# The design modeling and numerical simulation of a Bismuth-doped glass fiber amplifier

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**Abstract:** At present, the main communication window of fiber amplifier is in C-band ($1530-1565nm$), and the amplification technology in O-band ($1260-1360nm$) needs to be improved. The optical fiber amplification technology of $1200-1400nm$ band is studied in this paper. Based on three different Bismuth-doped glass materials, the design modeling and numerical simulation are carried out, and the corresponding amplification bands are $1199nm$, $1280nm$ and $1347nm$. The rate equation and transmission equation of the three-level transition model in steady state were established. The gain, the power of pump, the power of signal and ASE signal power of the three bands were simulated by MATLAB, and the material with the best performance was further analyzed. The results show that $1347nm$ signal light has the best amplification effect, and the maximum gain is $25.7687dB$ when the fiber length is $7.9m$. It is also found that the optical fiber length required to achieve the optical signal optical gain with the pump power is positive correlation, and with the doping concentration is negative correlation, which are complementary to each other. This conclusion has important significance for the design of bismuth-doped optical fiber amplifier.

**Keywords:** Fiber Optics, Bismuth-Doped Fiber, Fiber Amplifier, Gain Coefficient.

## 1. Introduction

In recent years, the demand for information capacity has been increasing rapidly. Optical communication plays a significant role in current communication tasks due to its excellent properties, such as anti-interference ability, low loss, low cost, and bidirectional transmission [1]. An optical fiber amplifier can amplify the transmitted optical signal and compensate for the loss happening in the transmission, making it an indispensable component in long-distance transmission. It is an important optical device in the optical fiber communication system. The preparation and application technology of the Erbium-doped Fiber Amplifier (EDFA) is mature. Through EDFA, the optical signal can be amplified directly, and the transmission rate can be improved with high gain, low noise, and low loss. However, the current commercial Erbium-doped fiber amplifiers can only cover $1520-1620\ nm$ (C and L band) [2], and the spectral range is too narrow, making it impossible to satisfy the needs of future communication technology development. In addition, other rare earth-doped quartz fiber amplifiers have also been developed, such as praseodymium doped fiber amplifier (PDFA), thulium-doped fiber amplifier (TDFA), and neodymium-doped fiber amplifier (NDFA). The main communication window is still in C-band ($1530-1565nm$), and the amplification technology in O-band ($1260-1360nm$) needs to be improved [3]. With further study of the Bismuth element, it is found that Bismuth-doped glass has special properties in the near-infrared band. Its outer layer of electrons is unsaturated, making it easy to lose electrons and form different valence ions. The Bismuth element incorporated into different crystals can emit fluorescence from ultraviolet to near-infrared light. It is possible to use the Bismuth- doped Fiber Amplifier (BDFA) to develop all-optical fiber amplifiers

In 2001, Fujimoto and Nakatsuka discovered a new infrared luminescence. It is from Bismuth-doped silicon glass (BiSG) and the width of fluorescence is from $1000nm$ to $1600nm$ that can be absorbed in the visible range [4]. The fluorescence lifetime at room temperature is $630\mu s$. In 2003,

they proved that the amplification phenomenon of optical signal existed at $1300nm$ under the excitation of 800nm laser [5]. In 2005, Dvoyrin et al. prepared the earliest Bismuth-doped silicon fiber, whose FWHM of the luminescence spectrum was $200nm$ [6]. In 2008, Bufetov et al. [7]observed light amplification in the $1300-1500nm$ range in Bismuth-doped silicates. In 2015, Cheng Mingsheng et al. established the rate equation and transmission equation of the three-level transition model in the steady state through the Giles model [3]. They studied the broadband optical amplification characteristics of BDF. The results show that the gain coefficient of $1384\sim1480\ nm$ exceeds $1.5\ dB/m$ and NF is approximate to $5\ dB$ when $830\ nm$ pump with $200\ mW$ power is used. In 2016, Firstov et al. reported a Bismuth-doped fiber amplifier with an operating wavelength of $1720\ nm$ [8]. When the pump power was $300mW$ and the center wavelength was $1550\ nm$, the maximum gain was $23\ dB$, with the noise coefficient not less than $7.5\ dB$. In 2019, Al-Azzawi et al. [9]developed a novel bandwidth Hafnia-Bismuth Erbium co-doped fiber amplifier (HB-EDFA), and studied the bi-pass series and parallel structures of the amplifier. The results show that the parallel HBEDFA achieves a flat gain of $12.1\ dB$ in the bandwidth range from $1525\ nm$ to $1605\ nm$ when the input signal power is $-10\ dBm$. In 2020, Fan et al. [10] prepared Bismuth-doped tellurite glass by a high-temperature melting process, tested the light absorption and stimulated emission performance, showing that Bismuth-doped tellurite glass is a good 2μm laser glass. In 2021, Bhemarajam et al. [11]developed a boron lead Bismuth-lithium glass system doped with different Er3+ ions and studied its optical properties. Through systematic spectral analysis, it is concluded that can use a glass to make a potential luminescent material in the fiber amplifier. In recent years, the research regarding all kinds of devices associated with Bismuth-doped fiber amplifier has made a lot of progress, with an enormous prospect. The technology can better meet the needs of the large capacity information, if the transmission bandwidth of Bismuth-doped fiber amplifier can be expanded.

In this paper, the Bismuth-doped glass of different materials is designed into corresponding amplifiers. The influence of different materials on the gain and the change of the gain with the length of fiber are explored. Under three different Bismuth-doped glass materials conditions, The signal gain, signal power, pump power and ASE power of Bismuth-doped fiber were observed as a function of fiber length, to compare which kind of Bismuth-doped glass has the greatest gain. Select the Bismuth-doped glass with maximum gain. The changes in the power of pump, the power of signal, and particle concentration with fiber length, the effects on gain, and the changes of gain with the power of pump, the power of signal, and particle concentration were analyzed. The whole optical fiber communication window can be covered by the bandwidth that covered by Bismuh-doped fiber.Enlarging the transmission bandwidth of Bismuth-doped fiber can greatly increase the transmission rate and reduce the cost. Bismuth-doped fiber plays an irreplaceable role in future communication.

## 2. The theoretical analysis

In order to research the influence of various parameters on the signal amplification gain, such as the fiber length, pump power, doping concentration and input signal power, The establishment of theoretical model is very important. The energy level structure and spectral characteristics of Bismuth ion can be concluded as a three-level system.

The transition diagram of the energy level transition of the Bismuth-doped fiber amplifier is shown in Figure 1. The particles in the fundamental level (E1) are excited by the pump light, absorb the pump energy, undergo stimulated absorption, then transition to the excited state level (E3). At the same time, the base particle will also absorb the signal energy and stimulate absorption, then transition to the E2 level. Since the particles at the E3 level have a very short emission lifetime, they quickly produce spontaneous radiation and transition to the E2 level. Particles at the E2 level will be stimulated by the signal light to produce stimulated radiation and transition to the base and will also undergo spontaneous radiation to produce ASE power and transition to the base. In general The stimulated radiation transition is the main process of optical amplifier amplifying the optical signal.

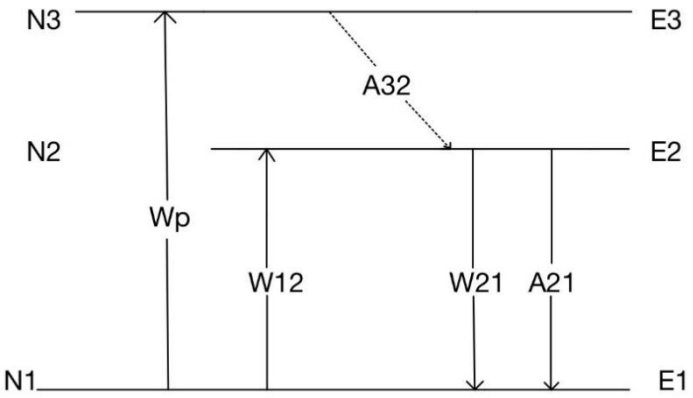



FIG. 1 Schematic diagram of the three-level transition

In order to obtain the numerical results of the experimentally designed optical amplifier, the equations of particle number density and optical power propagation are established. The particle number density equation is in order to obtain the symbolic solution of the particle number density at each energy level of the fiber. The exact numerical solution can be obtained by put the symbol solution into the power propagation equation.

According to the energy level structure, the particle number density equation is expressed as：

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

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

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

$$N = N_1(z) + N_2(z) + N_3(z) \quad (4)$$

Where, $N_3$、$N_2$and $N_1$ are ion number densities of the excited state, metastable state, base state, and $N$ are total ion number densities. $Wp$, $W12$, $W21$, $A32$, $A21$, represent pump light absorption rate, signal light absorption rate, signal light stimulated emission rate, non-radiative transition rate, and radiation transition probability, respectively. They're all in units of /s, respectively denoted as：

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

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

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

$$A_{eff} = \pi r^2 \quad (8)$$

Where r represents the radius of the fiber and $A_{eff}$ represents the effective area of light propagation. $\sigma_p$denoted pump light absorption cross-section, $\sigma_{12}$denoted signal light absorption cross-section, $\sigma_{21}$denoted signal light emission cross section. The ability of a particle to absorb or emit light is defined as a cross section H denotes Planck's constant, $v_{12}v_{21}$denotes optical signal frequency, $v_{13}$denotes pump optical frequency. Formula (1) describes the change rate equation of the base particle. The change rate of the base particle is expressed by taking the partial derivative of the Base particle number density with respect to time. According to the energy level diagram, the base particle change rate is equal to the rate of the transition to the base particle minus the rate of the transition away from the base particle. Similarly, equation (2) and equation (3) describe the particle change rate equation of metastable level and excited state level, respectively, whose particle change rate is also equal to the particle rate of the transition to the respective level minus the particle rate of the transition away from the individual level.

The power propagation equation, namely pump power, signal power and ASE power as a function of propagation length, can be expressed as

$$\frac{dP_p(z)}{dz} = \left(-\sigma_p N_1(z) - \alpha_a\right)P_p(z) \quad (9)$$

$$\frac{dP_s(z)}{dz} = (\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_s)P_s(z) \quad (10)$$

$$\frac{dP_{ase}(z)}{dz} = [\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_s]P_s(z) + 2\sigma_{21}N_2(z)hv\Delta v \quad (11)$$

Where $\alpha$ represents the loss coefficient of the fiber$\Delta v$, and $\Delta v$ represents the half-height and full-width of the frequency$(Hz)$.

The signal gain is expressed as

$$G\left(P_p(z), P_s(z), N_2, N_1, z\right) = \frac{P_s(z)}{P_s(0)}(100\%) \quad (12)$$

$$G\left(P_p(z), P_s(z), N_2, N_1, z\right) = 10 * log\,10\left(\frac{P_s(z)}{P_s(0)}\right)(dB) \quad (13)$$

Formula (9) describes the pump power propagation equation, and the change rate of pump power about length is expressed by taking the derivative of pump power with respect to fiber length. Similarly, equation (10) represents the signal optical power propagation equation; Equation (11) represents the ASE power propagation equation.

According to the theoretical model, the relationship between the gain of fiber amplifier and fiber length, doping concentration, pump power and signal power can be obtained.

## 3. Results and Analysis

According to the theoretical model, two experiments are carried out by numerical simulation. Three kinds of Bismuth-doped fiber amplifiers with amplifying bandwidths of 1199nm, 1347nm, and 1280nm were designed using corresponding Bismuth-doped fiber materials. The corresponding gain, pump power, signal power and ASE power were simulated with MATLAB and compared. At the same time, the one with the best performance is simulated in depth, and the relationship between gain and doping concentration, pump power, and the signal power is obtained.

### 3. 1 Analysis of the characteristics of three kinds of signal light amplification

The selected signal bands are $1199nm$, $1347nm$ and $1280nm$, and the corresponding optical fiber materials are Bismuth-doped Na2O-Cao-MGO-Al2O3-sio2 glass [12], Bismuth-doped Li2-Al2O3-sio2 glass [13] and Bismuth-doped Geo2-al2o3 glass [14]. The gain as a function of length, the signal power as a function of length, the pump power as a function of length and the ASE power as a function of length are simulated.

n the experiment, variables such as the fiber length, initial signal light power, initial pump light power and Bismuth-doped ion concentration were controlled to be fixed, and the parameters were shown in Table 1. The signal light parameters of the three signal lights corresponding materials and pump light parameters of the three signal lights' corresponding materials are shown in Table 2 (note: the radiation-free transition life of Geo2-al2o3 material in this experiment has not been obtained yet, because the emission spectrum of this material is similar to that of Na2O-CAO-MGO material, so $40\mu s$ is used instead in the experiment).

Table 1 Control variables and their parameters

| Physical quantities | Numerical value |
|---|---|
| fiber length $L(m)$ | 12 |
| initial signal power $P_s0(W)$ | $1.6 \times 10^{-6}$ |
| initial pump power $P_p0(W)$ | $50 \times 10^{-3}$ |
| doping concentration $N(ion/m\text{^}3)$ | $0.2 \times 10^{25}$ |

Table 2 Corresponding parameters of signal light and pump light of the three materials

| | Singal parameter | | | Pump parameter | | |
|---|---|---|---|---|---|---|
| | $Na_2O$-CaO-MgO | $Li_2$-$Al_2O_3$ - $SiO_2$ | $GeO_2$-$Al_2O_3$ | $Na_2O$-CaO-MgO | $Li_2$-$Al_2O_3$ | $GeO_2$-$Al_2O_3$ |
| $\lambda_0(nm)$ | 1199 | 1347 | 1280 | 874 | 1092 | 808 |
| $\Delta v(cm^{-1})$ | 1568 | 1617 | 332 | 2747 | 1404 | \ |
| $\tau(\mu s)$ | 337 | 270 | 273 | 40 | 549 | \ |
| $n$ | 1.508 | 1.519 | 1.612 | 1.512 | 1.521 | 1.616 |
| $\sigma_{em}$ $/10^{-22}(cm^2)$ | 1.5 | 2.3 | 1.55 | 3.8 | 7.3 | 1.61 |

The background loss of the signal and pump light used in the simulation is $0.1(/m)$, the overlap factor of them is 1, and the fiber radius is $1.5nm$. Radiative transition probability $A_{21}$, non-radiative transition probability $A_{32}$ and signal light absorption cross-section $\sigma_{12}$ cannot be directly obtained from the literature, so the following three formulas are used for calculation [15].

$$A_{21} = 1/\tau_s \quad (14)$$

$$A_{32} = 1/\tau_p \quad (15)$$

$$\sigma_{21} = \sigma_{12} exp\left[\frac{\varepsilon_0 - hf_s}{kT}\right] \quad (16)$$

Where $\varepsilon_0$ is the energy distance between the base and the second level, $H$ is Planck's constant, $k$ and $T$ represent Boltzmann's constant and absolute temperature respectively, and the simulation is carried out with room temperature ($T = 300$).

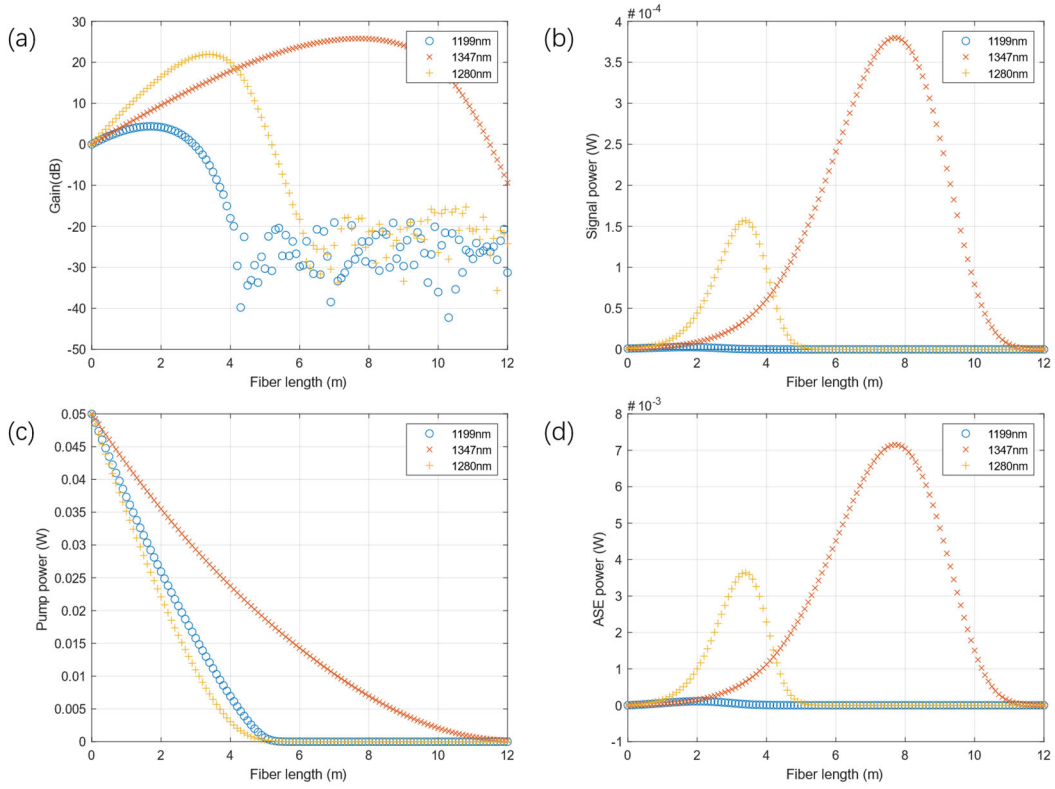



FIG. 2 (a) Gain changes with fiber length. (b) Signal power varies with fiber length. (c) Pump power varies with fiber length (d)ASE power varies with fiber length

Figure 2(a) depicts the relationship between the gain of the three materials and the fiber length. The gain changes of the three materials are similar. The gain first increases to the peak and then decreases with the increase of fiber length. The gain of three different signal bands is not the same. Among them, the maximum gain of $1347nm$ signal light amplification and the fiber length corresponding to the maximum gain are the largest among the three kinds of the signal light. It reaches

$25.7687dB$ at $7.9m$. The signal light at $1280nm$ reaches $21.7705dB$ at $3.5m$. The optical signal gain at $1199nm$ is relatively small, with a maximum gain of $4.3781dB$. FIG. 2(b) depicts the relationship between the signal power of the three materials and the fiber length. The figure of signal power experiences an increase to the peak and then witnesses a drop to zero. The maximum power and the corresponding fiber length can be obtained from the image. When the signal band is $1347nm$ , the maximum power is $0.37949mW$ at 7. 9m, and the maximum power of $1280nm$ signal light reaches $0.15026mW$ at $3.5m$. Among the three kinds of signal light, the signal power of $1347nm$ amplified by fiber amplifier is the largest, while the signal power of $1199nm$ signal is almost zero. FIG. 2(c) depicts the relationship between the pump power of the three materials and the fiber length. It can be seen from the figure that the pump optical power decreases with the increase of the fiber length, and when the fiber length increases to a certain value, the pump optical power decreases to $0W$. The pump power of $1199nm$ signal light and $1280nm$ signal light decreases to zero when the fiber length is $5m$, and the pump power of $1347nm$ signal light decreases the slowest, and it decreases to zero when the fiber length is 12m. FIG. 2(d) depicts the relationship between ASE signal power of the three materials and fiber length. The overall trend is consistent with signal optical power changing with fiber length. The maximum power of the ASE signal corresponding to $1347nm$ signal amplification is $8mW$.

The comparison shows that the gain, signal power, pump power and ASE power of 1347nm signal light amplified by a Bismuth-doped fiber amplifier are the largest among the three signal lights. The parameters of the three materials were analyzed, and some factors affecting the amplification performance were obtained.

When the central wavelength of the signal light in the emission spectrum corresponds to the absorption spectrum, there will be a certain shift. Among the three kinds of signal light selected in the experiment, the central wavelength of $1347nm$ signal light in the emission spectrum corresponds to $1350nm$ in the absorption spectrum, and the difference with the wavelength of signal light is the smallest. According to the calculation relation between emission cross section and absorption cross-section, the absorption cross-section of signal light will be much larger than the emission cross section when the central wavelength corresponding to the emission spectrum is different from that corresponding to the absorption spectrum. According to the gain calculation formula, the optical signal gain is not obvious when the absorption cross section is much larger than the emission cross-section. Therefore, the $1347nm$ signal light has a small central wavelength offset, and the gap between its two cross sections is small, so it may obtain a large gain. so it may obtain a large gain. At the same time, the material $\tau_p$ corresponding to the 1347nm signal light is the largest among the three materials, and the probability of non-radiative transition is the smallest. A large number of non-radiative transitions will not occur when the fiber length is short, making the fiber length corresponding to the maximum optical signal gain longer.

To sum up, when the fiber length is fixed, the result of $1347nm$ signal light amplification is the best one among the three kinds of signal light amplification. The following is to conduct further simulation and research on this band signal light.

### 3.2 The gain of 1347nm signal amplifying material was simulated and analyzed with doping concentration, pump power and signal power

The gain of $1347nm$ signal amplifier material was simulated and analyzed with doping concentration, pump power and signal power. The influence of doping concentration, pump power and signal power on Bismuth-doped fiber amplifier was explored. Under the condition that the initial signal power is $10^6W$ and the doping concentration is $2 \times 10^{24}ions/m^3$, the variation of the signal gain with fiber length is depicted in Figure 3(a) below. The greater the signal power is, the longer the optical fiber length is for the maximum gain. The pump power is $30mW$ and the signal gain is $12dB$ when the fiber length is 5m. The maximum signal gain of $80mW$ pump power is $35dB$ when the fiber length is 10m, which is much larger than the maximum signal gain of $30mW$ pump power. The signal gain of 80mW pump power is maintained when the fiber length is 8-10m. The best signal gain can be

obtained when the pump power is $80mW$. It can be concluded that with the increase of pump power, the maximum gain increases and the fiber length corresponding to the maximum gain increases.

FIG. 3(b) illustrates the change trend of the maximum signal gain with different pump powers. When the pump power is low, the signal gain increases rapidly with the increase of the pump power. When the pump optical power increases to $0.08W$, the signal gain increases slowly with the pump power. According to the data analysis, in the range of $0.01-0.08W$, the average maximum gain increase is $4.36dB$ for every $0.01\,W$ increase in pump power, while in the range of $0.2-0.3W$, the gain change decreases to $0.12dB$ for every $0.01\,W$. In the interval $0.6W$ to $0.7\,W$, the maximum gain increases by only $0.013dB$ for an average increase of $0.01\,W$ of pump power. This indicates that the pump power has a great influence on the signal gain when the pump power reaches a certain value, and the signal gain slowly increases and will reach saturation eventually.

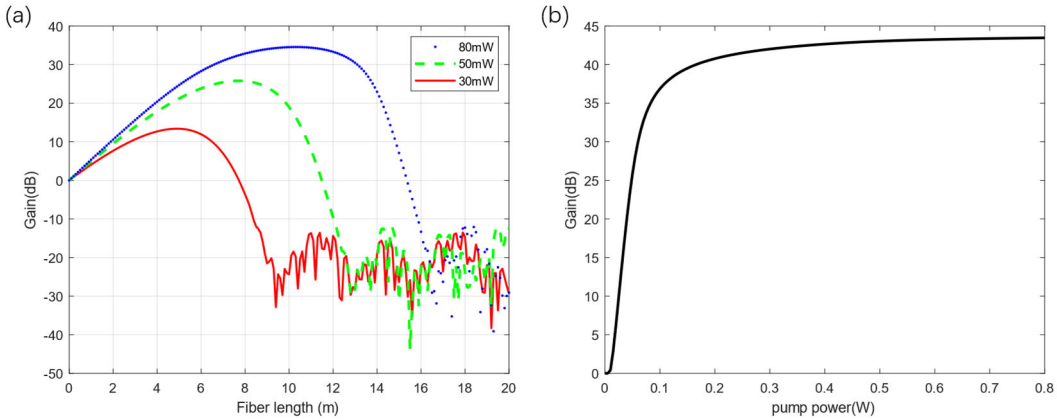



FIG. 3(a) Gain changes with fiber length. (b) The gain varies with the pump power

FIG. 4(a) shows that under the conditions of pump power is $5\times10^{-4}W$, ASE initial power is $0W$, and the doping concentration is $2\times10^{24}ions/m^3$, the signal gain firstly increases under different signal power, and then decreases rapidly after reaching the peak value. It is observed in the figure that the signal gain reaches the highest value when the optical fiber length is 8m when the signal power is $0.001mW$, $0.01mW$ and $0.1mW$, respectively. When the signal power is $0.001MW$, the signal gain reaches the highest value of $26dB$. Because the three different signal powers all obtain the maximum signal gain when the fiber length is 8 meters, the signal power change does not significantly affect the fiber length with the maximum gain.

FIG. 4(b) describes the maximum gain changes with signal power variation. According to the data analysis, the gain decreases by $10.22dB$ when the input signal power increases from $0.001mW$ to $0.1mW$, and only decreases by $0.08dB$ when the input signal power increases from $0.1MW$ to $3.5MW$. This indicates that as the input signal power increases, the gain decreases rapidly and gradually smooths. The reason is that as the input signal power increases, the amplifier needs more excited state particles to maintain the same gain, while the number of excited state particles is finite when the pump power and doping concentration are constant.

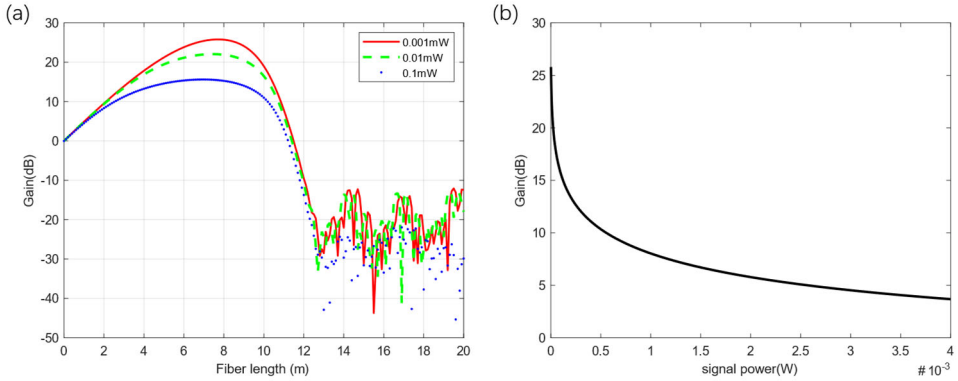



Figure 4. (a) Length variation of gain fiber. (b) The gain varies with the signal optical power

Under the conditions that the initial power of signal light is $10^{-6}$W, the initial pump power is $50 \times 10^{-3}$W , and the initial ASE power is $0W$, FIG. 5(a) describes the signal gain obtained by Bi ions with different doping concentrations as a function of fiber length. As can be seen from the figure, The maximum signal gain is obtained when the fiber length is 3m with doping concentration $N = 8 \times 10^{24}\text{ions/m}^3$ , which is the maximum signal gain obtained with three different doping concentrations. The signal gain obtained with doping concentration $N = 2 \times 10^{24}\text{ions/m}^3$ increases stably with fiber length from 0 to 8m, and the maximum signal gain is obtained at 8m. With the increase of doping concentration, the length of fiber with maximum gain decreases while the gain increases.

FIG. 5(b) describes the maximum gain as a function of doping concentration. According to data analysis, when the abscissa is 0. 5, every change of the abscissa by 0. 1 corresponds to a gain change of $1.48dB$, while at 3, every change of the abscissa by 0. 1 corresponds to a gain change of only $0.03dB$. It indicates that the signal gain increases with the increase of Bismuth-doped concentration. When the Bismuth-doped concentration reaches a certain level, the signal gain tends to be saturated. The main reason is that the number of pumped particles is limited because the pump power remains unchanged. With the increase of doping concentration, the increase rate of the number of pumped particles decreases and finally stops increasing.

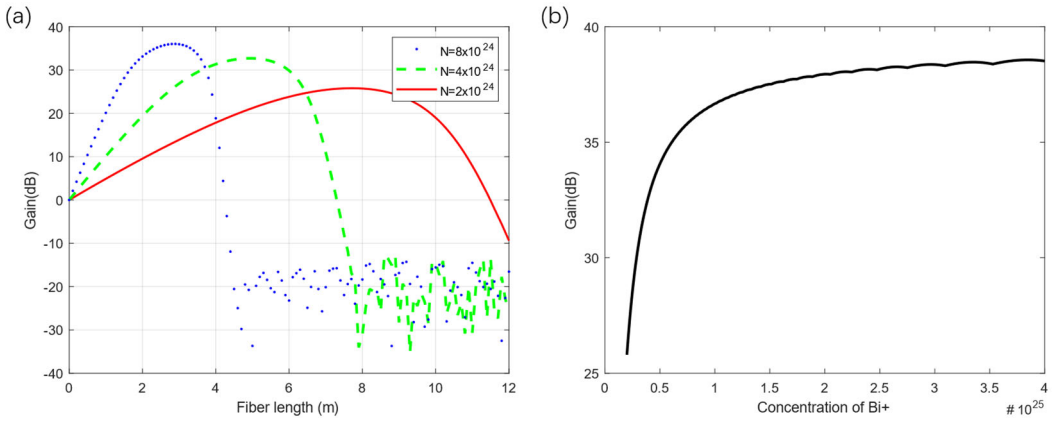



Figure 5. (a) Gain changes with fiber length. (b) The gain varies with Bismuth-doped concentration

## 4. Conclusion

Aiming at the problem of different amplifying bandwidth of optical fiber amplifiers made of Bismuth-doped glass materials, three kinds of Bismuth-doped glass materials and corresponding signal light bandwidth were selected. The experimental simulation of optical fiber amplifiers was carried out. The material amplifying the $1347nm$ light bandwidth showed good results in the experiment, and the maximum gain reached $25dB$. Further simulation of the material amplifying $1347nm$ bandwidth has the following conclusions. As the pump power increases from 0.03 W to 0.08 W, the length of the fiber required to achieve the maximum gain increases by 6 m. When the doping concentration increases from $2 \times 10^{24}\text{ions/m}^3$to $8 \times 10^{24}\text{ions/m}^3$, the fiber length corresponding to the maximum gain decreases by 5m while the gain increases. Furthermore, about pump power, doping concentration and input signal power, As long as either term keeps increasing, the gain will eventually reach saturation.

The experimental results show that the influence of pump power, doping concentration and input signal power on fiber amplification characteristics has significant rules, which are of great significance to the preparation of fiber amplifier, so how to flexibly find the required parameter combination is worth further exploration.

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