Modeling and numerical simulation of the gain of a 1310nm praseodymium-doped fiber amplifier

Zhiwen Chen [1†], Keyi Hao[2, *†], Tingting Xiao[3†]

[1]School of University of Electronic Science and technology, Chengdu, China

[2]School of Nanjing University of Aeronautics and Astronautics, Nanjing, China

[3]School of Nanjing University of Information Engineering, Nanjing, China

*Corresponding author: 041800207@nuaa.edu.cn

†These authors contributed equally.

Abstract: Optical fiber communication is of great importance in information transmission. Increasing the transmission capacity of optical fiber systems is a solution to meet the increasing demand for information, in which rare earth ion-doped fiber amplifiers play an important role. In this paper, the quasi-quadruple-energy structure of Pr^{3+} is equated and simplified to a conventional triple-energy structure to improve amplification's efficiency and significance. By exploring the influence of many factors on the praseodymium-doped fiber amplifier, the amplification band with gain window between 1250-1350nm is verified, and the amplification of the central wavelength of 1310nm is realized. It provides a theoretical reference for the subsequent application of praseodymium-doped fiber amplifiers in communication engineering, laser amplification and other fields. Since the amplification band of praseodymium-doped fiber amplifier matches the zero dispersion point of 6.652 optical fiber, it will have a huge application market in the 1310nm optical communication system.

Keywords: Praseodymium-Doped Fibers, Fiber Amplifiers, Gain Characteristics, Fiber Optic Communications.

1. Introduction

With the rapid development 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. There are three ways to increase the transmission capacity of optical communication systems: increasing the single-channel transmission rate, reducing channel spacing, and expanding transmission bandwidth [1]. Up to now, after more than fifty years of rapid development of optical fiber communication, the single channel transmission rate has reached 400GB/s and the channel spacing has reached 50GHz (0.4nm).

Further increases would increase inter-channel crosstalk and reduce system stability, while the high technical difficulty would also greatly increase production costs. Therefore, it is more advantageous to use the method of extending the transmission bandwidth. Therefore, extending the gain bandwidth has become an urgent problem for fiber optic communication [2].

Optical Fiber Amplifiers (OFA) are a new type of all-optical amplifier used in optical fiber communication lines to amplify signals. The OFA is a new all-optical amplifier for signal amplification in fiber optic communication lines. It can amplify signals directly without going through the complex processes of photoelectric conversion, electro-optical conversion and signal regeneration, and is particularly suitable for long-distance optical communication relay amplification. It can be assumed from the previous results that OFA has laid a technical foundation for the realization of all-optical communication.

The Erbium Doped Fiber Amplifier (EDFA) has successfully amplified optical signals in the 1550nm band window with a gain factor of 11dB/mW. However, the EDFA only works in the central wavelength of 1550nm and cannot meet the requirements of the 1300nm band. . For optical communication networks around the world, which operate in the zero-dispersion window at 1.3μm wavelengths, it is important to have an adaptable fiber amplifier.

Praseodymium-doped fiber amplifier (Pr-doped fiber amplifier, PDFA) has excellent amplification performance in the 1.3μm wavelength window. In recent years, long-range fiber optic communication system have had wide applications in the WDM. For fiber optic communication networks that generally work in the 1.3μm wavelength zero-dispersion window, it is important to have a suitable fiber amplifier [3]. The operating wavelength of praseodymium-doped fiber amplifiers falls exactly in the optimal wavelength region (1.3~1.6μm) for fiber optic communication, with simple structure, low coupling loss with the line, low noise, high gain, wide bandwidth, independent of the polarization state of the fiber, and low pumping power require. It can be used to replace the traditional electronic repeater in fiber optic communication systems or as a preamplifier for the receiver to improve the receiver sensitivity. Therefore, the study of praseodymium-doped fiber amplifiers is of great significance to developing the fiber optic communication industry.

In the late 1980s, erbium-doped quartz fiber amplifiers matching the low-loss window of 1.55μm of optical fiber were first developed successfully. And now, these amplifiers have been put into use in system engineering to achieve tens of thousands of kilometers of transoceanic fiber optic long-distance trunk communication systems through the connection of fiber amplifiers. The first amplification at 1.3 μm was demonstrated from a praseodymium-doped fiber based on ZrF (ZBLAN) [5]. By reducing the phonon or vibrational energy of the substrate glass, higher pump power can be obtained during amplification. Despite this, the typical efficiency in ZBLAN fibers is only 4%, so a great deal of research has been carried out to identify effective matrix glasses for PDFA. Potential substrates are InF-based systems, InF / Ga F-based systems, PbF / InF-based systems, hybrid halide glasses, and sulphur-based glasses such as Ga-La-S and As-S. In 1998, researchers at Mitsubishi Electric in Japan achieved reliable operation in praseodymium-doped In/Ga-based fluoride fibers using 1.01μm band LDs as pumping. A signal output power of 16.2dBm (42mw) was obtained using four 1.01μm LDs, corresponding to a gain factor of 18dB, which was 2dB-3dB higher than previously reported for Zr-based fluoride fibers, with a noise factor below 8dB [6]. In the same year, Japanese K. Isshiki et al. reported an In-Ga-based fluoride doped praseodymium fiber amplifier, which directly uses the 0.98 μm band LD as the pump source, using a grating that can be adjusted to the LD. The adjustment range of 0.98 ~ 1.0 μm, the maximum signal output power at 1.296 μm wavelength is 13.5 dBm. Using this fiber amplifier as a preamplifier, O-band PDFA transmission tests were conducted at signal wavelengths of 1.296μm, 1.301μm, 1.306μm, and 1.311μm, respectively, with a signal power of -21dBm per channel, and the results showed that the BER was less than 10-9 [7]. Commercial PDFA module-based amplification tests were verified in a study as early as 1995 [8]. Japan offers rare-earth-doped fluoride fiber and fiber amplifiers, the Praseodymium-doped fiber amplifier gains 25dB or more.

In recent years, rare earth ions with special spectral properties [9] have had important research and applications in many fields, with the most extensive research on Pr3+ doped crystals.2021, Lin et al. [10-11] obtained a laser with a maximum output power of 8.14W at 639nm red using a Pr: YLF crystal with a low doping concentration and blue LD as the pump source. In 2022, Cao Weihang, Li Shue et al. [12] pointed out the three laser output types of Pr^{3+} solid-state laser in their research results. So far, the more typical bands in continuous lasers are green, orange, and red, with the maximum output power at 522 nm green light. The maximum output power at 522 nm green light exceeds 4 W, the maximum power at 607 nm orange light reaches 4.88 W, and the maximum power at 639 nm red light is up to 8.14 W. The output power at 546 nm, 604 nm, 698 nm, and 720 nm and other wavelengths also reach the watt level, while the multi-wavelength excitation aspect is also developing.

This paper aims to verify the many characteristics of praseodymium-doped fiber amplifiers and to investigate the influence of multiple factors on the amplification of praseodymium-doped fibers for practical engineering applications. The basic theoretical study of praseodymium-doped fiber amplifiers for amplification in the 1250-1350 nm band is carried out to model and analyze the excited radiation and electron leap processes in praseodymium-doped fibers and to design the pumping wavelength. The numerical model of the praseodymium-doped fiber amplifier is constructed using

the rate equation and power propagation equation for the excited radiation of a conventional three-level structure system, which is approximately equivalent to the effect of quasi-four-level amplification. The variation of gain with fiber length, doping concentration, pump power and signal power is calculated using Matlab programming. In practical applications, the power is expected to be further increased by extending the frequency band of the praseodymium-doped fiber amplifier to play a greater role in laser color display, medicine, quantum information and optical communication.

2. Model construction

In order to study the amplification effect of praseodymium-doped fiber amplifier on the signal light with the input wavelength of 1310nm, this paper establishes the leap on the structure of the quasi-four energy levels of Pr^{3+} ions, set the pump light source with the wavelength of 1017nm and adjusts the certain emission power to achieve the inversion of the ion number, to obtain the excited amplified radiation and spontaneous amplified radiation between energy levels. MATLAB simulation software was used to write the code and image implementation. It was obtained that the optical signal power has a more obvious amplification effect within a certain fiber length. The specific construction process is as follows.

2.1 Equivalence of the Pr^{3+} ion quasi-four energy level leap model

In their 2009 study of praseodymium-doped amplifiers in the 1300 nm band, Xiaowei Liang reported that particles on the ground state $^3H_4$ can be directly pumped and excited to the upper energy level $^1G_4$ with a wide pump band (FWHM of about 50 nm) and a central wavelength of 1017 nm [13]. Pr^{3+} ions at $^1G_4$ to $^3H_5$ leap to produce a gain centered at a wavelength of 1310 nm, while a strong $^1G_4$ and $^3H_4$ still exists between 1050 nm spontaneous amplified radiation, i.e., generating the ASE power between the energy levels as shown in the figure. In addition, the jump from $^1G_4$ to $^1D_2$ produces an excited state absorption band with a peak near 1380 nm, whose short wavelength extends to 1290 nm, limiting the amplifier's performance. While the long wavelength portion of the amplifier is affected by the absorption of the ground state with a peak at 1440 nm, absorbing signals with wavelengths greater than 1290 nm[13,14]. As it is shown in Figure 1:

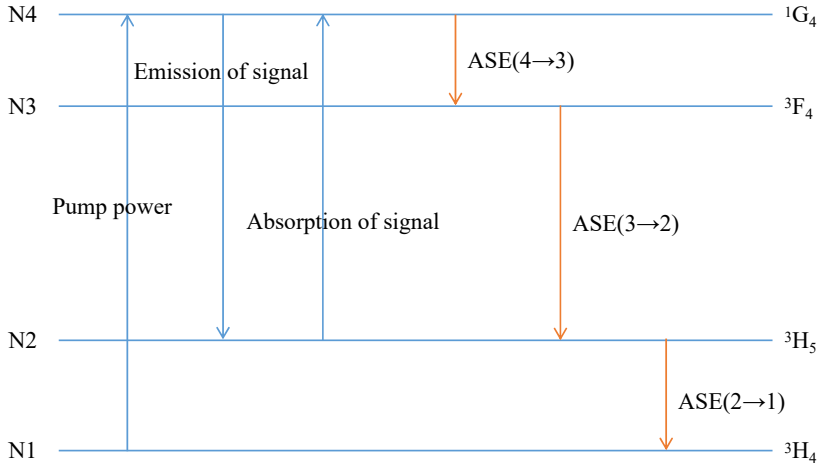


Figure 1. Schematic diagram of the Pr^{3+} energy leap

In the above amplification process, the Pr^{3+} ion at the upper energy level $^1G_4$ easily jumps to the $^3F_4$ energy level [14] due to multiphonon relaxation (ion transition from non-equilibrium to equilibrium state)[15]. Therefore, in order to improve the efficiency and significance of the amplification, the gain window between $^3F_4$ and $^3H_5$ is considered in the design of the energy level structure, and a simplified three-level structure (Figure 2), which is approximately equivalent to the quasi-four-level amplification, is used.

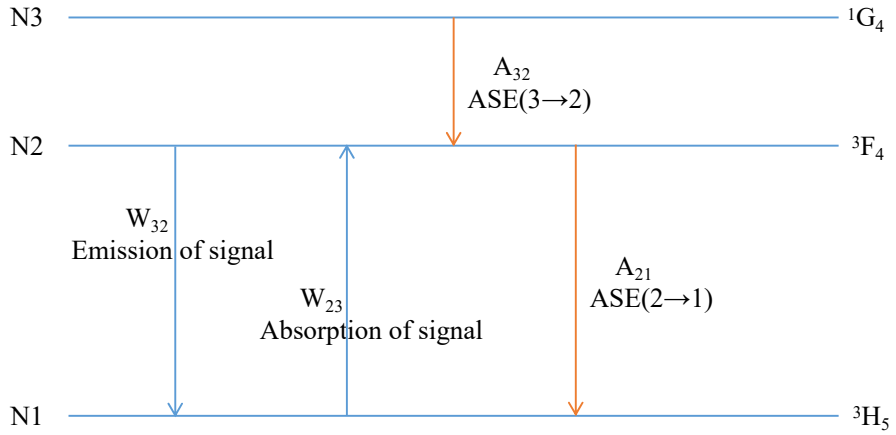


Figure 2. Schematic diagram of the simplified three-energy level structure of Pr^{3+}

By combining the two figures above, the gain window can be converted from two and three energy levels in a four-energy system to one and two energy levels in a three-energy system. This treatment reduces some of the non-radiative jumps in the original quasi-four-energy structure, ensuring a certain degree of amplification efficiency and prominence, improving pumping efficiency, etc. As shown in Figure 2, the equivalent structure is also the physical basis for the computational simulations that follow in this paper.

2.2 Numerical model of the rate and power of the Pr3+ ion leap

2.2.1 Numerical model of the rate equation

In this paper, the four-energy structure of the Pr^{3+}ion is equivalently simplified to a three-energy structure. Under the action of the pump light, the Pr^{3+} ion jumps from the ground state to the energy level, the Pr ion at the Pr^{3+} ion at the energy level leaps radiolessly to the sub-stable energy level. The rate equation for the Pr^{3+}ion leap can then be written as [16，17]

$$\frac{\partial \mathrm{N}_1(\mathrm{z})}{\partial \mathrm{t}} = -\left[\mathrm{W_p(z)} + \mathrm{W_{12}(z)}\right]\mathrm{N_1(z)} + \mathrm{A_{21}N_2(z)} + \mathrm{W_{21}(z)N_2(z)} \tag{1}$$

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

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

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

The following is an example of the above formula to explain: (1) formula corresponds to the first energy level photon change law. That is, the change in photons at the first energy level with time is equal to the sum of the number of the pump and signal radiation light emitted per unit time when the photons at the first energy level are reduced, and the signal absorption light and spontaneously amplified radiation photons generated by the second energy level jump. The rest of the equation is the same. (4) The equation uses N to denote the sum of the numbers of all photons at the three energy levels.

Pump Light Absorption Rate $W_p(z)$ signal light absorption rate $W_{12}(z)$, signal light stimulated radiation rate $W_{21}(z)$ are expressed as

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

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

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

Signal light emission cross-sectional area σ_{21} can be derived from the signal light absorption cross-sectional area σ_{12} calculated from

$$\sigma_{21} = \sigma_{12} \exp\left(\frac{\varepsilon - h\upsilon}{kT}\right) \tag{8}$$

The effective transmission area of the fiber A_{eff} can then be expressed as

$$A_{eff} = \pi r^2 \tag{9}$$

Where $N_1(z)$, $N_2(z)$, and $N_3(z)$ denotes the number of particles on the N1, N2 and N3 energy levels at z, respectively. N is the total number of particles at the three energy levels. A_{32} denotes the no radiative leap rate; and A_{21} denotes the radiative leap rate; and σ_{13} denotes the pump light absorption cross-sectional area σ_{12} denotes the signal light absorption cross-sectional area. σ_{21} denotes the signal light emission cross-sectional area. υ_{12} denotes the signal light absorption frequency. υ_{21} denotes the signal light emission frequency. υ_{13} denotes the pump light frequency. $h\upsilon_{13}$ denotes the photon energy of the pump light. $h\upsilon_{12}$ denotes the photon energy emitted by the signal light. $h\upsilon_{21}$ denotes the photon energy absorbed by the signal light. r denotes the fiber core radius. $P_s(z)$ denotes the signal light power. $P_p(z)$ denotes the pump light power. h denotes the Planck constant. k denotes the Boltzmann constant. T denotes the temperature at the international temperature scale, and ε is the energy difference between the two energy levels of the gain window.

The process of electron leap is the process of photon generation or absorption. Eqs. (1)-(3) represent the variation of electron volume density with time at each energy level located at z. Eq. (4) represents the total number of particles as the sum of the number of particles at each energy level, and Eqs. (5)-(7) represent the number of pump photons absorbed per unit area through the fiber, the number of signal photons absorbed, and the number of signal photons excited by radiation.

2.2.2 Numerical model of the power propagation equation

Pump optical power P_p, Signal Optical PowerP_s, Amplified Spontaneous Emission (ASE) P_{ase} The variation with propagation length is called the power equation, and $P_s(0)$ indicates the optical signal power at the input; and $P_p(0)$ indicates the pumped optical power at the input. A typical three-energy level structure power model is shown in Figure 3

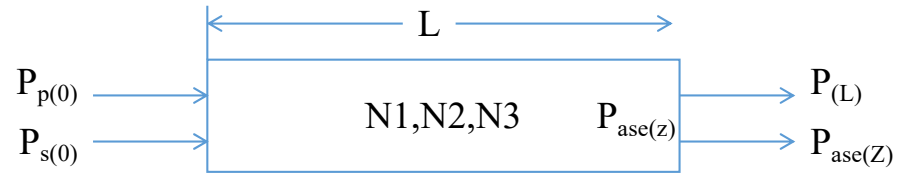


Figure 3. Typical three-energy level structure power model

Fetching fiber z to z + dz the length of a section of dz of praseodymium-doped fiber for analysis, the power equation of the praseodymium-doped fiber amplifier can be described as

$$\frac{dP_p(z)}{dz} = \left(-\sigma_p N_1(z) - \alpha_p\right)P_p(z) \tag{10}$$

$$\frac{dP_s(z)}{dz} = [\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_s]P_s(z) \tag{11}$$

$$\frac{dP_{ase}(z)}{dz} = [\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_s]P_s(z) + 2\sigma_{21}N_2(z)h\nu\Delta\upsilon \tag{12}$$

Where α is the loss coefficient of the fiber material, i.e. the absorption coefficient of the laser light by the impurity ions in the fiber. α_p denotes the absorption of pump light by the fiber, and α_s indicates the absorption of signal light by the optical fiber; the spectral band generated by spontaneous radiation is usually calculated using the frequency half-height full-width $\Delta\upsilon$ to calculate. Equation (10) can be derived from the pump light through dz The power of the length change is related to the pump light absorption cross section σ_p and the number of particles on the N1 energy level $N_1(z)$

Eq. (11) shows that both the emission and absorption of the signal light affect the power of the signal light through the dz. Equation (11) can be concluded that the emission and absorption of the signal light have an effect on the power of the signal light through the length change, and equation (12) represents the relationship between the ASE power in the range from 0 to $z + dz$ length range, and since the power of spontaneous radiation propagates positively and negatively along the fiber, respectively $2\sigma_{21}N_2(z)h\nu\Delta\upsilon$ denotes the difference in dz the newly generated spontaneous radiated power over the length range.

$$G\left(P_p(z), P_s(z), N_2, N_1, z\right) = \frac{P_s(z)}{P_s(0)}(100\%) \tag{13}$$

$$G\left(P_p(z), P_s(z), N_2, N_1, z\right) = 10 \times \log_{10}\left(\frac{P_s(z)}{P_s(0)}\right)(dB) \tag{14}$$

The fiber-optic amplifier is based on the principle of excited radiation for amplifying low-power incident light. Gain is realized when the optical medium produces a particle number inversion in the presence of pumped light. In equation (13), the optical signal power at z $P_s(z)$ and the signal light power at 0 $P_s(0)$ is the signal light amplification ratio, i.e., gain, and equation (14) converts the gain calculation into a ratio to gain in dB.

The gain of a praseodymium-doped fiber amplifier is related to the doping concentration, the absorption area of the excited state, the material parameters of the fiber, the wavelength and power of the pump and signal light, etc.

In general, the maximum gain value is limited by the ASE power. In practical engineering, using double-clad fibers with a large surface-to-volume ratio and stable single-mode transmission can achieve better output power. The ASE power can also be suppressed by adding filters or modulators between multi-stage amplifiers to improve the optical efficiency of praseodymium-doped fibers for transmission and reduce the impact of noise, thus improving the gain.

2.2.3 Numerical model simulation solution

Based on the rate equation and power propagation equation of the excited radiation of the three-energy-level system mentioned above. The numerical model of the praseodymium-doped fiber amplifier is constructed and simulated using MATLAB. The relationship between fiber length and gain, signal optical power, pump optical power, ASE (signal bandwidth at the input of the amplified spontaneous radiation) power. And the variation of gain with doping concentration, pump power and signal power are derived.

3. Experiments

3.1 Experimental scenario replication

This paper [14,18] uses a set of fiber parameters to simulate the praseodymium-doped fiber amplifier. The rate equation and the power propagation transcendence equation are solved with the help of MATLAB solver function and ode45 function, respectively. Since the pump light absorption cross-sectional area σ_{13} is not related to the pump light power, but only to the pump light wavelength. The pump light wavelength is determined in this paper, so σ_{13} is also a constant value, and similarly, the signal light absorption cross-sectional area σ_{12} is also a constant value.

The values of the parameters used in the experimental simulations are shown in Table 1.

Table.1. Parameters used in the simulation

Parameter name	Value	Unit
σ_{13}	2×10^{-24}	$/m^2$
σ_{12}	1×10^{-24}	$/m^2$
$P_s(0)$	1	μW
$P_p(0)$	100	mW
N	6.71×10^{25}	$ions/m^3$
h	6.626×10-34	J·s

k	1.380649×10^{-23}	J/K
T	300	K
A_{21}	1000	/s
A_{32}	10^6	/s
A_{eff}	10	μm^2
r	2.5×10^{-6}	/m
α_p	0.1	$/m^2$
α_s	0.1	$/m^2$
Δv	1.74×10^{12}	Hz

In this paper, by using the ode45 function, the factors are formed into a multivariate equation (i.e., column vector P = [Ps; Pp; Pase; N]) to derive the relationship between the variation of the different factors over the length range of a section of fiber, and the effect of these factors on the gain.

3.2 Experimental results

The experiments were initially carried out by setting the fiber length (L=1.2m) and substituting it into the ode45 equation as a parameter to represent the variation of the dependent variables over this range. The experimental results are presented in two parts to facilitate comparing the corresponding relationships between the parameters and present a more obvious pattern.

3.2.1 Relationship between different influencing factors and gain

The relationship between fiber length and gain is shown in Figure 4.(a). The fiber length has a more obvious gain effect between 0-0.33m, reaching a peak of 48.26dB at point A_1. Therefore, the optical power of the signal increases in the range of 0-0.4m fiber length and achieves a larger gain.

The relationship between the gain and doping concentration is shown in Figure 4.(b), the doping concentration between $0.4 - 1.9 \times 10^{26}$ions/ has gained, at point B_1 the gain reaches a peak of 48.3071dB. when the doping concentration exceeds 1.9×10^{26}ions/, the fiber amplifier shows a negative gain effect with the doping concentration As the doping concentration increases, the negative gain effect of the signal light becomes more and more obvious. Thus, in this paper, 9.5×10^{25} ions/ is chosen as the initial concentration, corresponding to the maximum gain point obtained above, so that a better particle number inversion effect can be obtained, and the most obvious amplification effect can be achieved.

The relationship between the gain and the initial input pump light power is shown in Figure 4.(c), where the gain increases at the input pump optical power of 0.1W and can be approximated as a linear relationship. The maximum gain of 48.2178 dB is reached at point C_1, and then decreases slowly.

The specific reasons for the decrease in gain as the pump light increases to a certain level are as follows: at higher pump powers, the ground state ions are emitted by the pump light to higher energy levels than $^1G_4$ (e.g. $^1D_2$, etc.), and this leap produces an excited absorption band at a wavelength near 1380 nm, with short wavelengths extending to 1290 nm, limiting the amplifier's performance

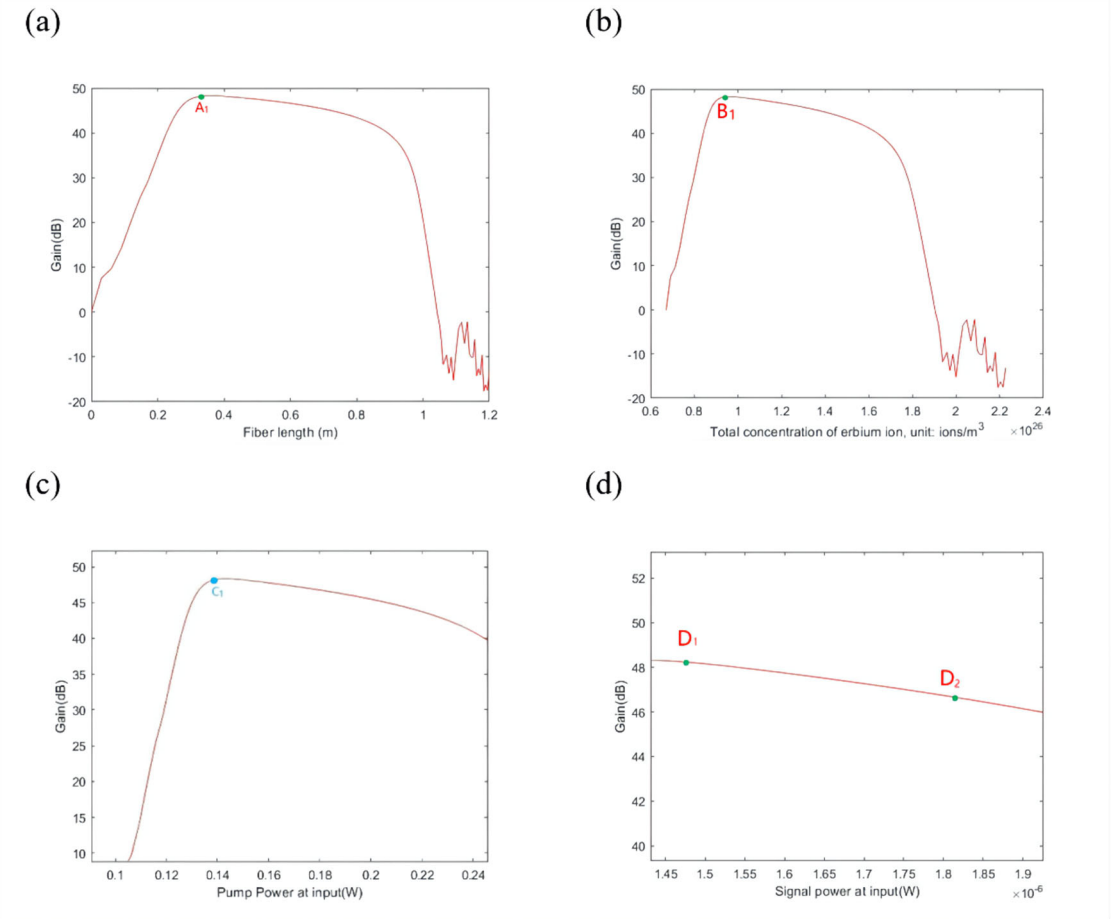


Figure 4. (a)The relationship between fiber length and gain. (b) Gain versus doping concentration. (c) Gain versus pumped optical power. (d) Relationship between gain and input signal optical power.

The relationship between gain and optical signal power is shown in Figure 4.(d). The gain decreases in an approximate one-time relationship with increasing initial input signal optical power, but the slope is very low. Point D_1 and point D_2 on the curve are arbitrarily selected to reflect the trend through calculation. Although more signal light is used for focused amplification, the scattering of signal light in the material is consumed to a greater extent than that of the excited radiation amplification to the upper energy level, and the two have opposite effects.

3.2.2 Relationships between factors over a range of fiber lengths

In order to achieve the particle number inversion to obtain the energy leap, the initial power of the pump light should be much larger than the signal light power (three orders of magnitude or more difference), so the initial pump power was set to 0.1W in this experiment, and the initial input power of the signal light front-end was 1μW.

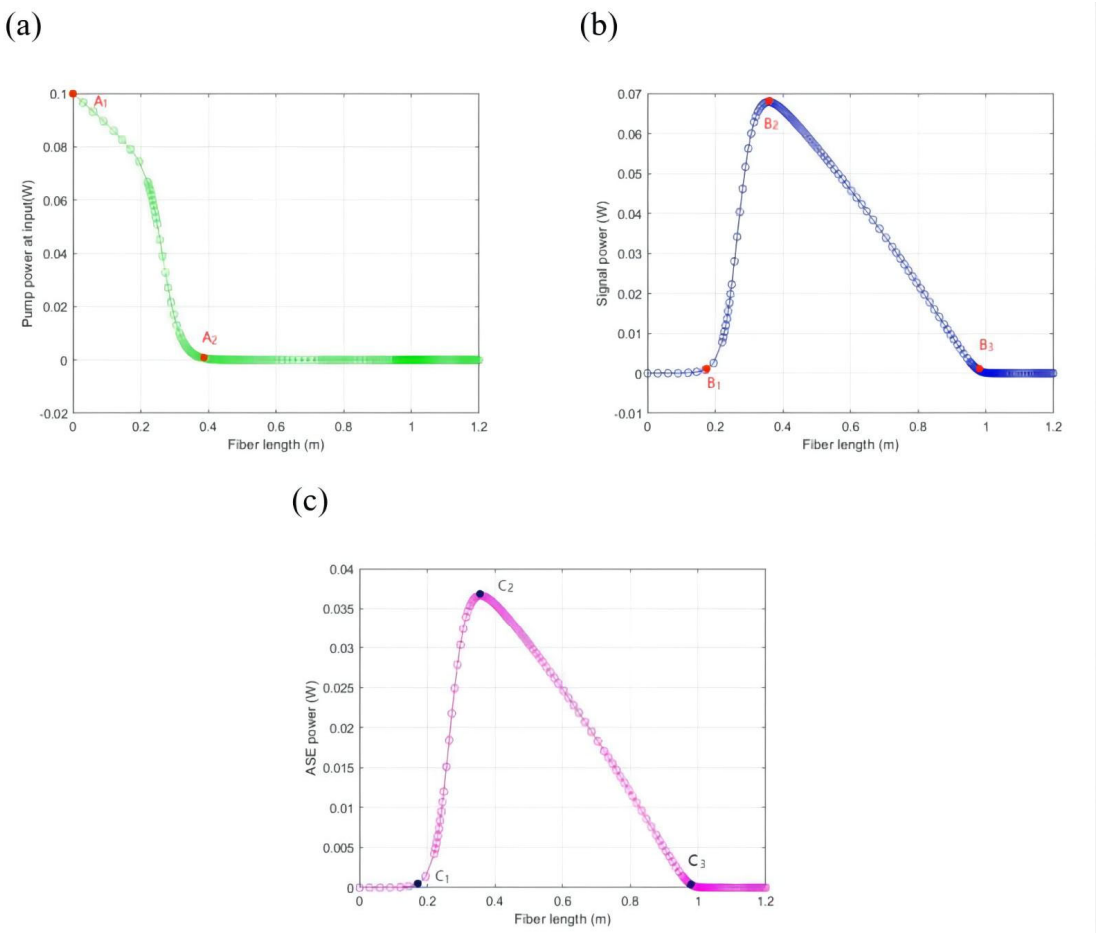


Figure 5. (a)Plot between fiber length and pumped optical power. (b)Relationship between optical fiber length and signal optical power. (c)Relationship between fiber length and ASE power.

The relationship between fiber length and pump light power is shown in Figure 5. (a). The pump light power decreases with increasing fiber length between 0 and 0.37 m, and tends to 0 after about point A_2, where the pump light power is at the maximum initial power at point A_1, which is the initial input of $0.1W$. Obviously, the pump light will continue to decay due to material loss, signal emission and other factors. The pump light will be decaying due to a series of factors, such as material loss and signal emission. Beyond a certain range the pump light will be very weak.

The relationship between fiber length and the signal power is shown in Fig. 5.(b). Three points were selected to show a clear trend of amplification: point B_1, peak point B_2 and point B_3 where the amplification effect basically disappears. The data were analyzed. The signal optical power increases and then decreases with the fiber length between 0.15-1.08m, the main area where the praseodymium-doped fiber amplifier amplifies the signal light. The signal power peaks at 0.068W at 0.37m at point B_2, showing a more pronounced amplification effect. Based on the gain calculation equation (14) in the second part of the modeling, the gain at 0.37m is exactly 48.26 dB, which verifies the previous experimental results of the maximum gain value obtained at the correspondence between particle concentration and gain. After continuous decay under the influence of various influences such as material loss and signal light scattering, the signal light finally exhibits a very small propagation power and gradually tends to zero.

The relationship between fiber length and ASE power is shown in Figure 5.(c). The same three points of inflection C_1, peak C_2 and inflection C_3 were chosen to reflect the trend of change. ASE power began to increase at 0.17m, reaching a peak of 0.037w at 0.36m, and then began to decline, gradually converging to 0. This is due to the increase in fiber length, spontaneous radiation emitted and the loss within the material intensifies, the pump optical power also decreases, as well as no spontaneous ion radiation and other factors. As can be observed experimentally, the ASE variation law is similar to the signal light. This is because the process of amplifying the signal light by excited

radiation is inevitably accompanied by spontaneous radiation, with both processes occurring simultaneously.

4. Conclusions

In this paper, the quasi-quadruple-energy structure of Pr^{3+} is equated and simplified to a conventional triple-energy structure, thereby improving the efficiency and significance of amplification. The effect of multiple factors on the praseodymium-doped fiber amplifier is investigated, and the amplification of the central wavelength of 1310 nm is verified for the amplification band with a gain window between 1250 and 1350 nm. The current praseodymium-doped fiber amplifier also has the characteristics of low noise and high gain. Still, the pumping efficiency is not high, the excitation efficiency under the effective excitation mode is low [19], the performance is unstable, and the temperature is set to room temperature (300 K) in the experiment. However, the praseodymium-doped fiber amplifier's gain was very sensitive to temperature, so there is still a distance to practical applications [20].

This paper explores the effect of fiber material on performance. Pump power matching can be achieved by reducing the loss coefficient, lowering the working temperature, and optimizing and adjusting the energy level structure. Future attempts to increase the transmission range and amplification of signal light and improve the amplification efficiency can be continued for more and wider applications.

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