Modeling and Numerical Simulation of the Gain Spectrum of 1250nm-1350nm Neodymium-doped Broadband Fibre Amplifiers

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Abstract. Nowadays, with the rapid development of information technology, the optical transmission of signals has replaced electrical transmission and become the most widely used method in the world. However, when transmitting the light signal, the loss in energy could not be ignored in the long distance transmission, which highlights the importance of fibre amplifiers. This research focuses on studying the Neodymium-doped fibre amplifier operating in the 1250nm-1350nm band. In this paper, the rate equation and power propagation equation of Neodymium ions are modeled using MATLAB based on its four-level system. With that model, the variations of the gain of the Neodymium-doped fibre amplifier with fibre length, the concentration of Neodymium ions and pumping power are simulated. The results demonstrate that as the fibre length increases in the certain range, the gain rises at first and then drops. The presented peak could be easily obtained. The changing trend of the gain when the concentration of Neodymium ions increases is similar. However, the gain continues to increase when the pump power increases in the practical range. This experiment provides great references in the production of the Neodymium-doped fibre amplifier in the future.

Keywords: Neodymium-doped fibre amplifier; fibre length; doping concentration; Pump power.

1. Introduction

In 1961, Snitzer and Koesker, working for American Optical Corporation, first discovered the laser radiation properties in Neodymium-doped and Erbium-doped fibres during their experimental research [1], which attracted the world's attention and inspired scientists to explore the doped fibre amplifiers. In 1985, Payne at the University of Southampton, invented an Erbium-doped fibre amplifier (EDFA) and achieved laser radiation with a low-loss window of 1.55um [2]. In 2005, IPG developed an all-fibre double-clad yttErbium-doped fibre laser with a record diffraction-limited power output [3]. During the same year, researchers conducted an experimental study of a high-power Erbium-yttErbium co-doped double cladding fibre amplifier, in which an output power value of 2.18W was obtained, with a calculated pumping light utilization rate higher than 35% and an amplifier gain higher than 20dB [4]. In 2019, Bisson experimentally concluded that losses can be reduced by orders of magnitude by lowering the temperature, showing that the laser oscillation threshold can be significantly reduced in cold solar pumping environments [5]. In 2022, Liwei Xu used an all-fiber Nd-doped passively mode-locked fiber laser operating in the 1.06um band based on a nonlinear polarization rotation mechanism to obtain a maximum average output power of 0.63mW at a pump power of 300mW [6]. Doped fibre amplifiers are now widely used in high power and space communications [7-9]. Based on the properties of the neodymium ions and the principle of fibre amplifiers, this experiment establishes a gain model through MATLAB that varies with light length, doping concentration, and pump power to investigate the gain. This experiment helps to promote the

performance of the Neodymium-doped fibre amplifiers and offer efficient solution to the long distance transmission of signals.

2. Model and Method

2.1. Energy Level System of Neodymium Ion

To amplifier the signal light at 1250-1350nm band, the wavelength of the pump light is set to 808nm [10]. As shown in Fig. 1, the Neodymium ion could be considered a four-level system. In this system, 4I9/2, 4I13/2, 4F3/2, and 4F5/2, 4H9/2 are the first, second, third and fourth energy levels, respectively. When pump light is applied on the ion, outer electrons will be pumped to the fourth energy level. Due to the instability of the electrons on the fourth energy level, they will rapidly transit to the third energy level in a non-radiative transition. The lattice will absorb the energy released during this transition in the core, which will not impact the amplification process. After that, when the signal light with a wavelength of 1333 nm irradiates the Neodymium ion, the radiative transition occurs among the electrons located on the third energy level, which amplifies the signal light.

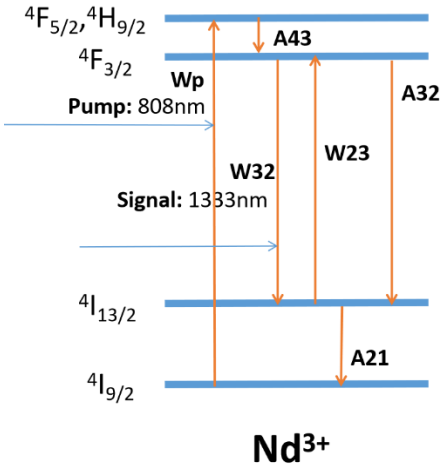

Fig 1. The energy level structure diagram of Nd^{3+}.

2.2. The Rate Equations and the Power Propagation Equations

The rate equations of the Neodymium-doped fibre amplifier are as follows:

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

$$\frac{\partial N_2(z)}{\partial t} = -A_{21}N_2(z) - W_{23}(z)N_2(z) + W_{32}(z)N_3(z) + A_{32}N_3(z) \tag{2}$$

$$\frac{\partial N_3(z)}{\partial t} = W_{23}(z)N_2(z) - W_{32}(z)N_3(z) - A_{32}N_3(z) + A_{43}N_4(z) \tag{3}$$

$$\frac{\partial N_4(z)}{\partial t} = W_p(z)N_1(z) - A_{43}N_4(z) \tag{4}$$

The rate equations are partial differential equations of the concentration of electrons on each energy level, which illustrates the transition of the electrons on each level. As a result, the expressions of the concentration of electrons on each energy level are solved.

The power propagation equations of the Neodymium-doped fibre amplifier are as follows:

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

$$\frac{dP_s(z)}{dz} = \Gamma_s(\sigma_{32}N_3(z) - \sigma_{23}N_2(z) - \alpha_s)P_s(z) \quad (6)$$

$$\frac{dP_{ase}(z)}{dz} = \Gamma_{ase}(\sigma_{32}N_3(z) - \sigma_{23}N_2(z) - \alpha_s)P_p(z) + \sigma_{32}N_3(z)h\nu\Delta\nu \quad (7)$$

The power propagation equations of the Neodymium-doped fibre amplifier are differential equations of the pump power, signal power and spontaneous emission light, respectively. With these equations, the power of spontaneous emission light is solved.

2.3. Experimental Methods and Expected Experimental Results

Based on the wavelength range of the signal light (1250-1350nm), the energy level system of Neodymium ions and the electron leap process, the pump light with a wavelength of 808nm was selected. And the rate and power propagation equations were established based on this energy level system. Secondly, the rate and power propagation equations were used to solve the bulk density of electrons at each energy level with respect to the length of the optical fibre, and the power propagation equations were used to solve for the received radiation power and signal power to obtain the gain of the fibre. Thirdly, through cycles, the values of the fibre gain in the wavelength interval of 1250-1350nm are obtained and plotted as images for different fibre lengths, doping concentrations, and pumping powers. The experiment is intended to simulate the variation of the gain spectrum of the Neodymium-doped fibre amplifier under different conditions and to derive the conditions under which the gain of the Neodymium-doped fibre amplifier achieves its maximum value.

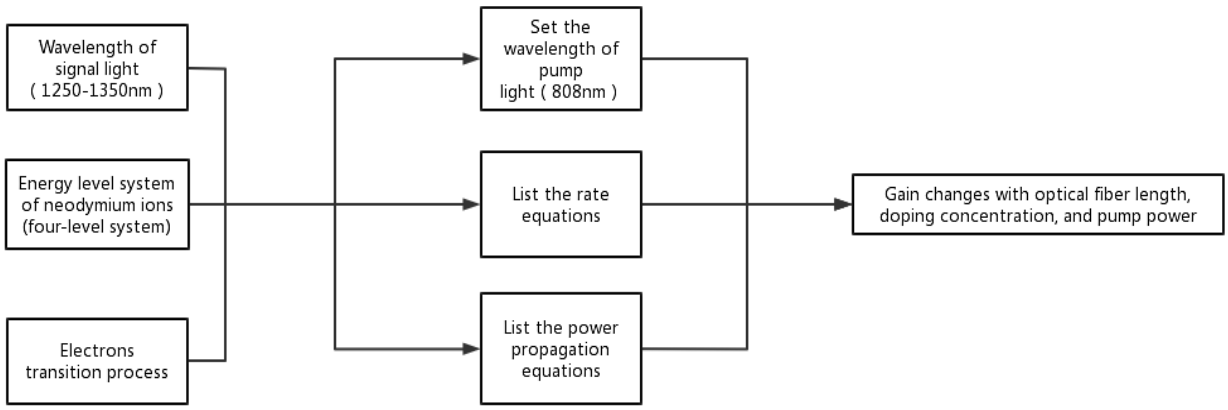

Fig 2. The procedure of the experiment.

3. Experimental results and analysis

For this experiment we used MATLAB for numerical simulations. We chose the wavelength of pump light as $\lambda p = 808nm$, the wavelength signal light as $\lambda s = 1333nm$, a background loss factor $\alpha = 0.1\,m^{-1}$, a radiative excursion chance at energy level 32 $A_{32} = 543.66s^{-1}$, a radiative excursion chance at energy level 43 $A_{43} = 2079.47s^{-1}$, a radiative excursion chance at energy level 21 $A_{21} = 2000s^{-1}$, a fibre radius $r = 3.0 \times 10^{-6}$ m, a signal light absorption cross section $\sigma_{sa} = 5.15 \times 10^{-25}\,m^2$, signal light emission cross section $\sigma_{se} = 5.15 \times 10^{-25}\,m^2$, pump light absorption cross section $\sigma_{pa} = 2.05 \times 10^{-24}\,m^2$, pump light emission cross section $\sigma_{\mathrm{pe}} = 0.8 \times 10^{-25}\,m^2$ [11].

3.1. Effect of fibre length on gain spectrum

At doping concentration $\mathrm{N} = 0.8 \times 10^{-25}$ (ions /m^3) and pump power $\mathrm{P_p} = 0.2\mathrm{W}$, the fibre length L varies from 6m to 14m and the simulation yields an image of the gain spectrum as a function of fibre length. Figure 1 shows the gain-fibre length line graph.

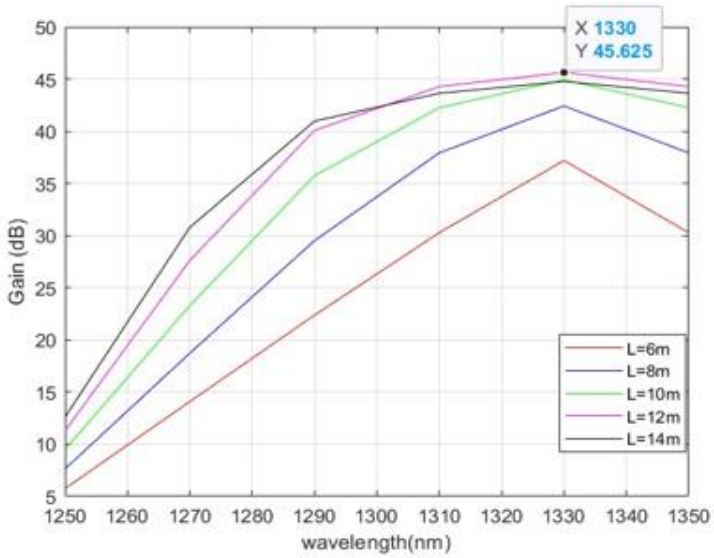

Fig 3. Variation of gain as a function of fibre length.

Fig. 3 shows that when the fibre length was increased by$L = 2m$, the gain increased in almost all of the measured wavelengths, and a decrease was observed at a small number of wavelengths. At 1330nm wavelength, when the fibre length L=6m is increased to about$L = 12m$, the gain increases by about 21. 6%. As the fibre length continues to increase to$L = 14m$, the gain gradually decreases. This phenomenon is due to the long length of the fibre, resulting in some ground state ions not being excited by the pump light and jumping to higher energy levels, resulting in poor gain. So the fibre length tries to choose the right length to avoid causing insufficient ion excitation due to too long length, which eventually causes gain reduction. This practice wastes fibre material, and the amplification efficiency of the fibre amplifier is reduced. This simulation took a maximum gain of 45. 625 at fibre length $L = 6m$, pump power $Pp = 0.7W$, and doping concentration $N = 0.8 \times 10^{25}$ (ions /m^3).

3.2. Effect of doping concentration on the gain spectrum

At a fibre length L=6m and pump power $Pp = 0.2W$, the doping concentration N varies from 0.5×10^{25} (ions /m^3) to 2.5×10^{25} (ions /m^3), and the simulation yields an image of the gain spectrum as a function of doping concentration. Figure 2 shows the gain-doping concentration line graph.

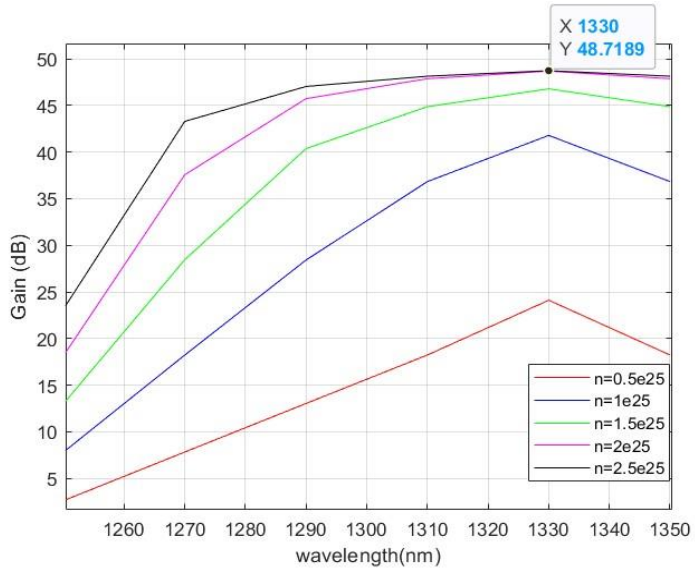

Fig 4. Folding graph of gain with doping concentration.

Fig. 4 shows that the doping concentration increases with $N = 0.5 \times 10^{25}$ (ions /m^3), the gain increases within the measured wavelength. The gain increases by about 100% from the initial $N = 0.5 \times 10^{25}$ (ions /m^3) to $N = 2.5 \times 10^{25}$ (ions /m^3). The maximum value was taken at around 1330nm for different doping concentrations because 1330nm is the central wavelength of the signal light where the absorption and emission cross sections of the signal light are maximum. The doping concentration is one of the factors affecting the gain. When the doping concentration increases, more ions are irradiated by the signal light to produce the radiation jump, and the gain becomes larger. This simulation took a maximum gain of 48.7189 at fibre length $L = 6$m, pump power$Pp = 0.2$W, and doping concentration $N = 2.5 \times 10^{25}$ (ions /m^3).

3.3. Effect of pump power on the gain spectrum

At a fibre length L=6m and a doping concentration N=0. 8×10^{25} (ions /m^3), the pump power Pp varies from 0. 1W to 0. 7W and the simulation yield an image of the gain spectrum as a function of pump power. Figure 3 shows the gain-pump power line graph.

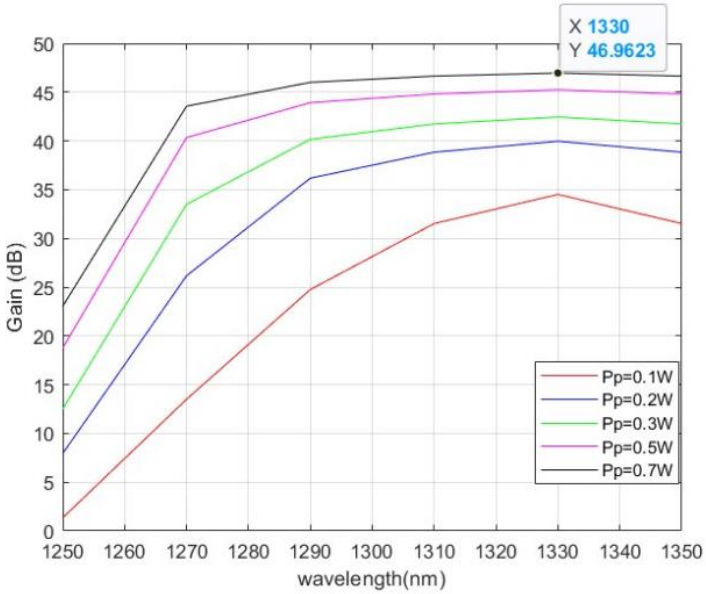

Fig 5. Variation of gain as a function of pump power.

Fig. 5 shows that when the pump power increases, the gain increases within the measured wavelength. The gain increased by about 31% when increasing from the initial $Pp = 0.1W$ to$Pp = 0.7W$. The maximum value was taken at around 1330nm for different pump powers because 1330nm is the central wavelength of the signal light where the absorption and emission cross sections of the signal light are maximum. The pump power is one of the factors affecting the gain. When the pump power increases, the more ions are excited to higher energy levels by the pump light, the more ions undergo radiative leap and the gain becomes larger. This simulation took a maximum gain of 46. 9623 at fibre length L=6m, pump power$Pp = 0.7$W, and doping concentration $N = 0.8 \times 10^{25}$ (ions /m^3). In Nd-doped fibre amplifiers, the pump power should not be taken too large, which may cause material damage.

4. Conclusion

According to the gain spectrum, with the increase of the wavelength in the range of 1250nm-1350nm, the gain rises rapidly at first, and then the increase slows down. Finally, the gain decreases. When the wavelength is 1330nm, the gain reaches its maximum. By setting different variables, the optimal fibre length and doping concentration are obtained as 12m and$2.5 \times 10^{25}(\text{ions}/\text{m}^3)$. In this experiment, the gain of fibre is simulated when the pump power is set as certain values. The gain continues to increase when pump power increases. Considering the practical application, larger pump

power will not be tested. In this experiment, Matlab is used to stimulate the change of gain with the wavelength between 1250-1350nm, under different fibre lengths, doping concentrations and pump power. The gain spectrum is also drawn to demonstrate the change tendency intuitively. However, this experiment does not involve all the factors that affect the gain of the Neodymium-doped fibre amplifier. Further experiments could be carried out to test the influence of the material of the fibre and temperature on the gain of the Neodymium-doped optical amplifier.

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