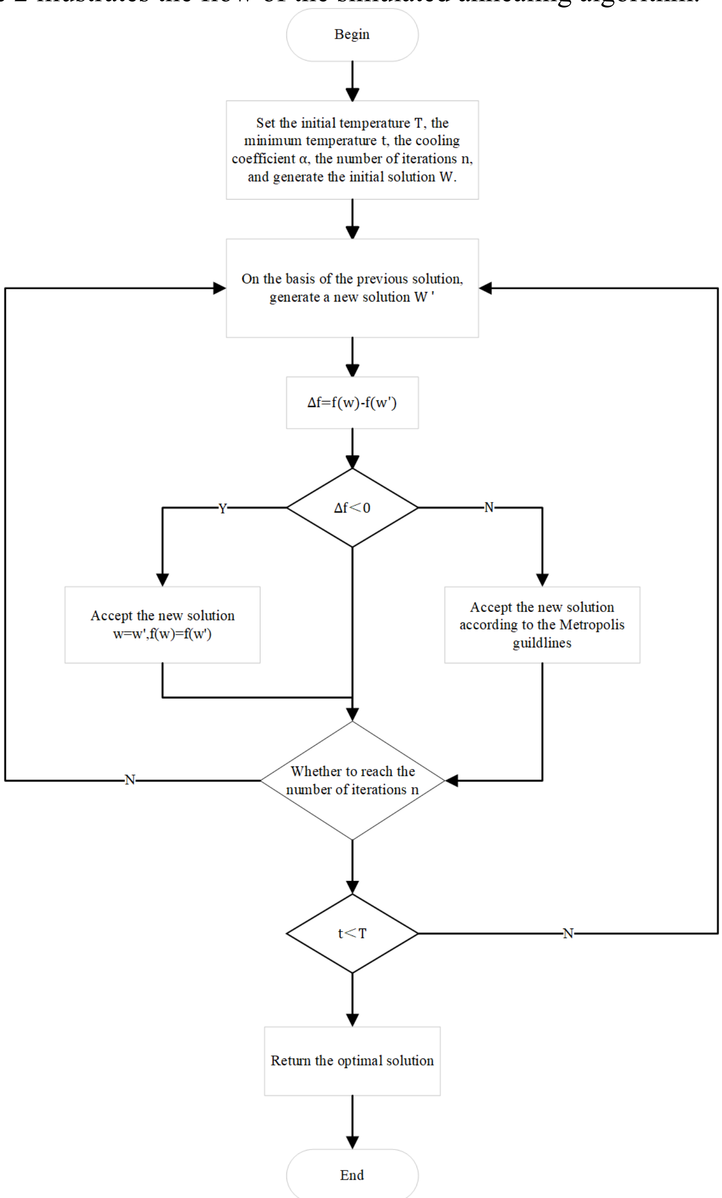

Figure 2. Flow chart of the simulated annealing algorithm.

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3.3. Power propagation equations for the three-level system

$$\frac{dP_p(z)}{dz} = \Gamma_p\ (-\sigma_p\ N_1(z) - \alpha_a)P_p\ (z) \tag{8}$$

$$\frac{dP_s(z)}{dz} = \Gamma_s\ (\sigma_{21}\ N_2(z) - -\sigma_{12}\ N_1(z) - \alpha_a)P_s\ (z) \tag{9}$$

$$\frac{dP_{ase}(z)}{dz} = \Gamma_{ase}\ (\sigma_{21}\ N_2(z) - \sigma_{12}\ N_1(z) - \alpha_a)P_s\ (z) + \sigma_{21}\ N_2(z)hv\Delta v \tag{10}$$

$$G(P_p(z\ ), P_s(z), N_2, N_1, z) = \frac{P_S(z)}{P_s(0)}(100\%) \tag{11}$$

$$G(P_p(z\ ), P_S(z), N_2, N_1, z) = 10\ * log10\frac{P_S(z)}{P_s(0)}(dB) \tag{12}$$

Where Ps is the power of the signal light, the Pp and PASE represent the pumped light and the amplified spontaneous radiation (ASE) optical power, respectively.

The a and v mean the loss coefficient (m^{-1}) and frequency half-height full width (Hz) of the optical fiber material, respectively.

3.4. Some parts of the model equations

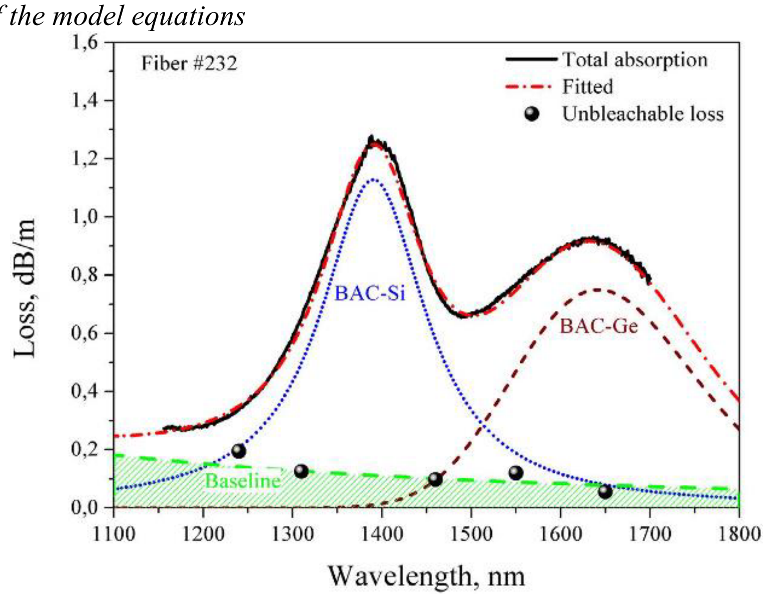

Figure 3. The image of loss coefficient and wavelength [2].

Through the image of loss coefficient and wavelength, the model equation between 1700-1800 nm is fitted. Several main model equations are given below [9].

The absorption coefficient is:

$$ab = 10^{\frac{-0.004\times\lambda\times10^9+7.58}{10}} \tag{13}$$

The absorption cross-section is:

$$\sigma_{sa} = \frac{ab}{N} \tag{14}$$

The emission cross-section is:

$$\sigma_{se} = \frac{ab}{N} exp(\frac{\varepsilon_0 - \hbar v}{\kappa T}) \tag{15}$$

In these equations, λ stands for wavelength, N stands for doping concentration of Bi, and T stands for room temperature in the scale of Kelvin. ε_0 stands for neutral energy which is the energy corresponding to the central wavelength of the spectrum when the absolute temperature is zero, and here

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it approximates the photon energy at the wavelength corresponding to the peak value of the absorption spectrum h and κ stand for Plank constant and Boltzmann constant respectively. And υ is the frequency of pump light.

Table 2. Rate equation parameters and the power propagation equation parameters.

Rate equation	Power propagation equation
Loss coefficient of optical fiber material $\alpha(m^{-1})$	0.1
Nonradiative transition rate $A_{21}(s^{-1})$	2000
Nonradiative transition rate $A_{32}(s^{-1})$	10000
Pump light power $P_p(mW)$	200
Pump light stimulated radiation cross-section $\sigma_{13_{pe}}(m^2)$	8×10^{-25}
Absorption cross-section of pimp light	7×10^{-24}
Fiber core radius $r(m)$	3×10^{-6}
Pumped light wavelength $\lambda_p(nm)$	1600

3.5. Some parts of the model equations

The overall construction of the code is as follows. First, the mathematical model of the BDFA is constructed with rate equations and power equations, and in this model, wavelength, fiber length, and doping concentration of Bi are variables, leading to different cross sections. Other parameters are set as constants to simplify the model to the greatest extent [10]. The model being a function, the method to get the solution of the gain is to solve the ordinary differential equations derived from the rate equations and power equations to calculate the input and output signal power and then the gain. After that, the simulated annealing algorithm is utilized to find the maximum value of the gain and, simultaneously, the corresponding fiber length and doping concentration of Bi.

4. Results and discussion

In this work, the wavelength is in the interval of 1700-1800 nm, but in order to reduce the number of variables, the wavelength is set as a constant, using the center value of the wavelength interval which is 1750 nm [11]. The intervals of fiber length and doping concentration of Bi are set as 2 m to 22 m and 2×10^{24} to 2.2×10^{25} (number of atoms), respectively. After employing the simulated annealing algorithm, the maximum gain is calculated to be 12.0936dB, at the fiber length of 12.8 m and doping concentration of Bi of 2×10^{24}.

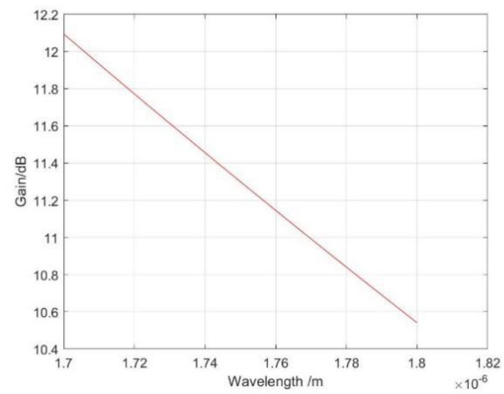

Figure 4. Image of gain as a function of wavelength with the optimal fiber length and doping concentr -ation of Bi.

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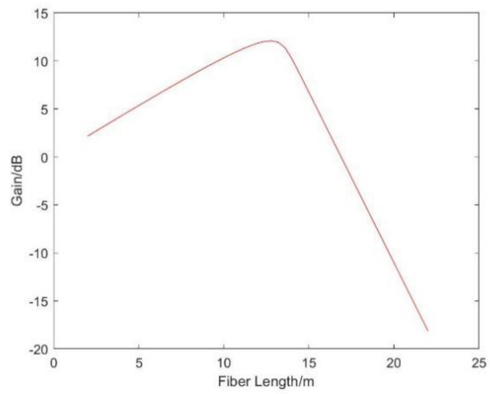

Figure 5. Image of gain as a function of fiber length.

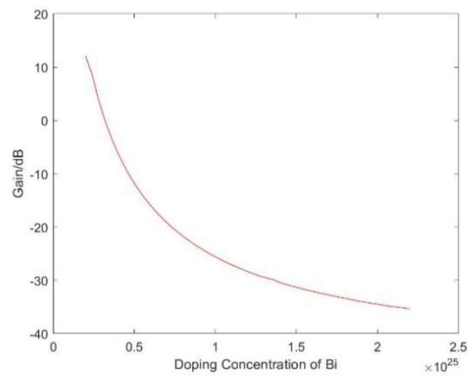

Figure 6. Image of gain as a function of the doping concentration of Bi.

The optimal fiber length and doping concentration of Bi being constant, the gain as a function of wavelength (1700-1800nm) is generated as shown in Figure 4. It can be seen from the figure that the gain changes linearly with neither fiber length nor doping concentration of Bi. Thus, the figures of gain as a function of fiber length and doping concentration of Bi are plotted respectively (Figure 5 and Figure 6). With a certain doping concentration of Bi, the gain increases with the increase of fiber length. It is because, in a certain range of fiber length, the attenuation of pump power in the fiber is not serious, and the gain still increases. However, beyond this range, the attenuation of pump power becomes so severe that its effect on gain exceeds the effect of fiber length, leading to a decrease in gain. When it comes to the principle how gain changes, with a constant doping concentration of Bi, as fiber length increases, it can be seen from Figure 6 that the gain decreases as the doping concentration of Bi increases, which is because the photons absorbed by doping atoms increases, which also leads to a decrease in pump power and consequently a decrease in gain.

5. Conclusion

Longer fiber and higher doping concentration may not result in better performance of BDFA. On the contrary, blindly increasing the fiber length and doping concentration of Bi will lead to a decrease in gain. It is a better alternative to find the parameter leading to the maximum value of gain in a wide range of parameters by simulated annealing algorithm.

Compared to EDFA, the amplification band of BDFA is mainly concentrated in the O-band, which is close to the communication window of quartz fiber with low loss and has a wide gain bandwidth. It also has the characteristics of high gain and low noise amplification similar to EDFA, which meets the basic conditions of being an optical fiber amplifier. In addition, by changing the doping component, BDFA can extend the amplification band to further bands, which has a huge advantage that EDFA

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cannot match, and is expected to become an indispensable optical device in the new generation of optical fiber communication in the future.

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