Design and Optimisation of L+ Band Fibre Optic Amplifier (1600-1650nm)

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Abstract. With the rapid development of the information age, there is an increasing demand for broadband high-speed communication systems and high-quality signal transmission. Numerous optical communication applications exist for the L+band fiber amplifier, providing high gain and low noise amplification effects. This report aims to improve the performance of L+band fibre amplifiers by researching and developing praseodymium-doped fibre materials and optimising various parameters and structures of fibre amplifiers. Through this study, we hope to provide an economical, and we hope to provide an economical and efficient design and optimization solution for L+band praseodymium ion doped fibre amplifiers, making them an essential component of optical communication systems. Improving the signal gain and quality provides a reliable signal amplification solution for the optical communication system to meet the challenges of high-speed and high bandwidth data transmission requirements in Kobee. In the established praseodymium doped fibre amplifier, 488nm wavelength was used as the pump light wavelength, 1625nm wavelength as the signal light wavelength, and a four-level system was used for analysis. After experiments, through three-dimensional diagrams and simulation optimisation algorithm results, the amplifier gain After investigations, the progress of the amplifier shows a specific positive growth with the increase of fibre length and doping ion concentration. When the fibre length increases to 2.479m, the gain of the amplifier no longer changes with the rise of fibre length—the concentration of doped ions.

Keywords: Praseodymium doped fibre amplifier, Fiber communication, L+band, Doping concentration.

1. Introduction

Given the quick growth of mobile Internet, short video, big data, cloud computing and 5G, the information demand is exploding at a rate of 30%-40% per year, putting higher demands on optical fiber communication volume.[9] Praseodymium-doped fiber amplifiers in the L+ band are gradually gaining attention [6] [8] as essential signal amplifiers due to the growing demand for high-speed and high-bandwidth data transmission in optical communications. Praseodymium (Pr3+) has promise for producing unique near-infrared emissions. [4] In the radiative transition from the metastable 1G4 to the 3H5 state, this ion is optically active at roughly 1.3 pm. [5] Conventional praseodymium-doped fibre amplifier design methods have some drawbacks in the L+ band, such as enhancing fibre nonlinear effects, the requirement of dispersion compensation, and other problems. [7] Attenuation is one of the main limiting factors for long-haul optical links and optical networks. Long-haul optical links and optical networks are restricted by numerous fiber-related defects. [10] To overcome these challenges, this topic aims to utilise the Pr^{3+} particular four-energy system signal model for an in-depth study to enhance the gain and performance of praseodymium-doped fiber amplifiers by optimizing their parametric design.Pr^{3+}ions have a broad gain bandwidth and small excitation power of excitation [1] and are therefore widely regarded as a promising material for amplifiers. However, to take full advantage of the Pr^{3+} benefits of ions, a detailed study and analysis of their four-energy level system are required. In this project, we will establish the Pr^{3+} signal model of the four-energy system of ions and explore in depth its design and optimisation for L+ band fibre-optic amplifiers.

Based on an in-depth study of the Pr^{3+} the signal model of the four-energy system of the ion [2], this topic will optimise the structure and parameter design of praseodymium-doped fibre amplifiers to improve their gain and performance. Particularly in terms of fibre nonlinear effect enhancement and dispersion compensation, this topic will explore novel amplifier structures and optimisation algorithms to overcome the impact of these issues on praseodymium-doped fiber amplifiers' performance in the L+ band.

This project aims to obtain an efficient and reliable design method for a praseodymium-doped fibre amplifier in the L+ band through experimental verification. By optimising the parameter design of the amplifier, including the fibre length, praseodymium-doped ion concentration, etc., to achieve the best gain and performance, we will use Matlab software to evaluate and optimise different parameter combinations to determine the best amplifier design solution. This study can provide a cost-effective and efficient design and optimisation of L+ band praseodymium-doped fiber amplifiers, promoting the development of optical communication systems in high-speed and high-bandwidth data transmission.

2. Modelling and Methodology

Praseodymium-doped fibre amplifier (PDFA) is a fibre amplifier that can work at 1450nm-1650nm wavelength and is a quasi-4-energy level system. Therefore, a four-energy level system is adopted in this experiment.

Praseodymium is a four-energy level system, where energy level one is the ground state, two and three are lasing upper and lower energy levels that are subtable, and energy level four is the excited state. The particles are first transported from the ground state energy level to the higher energy level by some imposed pumping mechanism. After a short period τ_{32}, the particles are transferred to the upper energy level of the laser in a radiation less leap. From the lasing upper to lower energy levels, the particles can leap by both spontaneous and excited radiation. The duration of this leap process is τ_{21}. Finally, it undergoes τ_{10}time the particle quickly returns to the ground state energy level in a non-radiative manner.

Four energy level rate equations:

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

$$\frac{\partial N_2(z)}{\partial t} = A_{12}(z)N_z(z) - W_{23}(z)N_2(z) + W_{32}N_3(z) + A_{32}N_3(z) \tag{2}$$

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

$$\frac{\partial N_3(z)}{\partial t} = W_p(z)N_1(z) - A_{32}N_3(z) \tag{4}$$

$$N = N_1(z) + N_2(z) + N_3(z) + N_4(z) \tag{5}$$

$$\mathrm{N1} = \frac{A_{21}A_{32}A_{43}N + A_{21}A_{43}NW_{32}}{A_{21}A_{32}A_{43} + A_{21}A_{43}W_{32} + A_{21}A_{32}W_P + A_{21}A_{43}W_P + A_{32}A_{43}W_P + A_{21}W_{32}W_P + A_{43}W_{23}W_P + A_{43}W_{32}W_P} \tag{6}$$

$$\mathrm{N2} = \frac{A_{43}NW_P(A_{32} + W_{32})}{A_{21}A_{32}A_{43} + A_{21}A_{43}W_{32} + A_{21}A_{32}W_P + A_{21}A_{43}W_P + A_{32}A_{43}W_P + A_{21}W_{32}W_P + A_{43}W_{23}W_P + A_{43}W_{32}W_P} \tag{7}$$

$$\mathrm{N3} = \frac{A_{43}NW_P(A_{21} + W_{32})}{A_{21}A_{32}A_{43} + A_{21}A_{43}W_{32} + A_{21}A_{32}W_P + A_{21}A_{43}W_P + A_{32}A_{43}W_P + A_{21}W_{32}W_P + A_{43}W_{23}W_P + A_{43}W_{32}W_P} \tag{8}$$

$$N4=\frac{NW_P(A_{21}A_{32}+A_{21}W_{32})}{A_{21}A_{32}A_{43}+A_{21}A_{43}W_{32}+A_{21}A_{32}W_P+A_{21}A_{43}W_P+A_{32}A_{43}W_P+A_{21}W_{32}W_P+A_{43}W_{23}W_P+A_{43}W_{32}W_P} \quad (9)$$

Four energy level power propagation equations:

$$\frac{dP_p(z)}{dz}=-\Gamma_p(\sigma N_1(z)+\alpha_a)P_P(z) \quad (10)$$

$$\frac{dP_s(z)}{dz}=\Gamma_s[\sigma_{32}N_3(z)-\sigma_{23}N_2(z)-\alpha_s]P_s(z) \quad (11)$$

$$\pm\frac{dP_{are}(z)}{dz}=\pm\Gamma_{are}[\sigma_{32}N_3(z)-\sigma_{23}N_2(z)-\alpha_s]P_s(z)\pm 2\sigma_{32}N_3(z)hv\bigtriangleup v \quad (12)$$

Table 1. Description of the parameters of the rate equation and power propagation equation

parametric	Parameter description
W_P	pump light absorption rate
W_{12}	Signal light absorption rate
W_{21}	Signal light stimulated emission rate
A_{32}	radiation jump rate
A_{21}	radiation-free jump rate
A_{43}	radiation-free jump rate
N_1	Particle number density in the first energy level
N_2	Particle number density in the second energy level
N_3	Particle number density in the third energy level
N_4	Particle number density in the fourth energy level
N	Total particle number density
α	Loss factor of fibre optic materials
Δv	Frequency Half Height Full Width

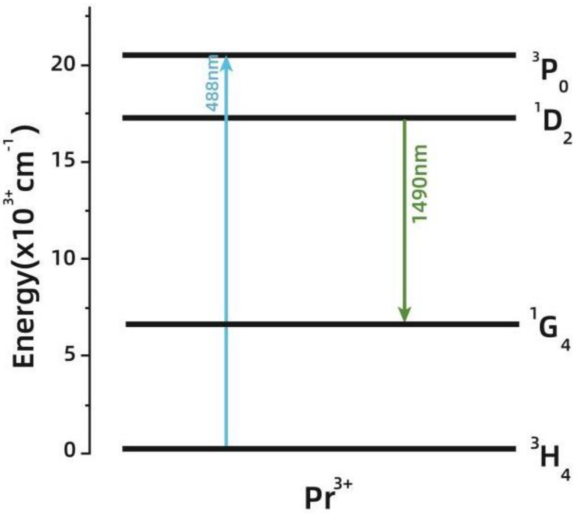

Figure 1. Schematic energy levels of Pr3+ in glass fibre materials

Selected for this experiment is a four-energy level system from Fig.1 energy level schematic, want to deal with the centre wavelength of 1625nm signal light in the four-energy level state, then need to choose 488nm as the wavelength of the pump light for pumping, then the pump light has been determined.

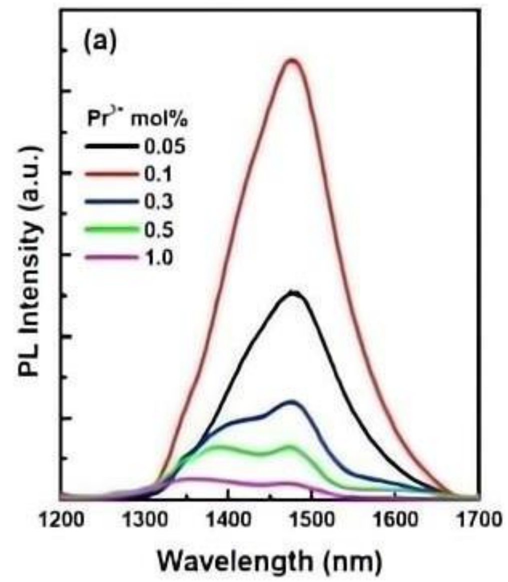

Figure 2. Near-IR PL spectra of Pr3+ -doped fluoro-tellurite glasses under 488 nm wavelength excitation [3]

After determining the pumping light, due to the experimental study of the 1600-1650nm wavelength range, from Fig.2, we can see that the signal stimulated emission centre wavelength of 1490nm, the wavelength range can be covered by the subject of the wavelength range of the study, in Figure 1.1, the 1490nm signal light stimulated emission from the 1D2 energy level to the 1G4 level, the entire praseodymium-doped fibre amplifier using a four-energy-level The real praseodymium-doped fibre amplifier is a four-stage system, pumped at 488 nm. Several of the more critical parameters of the praseodymium-doped amplifier model established for the subject have been determined.

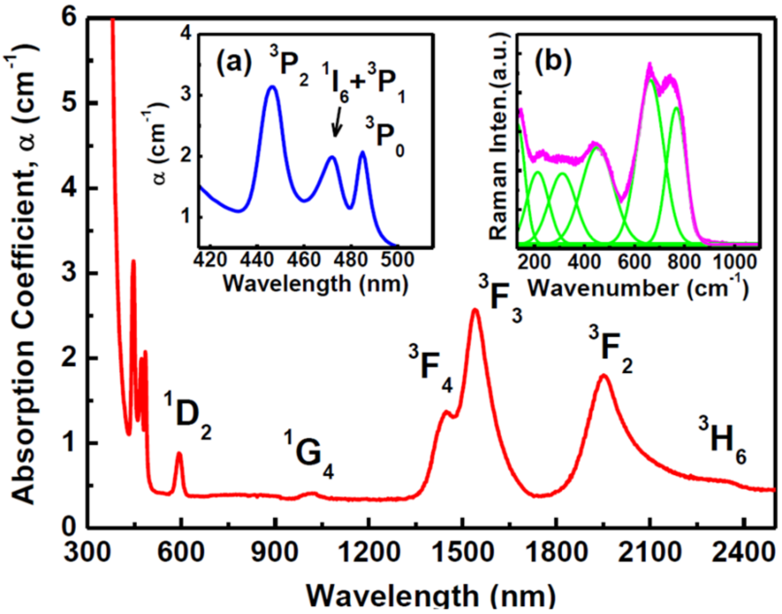

Figure 3. The optical absorption spectrum of (0.5 mol%) Pr3+-doped fluoro-tellurite glass [3]

When the pump light wavelength is 488nm, and the signal light wavelength is 1625nm, the approximate Absorption Coefficient can be obtained from Fig. 3 by tracing the points using Get Data software.

$$ab(488)=0.6cm^{-1} \tag{13}$$

$$ab(1625)=1.1cm^{-1} \tag{14}$$

$$M_{P_{rF3}} = 197.9_{g/mol} \tag{15}$$

$$d = 6300kg/m^3 = 6.3g/cm^3 \tag{16}$$

Depending on the chemical formula of the glass fibre optic material used:

$$3L_{aF3} - 4BaF_2 - 4BaCO_3 - 9ZnO - 80TeO_2 - Pr\,F_3 \tag{17}$$

PrF_3 The doping concentration ofW_{PrF_3} is approximately 1.255%

$$Av = 6.02214076 \times 10^{23}/mol \tag{18}$$

Avogadro's number:

$$mol_{Pr\,F_3} = d \times Wt_{Pr\,F_3}/M_{Pr\,F_3} = 0.39952_{mol} \tag{19}$$

$$N_{Pr} = 1 \times mol_{Pr\,F_3} \times Av = 2.368 \times 10^{23} \tag{20}$$

Praseodymium ion absorption cross-section:

$$\sigma_{14} = ab(488)/Ne_{Pr} \tag{21}$$

$$\sigma_{23} = {}_{ab}(1625)/Ne_{Pr} \tag{22}$$

By the emission cross section and the absorption cross-section:

$$v = \frac{c \times l \times 10^9}{1625} \tag{23}$$

$$\sigma_{em}(v) = \sigma_{ab}(v)\,exp(\frac{\varepsilon_0 - hv}{KT}) \tag{24}$$

It can be obtained that the firing cross-sectional area:

$$\sigma_{32} = 4.646 \times 10^{-25} \tag{25}$$

This gives the absorption cross section at a pump light of 488 nm and a signal light wavelength of 1625 nm σ_{23} and emission cross section σ_{32} and σ_{14}. At the same time theA_{21}, A_{43}, and A_{32} Equivalent values [4] substitute the values into the code written.

The Matlab software used in this experiment is designed to design the pumping wavelength according to the signal wavelength range, energy level structure and electron jump process, establish the rate equation and power propagation equation and programmed to calculate the change of gain spectrum with the fibre length and doping concentration. The simulated annealing algorithm optimises the fibre length to maximise the peak gain.

3. Results and Discussion

3.1. Sub heading

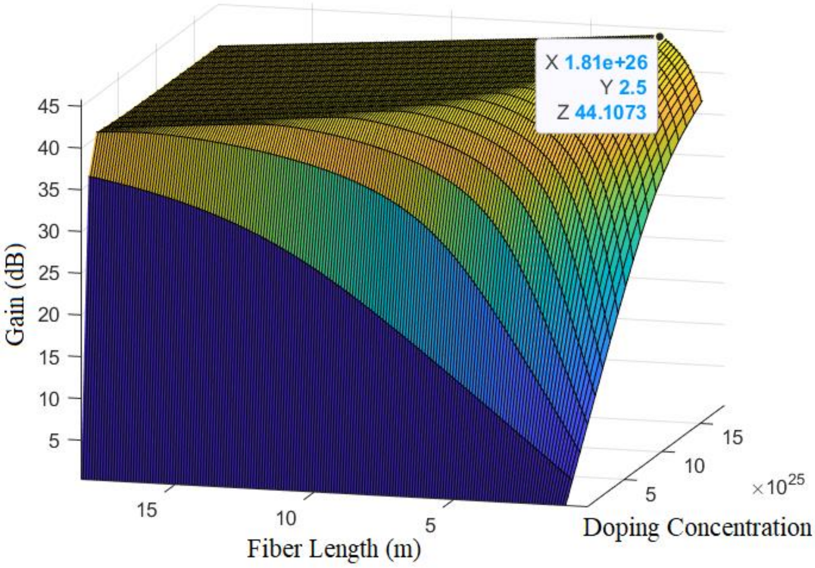

Figure 4. Operational results

After running the program, the experiment obtained a three-dimensional view of the gain (dB) with the fibre length (m) and the dopant ion concentration (a/m^2) changes due to the fibre length of the range of changes in the interval of 0.1. It can be concluded from the figure the gain of the optical fibre amplifier with the size of the light and the ion dopant ion concentration of the increase in the increase of the gain has been a certain amount of expansion when the fibre length is unchanged, the gain with the dopant concentration of the positive growth; dopant When the doping attention is constant, the gain grows positively with the size of the fibre, but when the length of the thread reaches a specific value, the edge no longer grows. When the fibre length is 2.5m and the doping concentration is 1.81×1026 units/m^2, the maximum gain is 44.1073dB.

3.2. Optimisation of the Simulated Annealing Algorithm

The developed praseodymium-doped fiber amplifier model is then optimized using the simulated annealing technique. The principle of simulated annealing algorithm: The simulated annealing algorithm begins with a higher initial temperature and a decreasing temperature parameter, combined with a particular probabilistic jump characteristic in the solution space to haphazardly search for the global optimal solution of the objective function. In other words, the local optimal solution can be probabilistically outside the solution and eventually converge to the globally optimal solution. The obtained results are shown in Fig.5 below:

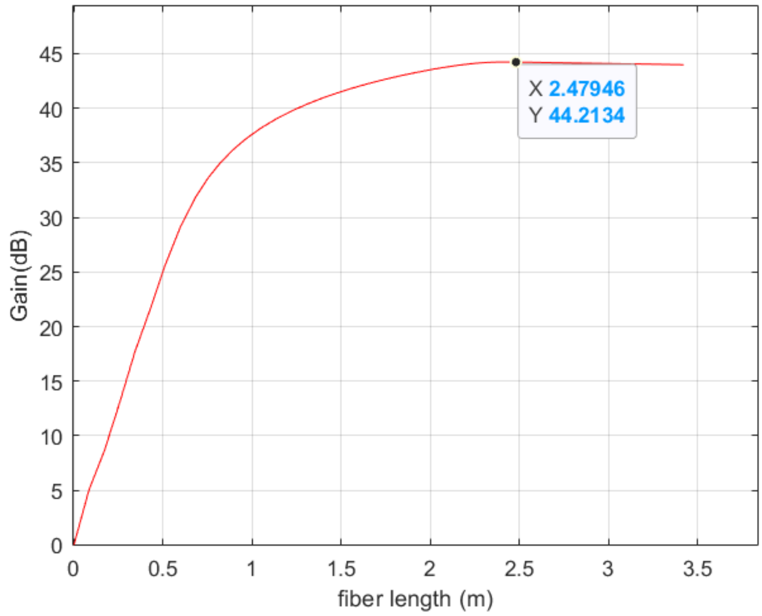

Figure 5. Optimisation results

From Fig.5, it can be seen that when the fibre length is less than 2.479m, the gain of the amplifier grows positively with the fibre length, and the slope decreases continuously. When the fibre length is more significant than 2.479m, the amplifier gains no more extended changes or slowly decreases with the fibre length.

The praseodymium-doped fibre amplifier has a maximum gain of 44.2134 dB when the length of the fibre L = 2.479 m and the ion concentration is 1.81 × 1026 ions/m^2, which is the same as the result of the three-dimensional diagram in the main program.

3.3. Error Analysis

Also, the experiment itself can have errors. The reason for the mistakes is that in the 3D model, the spacing range used is 0.1 m, and all the points obtained in the graph are discrete. Whereas in simulated annealing, the curve of fibre length with gain can be obtained, and more accurate values can be obtained.

4. Conclusion

In selecting doping ion types for fibre amplifiers in the L+band (1600-1650 nm) studied in this experiment, praseodymium-doped fibre amplifiers were ultimately chosen as the fibre amplifiers for this experiment through the exploration of Pr^{3+}. This experiment investigates the gain variation in praseodymium-doped fibre amplifiers with doping concentration and fibre length. When the pump wavelength is 488nm and the signal wavelength is 1625nm, Matlab simulation results show that the gain of the amplifier increases positively with the increase of fibre length and doping ion concentration. When the fibre length rises to 2.479m, the growth of the amplifier no longer changes with the addition of fibre length. At this point, the gain of the fibre optic amplifier is only related to the concentration of doped ions.

When the fibre length is 2.479m, and the doping ion concentration is 1.81×1026 pieces/m^2. At this time, the gain of the praseodymium-doped fibre amplifier reaches its maximum value, which is 44.2134dB.

Overall, in the experiment, we used a praseodymium-doped fibre amplifier to study the optical signal at 1625nm wavelength. However, the praseodymium-doped fiber amplifier's performance in amplifying optical signal light with a wavelength of 1600–1650 nm is not very excellent. In the future, multiple experiments are needed to find a better ion-doped fibre amplifier to achieve the maximum gain of the optical signal at 1600-1650 nm wavelength.

Authors Contribution

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

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