Design and Optimization of E-Band Fluor tellurate Fiber Amplifier Doped with Praseodymium

Xiangyuan Huang *

Xuhai College, China University of Mining and Technology, Xuzhou, China

* Corresponding author: 1910841137@mail.sit.edu.cn

Abstract. This study focuses on investigating and selecting an appropriate optical fiber material, specifically emphasizing the utilization of fluorotellurate as the base material. The objective is to enhance the performance of the optical fiber material by incorporating praseodymium ions, which possess unique properties advantageous for optical amplification.To gain an accurate understanding of the working principle of the fiber optic amplifier, a mathematical model is developed. This model acts as a valuable tool for simulating and optimizing the amplifier's performance. By conducting rigorous simulations and optimization processes using this model, critical parameters can be identified and fine-tuned to achieve optimal gain characteristics.To verify the efficacy of the designed fiber amplifier, comprehensive experimental tests are conducted. The results from these experiments convincingly demonstrate the amplifier's remarkable gain characteristics, particularly within the E-band frequency range. This research breakthrough not only highlights the amplification capabilities of the designed fiber amplifier but also presents a promising design scheme for future E-band communication systems. By selecting fluorotellurate as the base material and incorporating praseodymium ions, this study introduces an innovative approach to enhance the performance of optical fiber amplifiers. The development of a robust mathematical model enables efficient simulation and optimization, thus acting as a valuable tool for the future design and development of amplifiers. The successful experimental validation further emphasizes the potential of the designed fiber amplifier as a pivotal component for advanced E-band communication systems.

Keywords: amplifier, The fifth optical telecommunication window, Genetic algorithm, Energy level transition.

1. Introduction

An optical amplifier based on a fiber doped with praseodymium ions is known as an erbium-doped fiber amplifier (EDFA).

In the last century, this material was widely used in cable TV signal amplification, but with the withdrawal of cable TV from the historical stage and the gap with mainstream material gain efficiency, it temporarily lost its important position. However, it is expected that in the future, this material is expected to show compelling characteristics again [1].

Currently, an important research direction of praseodymium-doped fiber amplifiers is to use new fiber materials, such as silicon-based praseodymium-doped fiber and microstructure fiber, to expand the application range of praseodymium-doped fiber amplifiers [6,7]. These new materials can achieve higher gain and lower noise, and have better compatibility and preparation flexibility compared to traditional optical fibers [9, 10].

In addition, with the development of optical communication and optical networks, praseodym-doped fiber amplifiers are also facing new challenges. For example, in order to adapt to the needs of high rate, multi-wavelength, multi-channel and so on, its application, and has made important contributions to the development of optical communication and optical networks.

2. Literature review

Rare earth ions are widely used in optical amplifiers of multiple bands because of their activity, and they play a role as dopants in optical fibers. In order to create optical gain media like silicate glass, transition metals and main group metals are also utilized as dopants. These substances in metals

have an emission window of 500 nm, centered at 1300 nm. However, the development of these materials faces additional difficulties because these ions lack the shielding properties of rare earth ions, resulting in an energy profile dependent on the host material. In addition, these materials may have polyvalent states that limit the concentration of active ions [11].

In previous studies, it has been demonstrated that Praseodymium(Pr^{3+})-doped fluoro-tellurate glass can observe wide-band photoluminescence (PL) in the wavelength range of 1.30 ~ 1.67μm at both 488 nm and 590 nm excitation[2].In Pr^{3+} -doped phosphate (LCBALP) glass showed effective near-infrared emission encompassing the fifth optical communications window (1350-1450 nm).The quantum efficiency of Pr^{3+} doping in fluoro-tellurate glass is as high as 73.7% at a low dose of 0.05 mol%. At 1467.5 nm, the highest stimulated emission cross section (rem) of phosphate-doped glass (LCBALP) is 1.29×10^{-20} cm^2 . It is calculated that the Pr^{3+} - $_1D^2$ level's quantum efficiency is 85.36%.

Moreover, Pr^{3+} doping concentration changes the linear shape, band width and lifetime of PL. The above studies show that praseodymium doped glass fiber has a broad application prospect in realizing effective broadband amplification, especially in the E-band.

3. Model and method

To fine-tune the gain effect, researchers can modify the length of the fiber and the doping concentration. This adjustment allows for precise control over the gain effect. Monitoring the output optical signal serves as a reliable indicator to gauge the effectiveness of the gain achieved. Praseodymium (Pr) ions have been chosen as the dopant in this study. One of the main reasons for this choice is the unique four-level structure that praseodymium possesses. The praseodymium ion can occupy four different energy levels, which are described by the four-level structure. The gain effect of praseodymium ions is due to their four-level structure. The doping concentration and fiber length can be changed to alter the energy levels of praseodymium ions.

This structural feature plays a crucial role in enabling efficient amplification of light signals within the fiber. By leveraging the distinctive energy levels of praseodymium ions, researchers can utilize their inherent properties to achieve the desired gain effect in the fiber. This capability allows for precise manipulation and control of the optical signal, which is crucial in a wide range of applications, including telecommunications, optical amplification, and signal processing. Overall, the flexibility to adjust gain through altering fiber length and doping concentration, along with the remarkable four-level structure of praseodymium ions, presents promising opportunities for improving optical amplification and signal transmission efficiency in various optical devices and systems.

According to previous studies, it is widely recognized that samples doped with Praseodymium (Pr^{3+}) and excited at 488 nm exhibit characteristic near-infrared photoluminescence (PL) spectra. Specifically, in samples with low Pr^{3+} doping concentrations, a broad emission band spanning the wavelength range of 1.30-1.67 μm can be observed. As the Pr^{3+} ion concentration increases [8], there is an initial surge in PL intensity. However, beyond a certain threshold, the PL intensity starts to decline. Simultaneously, the emission peak undergoes a shift towards shorter wavelengths, while the emission band diminishes at longer wavelengths [3]. This observation indicates that the presence of Pr^{3+} ions have a direct effect on the emission properties of the material. An increase in ion concentration leads to the formation of more active centers, which enhances the material's emission properties. resulting in enhanced photoluminescence intensity. Nevertheless, once the concentration surpasses a certain level, undesired energy transfer processes may occur, leading to a reduction in overall photoluminescence intensity. Furthermore, the observed shift of the emission peak towards shorter wavelengths can be attributed to changes in the energy states of the Pr^{3+} ions within the material. This shift indicates alterations in the local environment surrounding the Pr^{3+} dopants, such

as modifications in the crystal lattice structure or neighboring ligands. Additionally, the decrease in the emission band at longer wavelengths strengthens the influence of higher Pr^{3+} doping concentrations. This suggests that an increased concentration of Pr^{3+} ions can potentially enhance interactions and energy transfer processes, resulting in a narrower emission spectrum at longer wavelengths. For materials to be optimized and tailored for a variety of applications in the disciplines of photonics, telecommunications, and related sectors, it is essential to accurately understand these effects and their connection with doping concentration. Further in-depth research and exploration are required to fully uncover the underlying mechanisms and harness their potential [4].

At 996 nm wavelength excitation, a strong emission of about 1.33μm corresponding to this transition was observed. The emission band ($_1D^2 \rightarrow {}_1G^4$) and absorption band ($_3F^4 \leftarrow {}_3H^4$) have a spectral overlap. The decrease in PL intensity at higher Pr^{3+} doping levels, is caused by the cross-relaxation process, especially on the longer wavelength side. [$_1D^2$, $_3H^4$]→ [$_1G^4$, $_3F^4$][5].The closer the separation of Pr^{3+} - Pr^{3+} at higher Pr^{3+} doping level, the easier this process is to occur, causing the emission energy level of Pr^{3+}:$_1D^2$, whose emission spectra peak is 1330 nm, to be exhausted.

The excitation band near 590nm shows that at higher Pr^{3+} doping concentration, the emission level Pr^{3+}:$_1D^2$ is directly filled due to the resonance excitation route. The peak of the emission spectrum is 1487nm.

It can be seen that the emission spectrum of praseodymium ion can well cover the E-band (1350nm~1450nm), so praseodymium ion is chosen as the doped ion in this topic.

The rate equation is as follows:

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

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

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

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

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

The power propagation equation is as follows:

$$\frac{dP(z)}{dz} = \Gamma_p(-\sigma_p N_1(z) - \alpha_\alpha)P_p(z) \tag{6}$$

$$\frac{dP(z)}{dz} = \Gamma_s[\sigma_{32}N_3(z) - \sigma_{23}N_2(z) - \alpha_s]P_s(z) \tag{7}$$

$$\frac{dP_{ase}(z)}{dz} = \Gamma ase[\sigma_{32}N_3(z) - \sigma_{23}N_2(z) - \alpha_s]P_s(z) + \sigma_{32}N_3(z)h\nu\Delta\nu \tag{8}$$

In this study, Matlab was selected as the programming tool to calculate the relationship between the gain spectrum of praseodymium-doped fiber and the doping concentration over the fiber length under experimental conditions of 200mW pump power. The purpose of using Matlab was to perform accurate calculations and analyze the data effectively.

In addition, a genetic algorithm was employed to optimize the experimental results. This algorithm is renowned for its applicability, robustness, and global search capability, making it well-suited for solving complex optimization problems. By utilizing the genetic algorithm, the researchers were able to explore a wide range of possible solutions and identify the optimal configuration that maximized the gain.

The final experimental results showed that the gain reached a peak value, indicating a significant improvement in the performance of the praseodymium-doped fiber. The results also provided valuable insights into the relationship between the gain spectrum and the doping concentration, contributing to a better understanding of the underlying physics of the fiber and its potential applications. The parameters used in the calculation have been listed in Table 1 for reference.

Table 1. Study the parameters used in the calculation

argument	numerical value	unit
Lambda_P	996	Nm
Lambda_S	1400	Nm
Ps	1×10^{-6}	dBm
Pp	0.2	dBm
Pase	0	dBm
C	3×10^{8}	m/s
T	300	F
K	1.38×10^{-23}	J/K
Alpha	0.1	dB/m
Delta	12.5×10^{9}	
H	6.626×10^{-34}	
Sig_se	0.5×10^{-25}	
Sig_sa	0.5×10^{-25}	

3.1. Results of differential equation solution

After studying the fiber length and sufficient doping concentration, the peak gain is obtained.

From Figure 1, we can see that when the doping concentration is 8.5×10^{25} and the fiber length is 2.2 m, the maximum gain is 42.7184 dB.

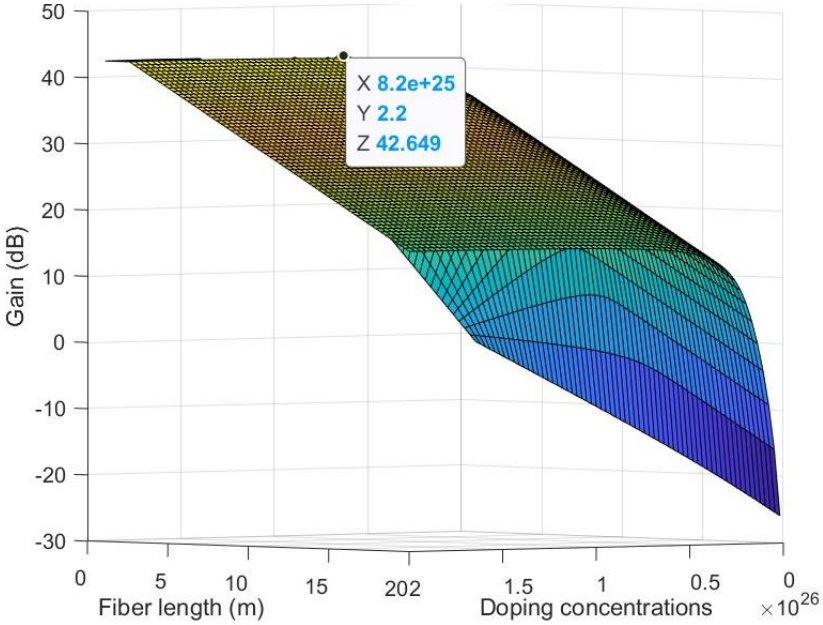


Figure 1. The doping concentration and fiber length of the optimal gain are obtained based on matlab 3D drawing

3.2. Genetic algorithm result

After running the genetic algorithm multiple times and excluding any results that were obtained due to premature maturation of the algorithm, we obtained the optimal configuration of the gain fiber. The length of the gain fiber reached its peak at 2.2061 meters, and there was little deviation from the result obtained through three-dimensional drawing.

As illustrated in Figure 2, This finding indicates that the optimal configuration for the gain fiber is 2.2061 meters, and this configuration can maximize the gain of the praseodymium-doped fiber.

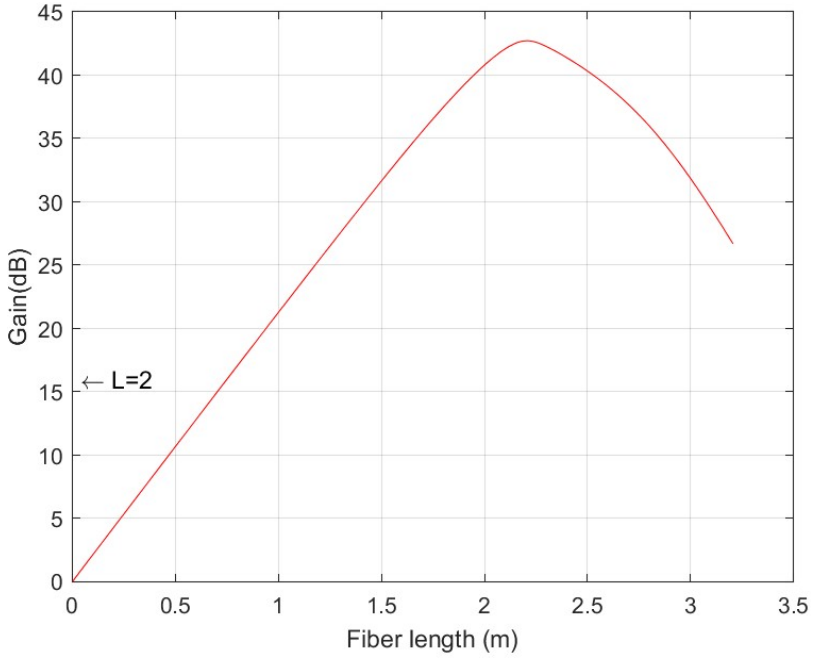


Figure 2. Relationship between doping concentration and fiber length the optimal gain is obtained on the basis of genetic algorithm

4. Conclusion

In this experiment, we used a praseodymium-doped fiber amplifier to amplify a specific band. To aid our research, we employed suitable programming algorithms to optimize the results, and successfully achieved peak amplification gain under specific fiber length and doping concentration conditions.

The experimental findings indicate that the gain of the praseodymium-doped fiber flu tellurate amplifier reaches a maximum of 42.7184 dB when the praseodymium doping concentration is 8.5×10^{25} and the fiber length is 2.2 m. The accuracy of the results obtained in this study was validated through multiple iterations of the genetic algorithm. Although the expected outcomes were successfully achieved, there are areas within the study that require further improvement.

One aspect that needs attention is the examination of the reference literature. Despite thorough research, there still exist certain deficiencies in comprehensively reviewing the relevant literature. To address this, it is recommended to broaden the scope of the literature review by delving into additional sources within related fields. This approach will ensure the integration of the latest and most comprehensive theoretical knowledge and practical findings into the research, thereby enhancing its overall quality and validity. Additionally, strengthening familiarity with the coding aspects of the study is essential. Improving expertise in the programming languages and tools utilized can significantly contribute to increased efficiency and reliability throughout the research process. It is essential for the author to invest time and effort into acquiring a higher level of proficiency in these areas.

Moving forward, the author should take proactive measures to address the identified areas for improvement. It is recommended to conduct a more comprehensive literature review and allocate time to enhance coding skills. By doing so, the research can be elevated to a higher level, ensuring a deeper understanding of the subject matter and more reliable results.

In conclusion, while the current study has achieved the intended outcomes, it is essential to recognize and address the identified areas for improvement to enhance the research quality. By expanding the literature review and strengthening coding skills, the author can contribute to expanding the knowledge base within the field and improving overall research outcomes.

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