Modeling the gain spectrum of Bismuth-doped broadband fiber amplifier and its numerical simulation (1200-1600nm)

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Abstract. Broadband fiber amplifiers with materials doped with metal elements as optical media play an irreplaceable and important role in the current network hardware facilities. In this paper, based on the development of broadband fiber amplifiers and previous studies in the reference literature, this study has completed the modeling of gain spectrum of Bismuth-doped broadband fiber amplifier and its numerical simulation, mainly focusing on signal amplification in the 1200-1600nm band, and studied and simulated the relationship between gain spectrum of Bismuth-doped broadband fiber amplifier and fiber length, pumping power and ion doping concentration in this band. In the case of pumping light at a wavelength of 900nm, good gain results were obtained at the central wavelength of 1350nm. The bismuth-doped fiber performs well in terms of gain performance in the spectral range of 1200-1600 nm when the pump power is greater, the fiber length is around 3 m, and the doping concentration is approximately 0.61025. This is a brand-new, highly useful active medium for NIR lasers and fiber amplifiers.

Keywords: Fiber Optic Amplifier; Fiber Optic Communication; Bismuth Doped Fiber; Broadband Amplification.

1. Introduction

A fiber optic amplifier is an important device in a fiber optic communication system, which can compensate for the loss of optical signal in fiber optics to achieve long-distance transmission. With the development of the global mobile Internet, Internet of Things, cloud computing, and 5G technology, the increasing demand for information have put forward higher requirements for fiber optic communication systems. The erbium-doped fiber amplifier is the most widely commercialized, and the emergence of erbium-doped fiber is a disruptive technological breakthrough in fiber optic communication, which greatly improves the data transmission capability of existing communication systems but is far from meeting the growing data transmission demand [1, 2]. Due to the limitation of erbium ion 4f narrow-band forbidden ring leap structure, it can only perform optical amplification of signal light in the wavelength range of 1530-1620nm, which only covers a small part of the low-loss transmission window of quartz fiber [3]. Currently, praseodymium-doped fiber amplifiers (PDFA), thulium-doped fiber amplifiers (TDFA), and neodymium-doped fiber amplifiers (NDFA) have been developed, but there is not yet a particular individual fiber amplifier that can cover the full optical communication window. Therefore, Bismuth-doped fiber amplifiers are also of great interest due to the ultra-broadband amplification properties of Bismuth ions [4-7]. Such Bismuth-doped glasses and fibers emitting in the ultra-broadband NIR at 1200-1600nm become very promising gain media for realizing ultra-broadband fiber amplifiers and lasers, and at the same time, they can make up for the shortcomings of conventional rare-earth ion-doped fiber lasers and amplifiers. Since the world's first Bismuth-doped fiber was developed by MCVD technology in 2005, a lot of practice and exploration has been carried out to explore the application and principle of Bismuth-doped broadband fiber amplifiers.

In recent years, people have studied a variety of fiber amplifiers and laser gain media to increase the transmission bandwidth of fiber optic communication systems. To grasp the principle of their luminescence, researchers have conducted a lot of research on Bismuth-doped optical fibers and put forward many hypotheses about Bismuth activity [8-11]. For example, in 2020, Baonan Jia et al. conducted a theoretical study on the luminescence mechanism of Bismuth-doped fiber Bismuth activity center based on the self-developed Bismuth-doped fiber [12]. 2022 Wang Dingchen et al. in the forward pumping scheme, the signal input power is -10dBm when the pump power is 500mW, the signal received a gain of more than 25dB, while the noise factor is about 3.2dB [13], and in the article, the structure and luminescence properties of these Bismuth active centers are introduced systematically, which provides valuable theoretical guidance for further development of high-performance Bismuth-doped materials. However, the diversity of Bismuth ion valence states complicates the luminescence mechanism of Bismuth-doped fibers. For example, how to achieve effective laser output at ultra-low Bismuth doping concentration, how to overcome the ion clustering problem caused by high Bismuth doping in the matrix material, and so on [10]. In general, although the NIR ultra-broadband luminescence of Bismuth-doped materials has attracted the attention of many researchers and the corresponding materials and devices have been developed rapidly, the mechanism of Bismuth-related NIR luminescence is still unclear. Bismuth-doped materials are expected to be more widely used in ultra-wideband light sources, ultra-wideband amplifiers, tunable lasers, and other fields because of their long fluorescence lifetime and wide spectral range.

Therefore, to study and explore the maximum gain of broadband fiber amplifier, this paper carries out experimental simulation according to the three-energy level system model of Bismuth ion, the modeling of gain spectrum of Bismuth-doped broadband fiber amplifier in 1200-1600nm band and its numerical simulation, the design of pumping wavelength according to the signal wavelength range, energy level structure, and electron leap process, the establishment of rate equation and power propagation equation, the MATLAB The gain spectrum is programmed to calculate the variation law of the gain spectrum with the fiber length (L), doping concentration (N) and pump power (Pp). Based on this model, the optimized parameters such as the fiber length and pump power were selected to achieve a better gain coefficient and noise index. To verify the feasibility of the subsequent research direction of the Bismuth-doped broadband fiber amplifier development.

2. Theory And Model

2.1. Energy level structure

According to the paper [14], the three-level system structure was adopted for experimental simulation, as shown in Figure 1. Three-level systems contain ground states (first energy level), i.e. steady state, metastable state (second energy level), and excited state (third energy level). In this model, it is assumed that the lifetime of excited ions is much smaller than that of metastable ions. When we construct the rate and power equations, the number of excited ions can be ignored, that is, the ground state ion transitions to the excited state and then transitions to the metastable state again in a very short time.

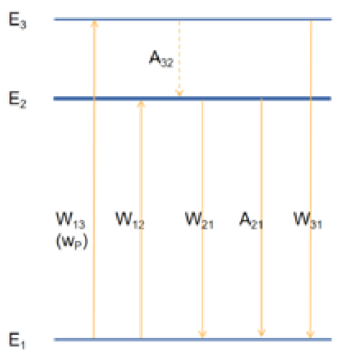


Fig 1. Three-level energy system.

2.2. Software and objectives

In this experiment, we code and simulate with MATLAB. According to the range of the signal light wavelength, energy level structure, and electron transition process, the rate equation and power propagation equation are established. To calculate the change of gain spectrum with fiber length, doping concentration, and pump power, MATLAB is used to program.

As shown in Figure 2 below, the required spectral range is obtained by the spontaneous spectral line after the material is pumped. The radiation absorption section and loss coefficient are obtained from the material parameters. Then, the rate and power equations are written through these parameters, the rate equation explains the absorption and radiation of particles between energy levels. The power equation explains the results of the change of self-luminous power, pump power, and amplificated spontaneous emission light power with the change of various material parameters. Finally, a simulation is carried out in MATLAB.

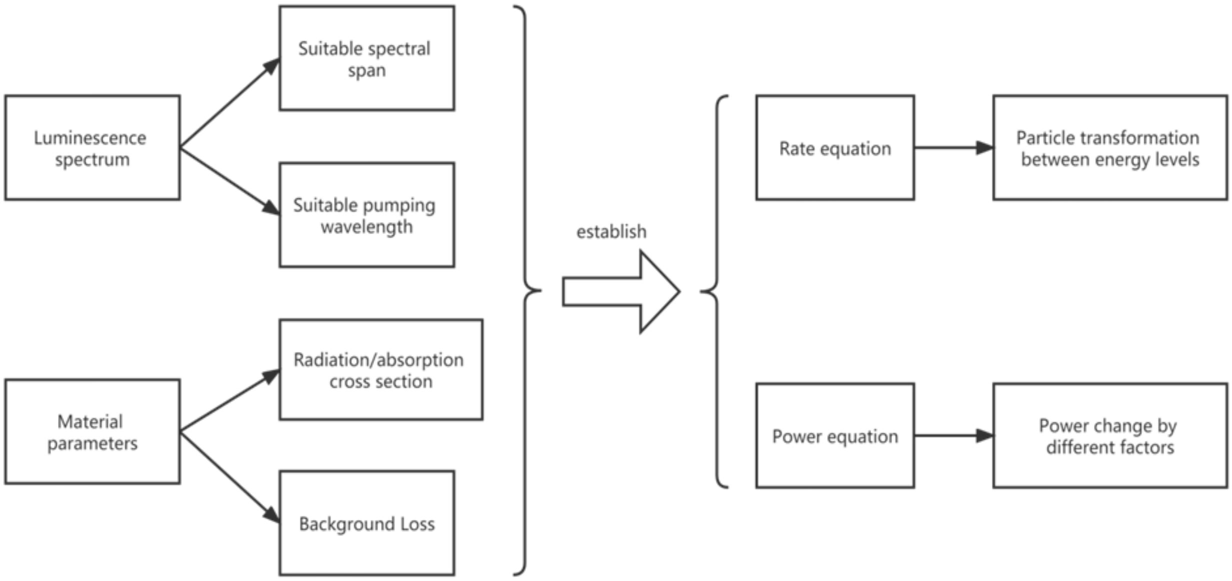


Fig 2. Simulation flow chart.

3. Results and Discussion

3.1. Confirmation of the model parameters

According to the literature [15], it is known that in Bi-doped LAS (lithium aluminosilicate) glass, the emission spectrum can be well fitted by a Gaussian curve, as shown in Figure 3, where the pink dashed line is the overall presented emission spectrum, which can be split into a blue dotted line with 1100nm as the emission center and a Green solid line with 1350nm as the emission center. The curves shown here are the emission spectra after being normalized.

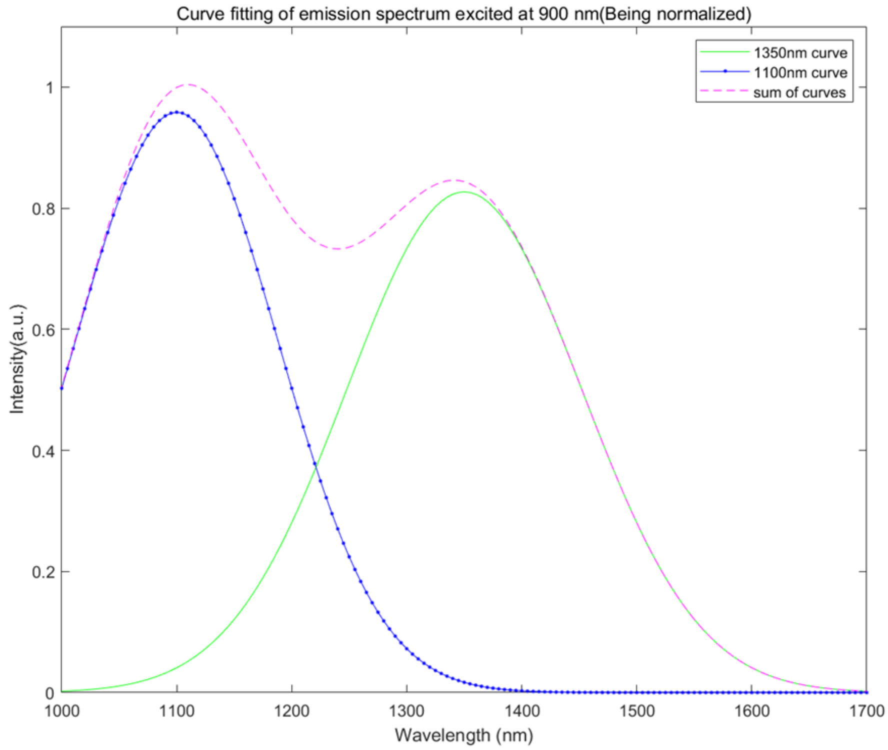


Fig 3. Spectral profile at 900nm pumping [15].

In this project, Bi-doped LAS glass was used, and 900nm pump light was selected. Gain spectra centered at 1350nm were generated, and according to the literature [15], the radiation and absorption cross-section of the signal light was approximated as a function of the wavelength of the emission spectrum, so the radiation and absorption cross-section was approximated by a Gaussian function in this model. A series of property parameters of spontaneous spectra with 1350nm centered wavelength are shown in Table 1.

Table 1. Parameters used in the model.

Property	Parameter
Composition, mol%	$63SiO_2$-$23Al_2O_3$-$13Li_2O$-$1Bi_2O_3$ [15]
Background loss, %	2.28
Refractive index	1.519 [15]
λ_s, nm	1350 [15]
λ_p, nm	900 [15]
FWHM, nm	240 [15]
Radiation emission rate, s^{-1}	3700
Non-radiation emission rate, s^{-1}	25000
Absorption cross-section at pump wavelength, m^2	8.82×10^{-26}
Emission cross section at pump wavelength, m^2	1.6826×10^{-33}
Absorption cross-section and emission cross-section of central wavelength of signal, m^2	2.3×10^{-24} [15]
Core radius of the fiber, m	3.0×10^{-6}

Based on the data in the literature [16], the emission lifetime is 270μs, from which the 3 and 2 non-radiation emission rate and the 2 and 1 energy level radiation emission rate can be derived. In this experiment, the approximate values of 25000s^{-1} and 3700s^{-1} for the 3 and 2 non-radiation emission rate and the 2 and 1 energy level radiation emission rate respectively were used for the calculation.

In the simulation, the speed of light in a vacuum $c=3\times10^{8}$m/s, Planck's constant $h=6.6626\times10^{-34}\mathrm{m}^2\cdot\mathrm{kg/s}$, background loss $\alpha=0.0228$(0.1dB/m), pump light wavelength $\lambda_p=0.9\times10^{-6}$m, signal light center wavelength $\lambda_s=1.35\times10^{-6}$m, fiber core radius $r=3\times10^{-6}$m.

3.2. Gain of signal light for different pump powers

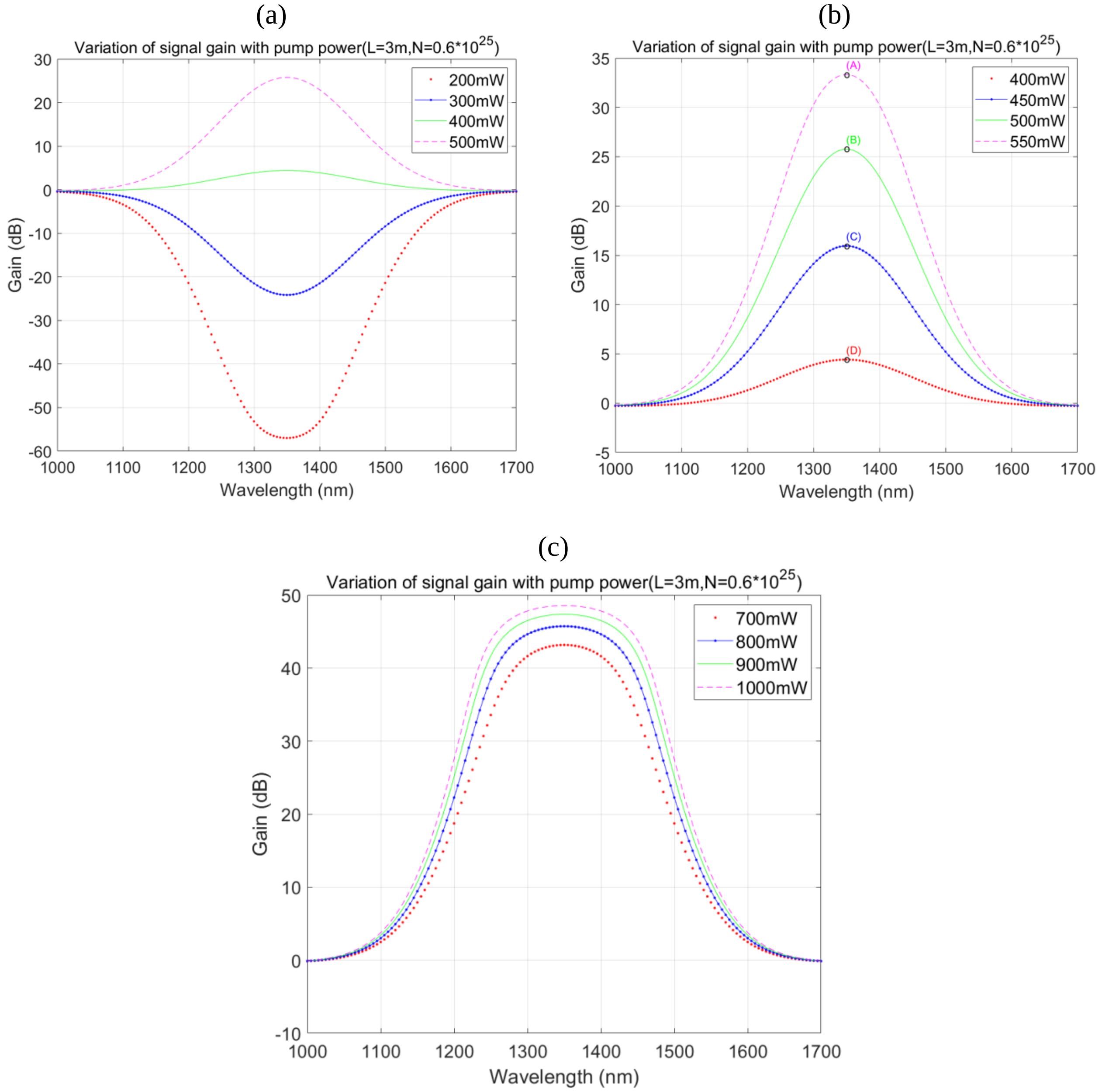


Fig 4. (a) Variation curve of optical gain of fiber signal at different pumping power (L=3m, $N=0.6\times10^{25}$), red dotted line, blue dotted line, green solid line, and pink dashed line correspond to the gain curves at 200mW, 300mW, 400mW, and 500mW, respectively. (b) Variation curve of optical gain of fiber signal at different pumping power (L=3m, $N=0.6\times10^{25}$), red dotted line, blue dotted line, green solid line, and pink dashed line correspond to the gain curves at 400mW, 450mW, 500mW, and 550mW respectively. (c) Variation curve of optical gain of fiber signal at different pumping power (L=3m, $N=0.6\times10^{25}$), red dotted line, blue dotted line, green solid line, and pink dashed line correspond to the gain curves at 700mW, 800mW, 900mW and 1000mW respectively.

As shown in Fig. 4(a), the gain curve of the signal light at fiber length of 3m and doping concentration of 0.6×10^{25} can be found to have a peak or trough at the central wavelength of about 1350nm. Under the experimental conditions, the gain is negative at pump power of 200mW and

300mW, and the depression of the curve becomes smaller when the pump power increases from 200mW to 300mW. The gain is positive for pump power of 300mW and 400mW, and the signal optical gain increases with increasing pump power as the pump power increases from 300mW to 400mW.

As in Figure 4(b) the power continues to increase to 400mW, 450mW, 500mW, and 550mW respectively. In the comparison of the four different pump powers, the signal light gain also increases when the pump power increases, with the maximum gain of approximately 33.33 at a pump power of 550mW. As the pump power increases from 450mW to 550mW, only a 100mW increase in power will bring more than twice the signal light gain value, when increasing the pump light power will bring a high gain return.

To test the signal light gain at larger pump light powers, the gain curves are calculated and plotted here for powers of 700mW, 800mW, 900mW, and 1000mW, respectively, as shown in Figure 4(c). It can be seen that as the pump power increases, the signal light gain still increases, but the return from increasing the pump light power has become significantly lower, the pump power increases from 700mW to 1000mW, increasing the power by 300mW, which only brings about a 12% gain increase, indicating that the gain spectrum is close to saturation at this point.

3.3. Gain of signal light for different fibre lengths

(a) (b)

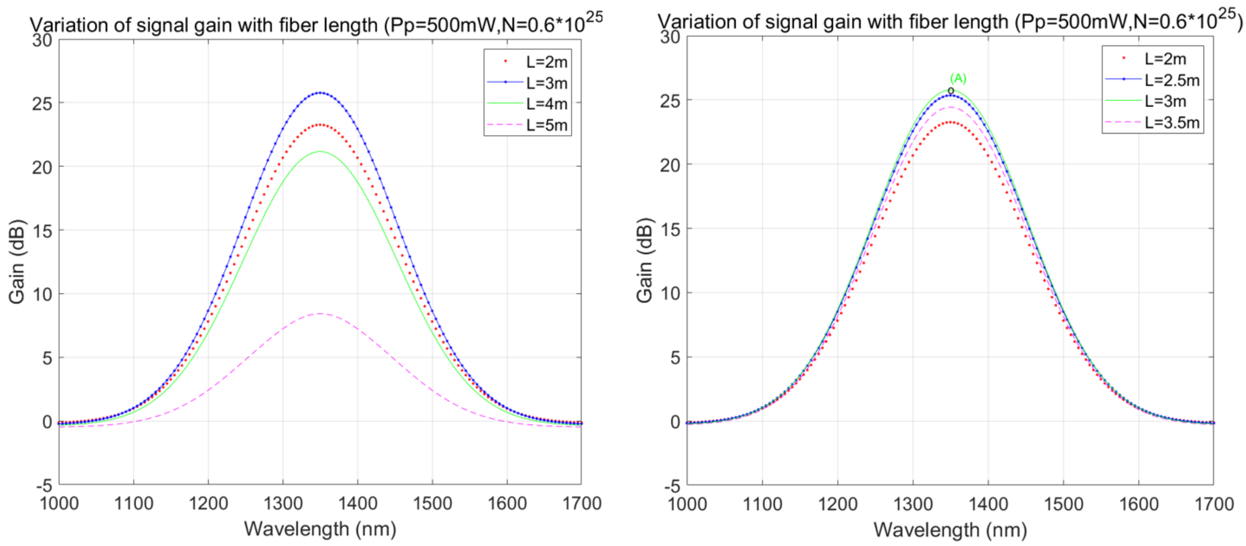
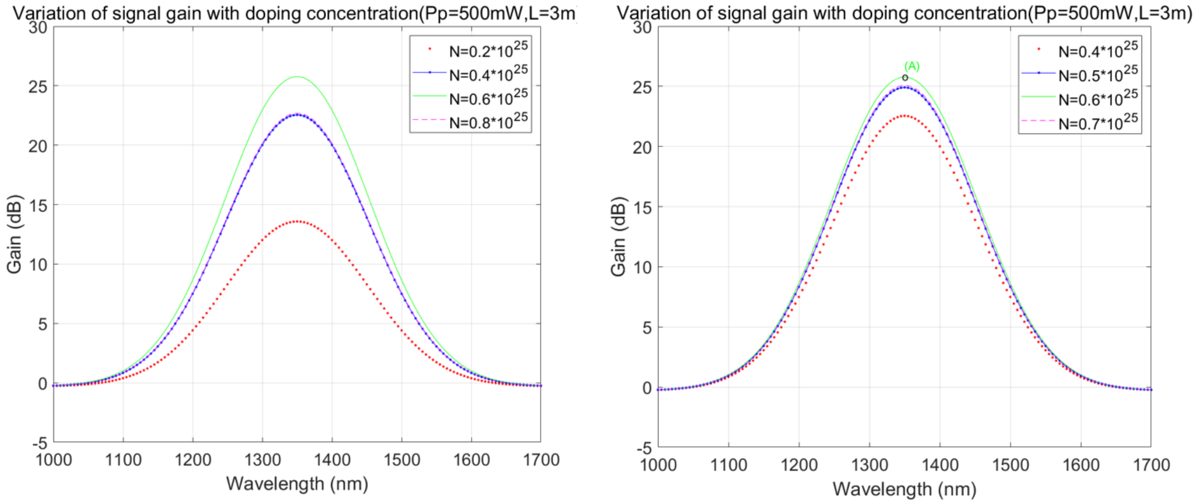


Fig 5. (a) Variation curve of optical gain of fiber signal at different fiber length (P_p =500mW, N=0.6×10^{25}) red dotted line, blue dotted line, solid green line, and pink dashed line correspond to the gain curve at 2m, 3m, 4m, and 5m respectively. (b) Variation curve of optical gain of fiber signal at different fiber length (P_p =500mW, N=0.6×10^{25}) The red dotted line, blue dotted line, green solid line, and pink dashed line correspond to the gain curves at 2m, 2.5m, 3m and 3.5m respectively.

It can be seen that the signal optical gain corresponding to fiber lengths of 2m, 3m, 4m, and 5m at doping concentration N = 0.6×10^{25} and pump power of P_p = 500mW are shown in Fig. 5(a). In the comparison of the four different fiber lengths, the gain is greatest for a fiber length of 3m.

As can be seen in Figure 5(b), with a pump power of 500mW and a doping concentration of 0.6×10^{25}, further reduction of the test interval shows that the maximum gain is about 25.77 at a fiber length of 3m for the four different fiber lengths. The fiber length value corresponding to the maximum signal optical gain also changes when the test conditions (pump power, doping concentration) are changed.

3.4. Gain of signal light for different doping concentrations



(a) (b)

Fig 6. (a) Variation curve of optical gain of fiber signal at different doping concentration (P_P =500mW, L=3m) red dotted line, blue dotted line, green solid line, and pink dashed line correspond to the gain curves at 0.2×10^{25}, 0.4×10^{25}, 0.6×10^{25}, 0.8×10^{25} respectively. (b) Variation curve of optical gain of fiber signal at different doping concentration (P_P =500mW, L=3m) red dotted line, blue dotted line, green solid line, and pink dashed line correspond to the gain curves at 0.4×10^{25}, 0.5×10^{25}, 0.6×10^{25}, 0.7×10^{25} respectively.

The signal optical gain corresponding to doping concentrations of 0.2×10^{25}, 0.4×10^{25}, 0.6×10^{25}, and 0.8×10^{25} at fiber length L=3m and pump power P_P =500mW are shown in Fig. 6(a). Among the four parameter contrasts, the signal optical gain is maximum when the doping concentration N=0.6×10^{25}.

From Fig. 6(b), it can be seen that at pumping power of 500mW and fiber length of 3m, the gain is the highest at a doping concentration of 0.6×10^{25}, which is about 25.77dB. When the doping concentration reaches 0.8×10^{25}, the gain decreases due to the generation of ion clusters [10]. It can be concluded that a doping concentration of around 0.6×10^{25} is the optimum solution for gain under the current conditions. Similarly, the doping concentration value corresponding to the maximum signal optical gain changes when the test conditions (pump power, fiber length) are changed.

4. Conclusion

In three simulations, Bismuth-doped broadband fiber amplifier bandwidth and gain have good performance, in the experiment we get: when the pump power is high, the fiber length is about 3m, the doping concentration is about 0.6×10^{25}, Bismuth-doped fiber has good gain performance in the spectral region of 1200-1600 nm, is a new promising active medium in near-infrared lasers and fiber amplifiers, has great application value. However, this paper also found that the gain of Bismuth-doped fibers decreases significantly with decreasing pump power, and when the fiber length is too long or too short and the doping concentration is too high or too low, even negative gain occurs. This requires more fundamental research to solve the above problems to improve the efficiency of Bismuth-doped lasers and fiber amplifiers for eventual applications [9]. In future research, enhancing the gain value of Bismuth-doped broadband fiber amplifiers is still an important topic.

References

[1] Xue Wenyuan. Development and prospects of modern communication technology[J]. Information Communication,2015(03):223.

[2] Tian Jinli. Brief description of the application and development of DWDM technology in the communication industry [J]. China Science and Technology Expo, 2015(34):369.

[3] Peng Mingying et al. New Bismuth-doped light-emitting materials for ultra-wideband fiber amplifiers [J]. Advances in Laser and Optoelectronics, 2005(12):41-45.

[4] Zhou Shifeng et al. Infrared luminescence mechanism and broadband optical amplification of Bismuth-doped glass [J]. Advances in Laser and Optoelectronics, 2009, 46(02):36.

[5] Zhou Shifeng and Qiu Jianrong. Ultra-broadband optical amplification of novel Bismuth-doped glass [J]. Advances in Laser and Optoelectronics, 2008(02):29.

[6] Wu Jindong et al. Development of near-infrared broadband light-emitting Bismuth-doped quartz fiber [J]. Journal of Optics, 2011, 31(04):80-84.

[7] Wu Jindong. Design and fabrication process of new optical fiber [D]. Zhejiang University,2012.

[8] Gao Yanyang et al. Spectral properties of erbium-Bismuth co-doped borate glasses [J]. China Laser,2013,40(12):249-252.

[9] Shi Canyuan. Preparation of Bismuth-doped optical fiber and its amplification performance[D]. Huazhong University of Science and Technology,2021.DOI:10.27157/d.cnki.ghzku.2021.000769.

[10] Evgeny Dyalov. History, development and prospects of Bismuth-doped optical fibers [J]. Optics and Optoelectronics,2020,18(01):1-4.DOI:10.19519/j.cnki.1672-3392.2020.01.001.

[11] Jiao Yan et al. Research progress of near-infrared ultra-wideband fiber amplification[J]. Journal of Applied Sciences,2020,38(04):520-541.

[12] Jia Baonan et al. Research progress on the luminescence mechanism of Bismuth-doped fiber with Bismuth active center[J]. Laser Technology,2020,44(06):657-663.

[13] Wang Dingchen et al. Numerical and limited experimental study of 1150 nm signal amplification based on Bismuth-doped fiber using 980 nm pumping. Optik, 2022,268

[14] Chun Jiang. Modeling a Broadband Bismuth-Doped Fiber Amplifier. IEEE journal of selected topics in quantum electronics: A publication of the IEEE Lasers and Electro-optics Society 15.1(2009): 79-84.

[15] Takenobu Suzuki and Yasutake Ohishi, Ultrabroadband near-infrared emission from Bi-doped Li_ (2)O-Al_ (2)O_ (3)-SiO_ (2) glass. Applied physics letters 88.19(2006): 191912-1-191912-3.

[16] Meng XianGeng et al. Near infrared broadband emission of Bismuth-doped aluminophosphate glass. Optics express 13.5(2005): 1628-34.