The Gain Spectrum of A Bismuth-Doped Broadband Fiber Amplifier in 1700-1800nm

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Abstract. In today’s world of communication and rapid growth in demand, erbium-doped optical fiber amplifiers only cover the C-band and L-band wavelengths, and only a small portion of these wavelengths are used. While the O, E, S, and U-bands are not fully utilized and developed to meet the increasing demand for optical fiber communication networks. Bismuth-doped fiber-optic amplifiers can produce broadband light sources and fiber-optic amplifiers due to their ultra-broadband near-infrared radiation properties, thus solving the problem of communication transmission needs. This essay will examine the fiber amplifier doped with Bismuth. This paper focuses on the excitation-emission theory as well as the working principle and process of the fiber-optic amplifier. Meanwhile, this study establishes the optical gain model of the Bismuth-doped fiber amplifier and uses numerical simulation with MATLAB. The signal light works in the wavelength band of 1700-1800nm, and the optimal fiber gain under various conditions is obtained. From this, the maximum gain of the fiber is found to be about 39dB. Bismuth-doped fiber can act as an active carrier for a new kind of continuous wave laser, and the spectral range from 1700 to 1800 nm can be employed with the Bismuth-doped fiber amplifier.

Keywords: Bismuth-Doped Fiber Amplifier; Optical Amplification; Optical Gain Modeling; Numerical Simulation.

1. Introduction

Network data traffic is growing quickly because of the emergence of the mobile Internet, the Internet of Things, cloud computing, and 5G networks. A fiber optic amplifier is an important optical device in a fiber optic communication system, compensating for the fiber’s loss of light to achieve long-distance transmission. Nowadays, the global demand for information capacity is increasing by 30%-40% per year [1]. Still, the use of the C-band (1530-1565 nm main conventional band) has been stretched to its limit under the influence of existing technologies. There are three approaches to increase optical communication systems’ transmission capacity: increasing the single-channel transmission rate, reducing the channel spacing, and extending the transmission bandwidth [2]. After years of fast advancement, optical fiber’s single-channel transmission rate has reached 400 GB/s, and channel spacing has surpassed 50 GHz (0.4 nm wavelength). Improvements in the first two technologies have reached the Shannon limit in terms of increasing system transmission capacity. As a result, inter-channel crosstalk has grown, reducing system stability. In a single-mode fiber optic transmission system, the core component is the optical amplifier. If the operating band of the optical amplifier can be expanded, the communication capacity can be increased more than several times. With its unfilled outer electron layer, the main group heavy metal element Bismuth is prone to leap and lose electrons, thus forming Bismuth ions of various valence states [3]. This structure makes it sensitive to the surrounding ligand field environment. When doped into different matrices and driven by various pump sources, it has the ability to emit ultra-broadband fluorescence that spans the near-infrared spectrum [4]. Bismuth-doped glass emits ultra-broadband infrared emission over a wavelength range when activated at a certain wavelength. It has a half-height breadth of more than 200 nm and a fluorescence lifetime of hundreds of microseconds. As a result, this material is promising for ultra-broadband optical amplification and will serve as the foundation for a new generation of fiber-optic amplifiers [5].

Researchers have been intrigued to create novel active laser materials since American physicist Meyman created the first ruby laser in 1960. As a result, it became probable to enhance the performance of already-existing lasers or invent brand-new ones. In 1966, the British-Chinese scientist Charles Kao and his collaborator Hockham proposed a new term, transmission medium, and they thought that low-loss optical fibers suitable for long-distance communication use could be manufactured by purifying raw materials [3].

As seen in Fig. 1, these generations generally correspond to the evolution of fiber optic transmission.

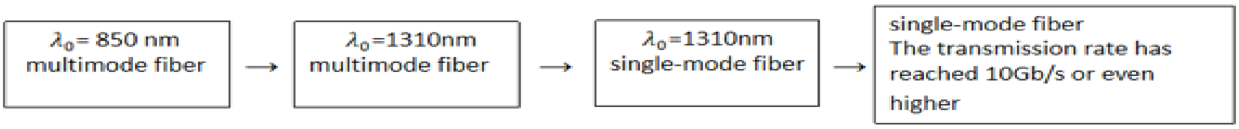

Fig 1. A brief diagram of fiber optic development.

The first generation of fiber optic communication works at λ_0= 850 nm, a short wavelength band, and the transmission fiber use multimode fiber. This generation of fiber optic communication is marked by a field experiment with a code rate of 44.736 Mb/s conducted in Atlanta, USA, in 1977. The second generation of fiber optic communication works at 1310nm, which belongs to the long wavelength band and is the second low-loss window of quartz fiber. 1984 saw the realization of a single-mode fiber optic communication system that works at λ_0=1310nm, the third generation of fiber optic communication system. Single-mode fiber has much lower dispersion and less loss than multimode fiber, which is widely used in long-distance trunks and transoceanic communications. The transmission rate has reached 10 GB/s or even higher [6].

Since the discovery of very wideband near-infrared luminescence from Bismuth-doped materials by Dvoyrin et al. in 2005 using an improved chemical vapor deposition process, the study of bismuth-doped materials has grown in popularity. The width of its emission spectrum's half-peak was 200 nm, and the emission cross section was as high as $6 \times 10^{-21} cm^2$ [7]. Some scientific institutions in China subsequently observed optical amplification and excitation phenomena in the 1300-1500 nm range in Bismuth-doped laureate fibers, so Bismuth-doped fibers are expected to play an important role in future ultra-broadband optical amplifier devices [8]. First reported in 2011, Dianov et al. used a home-made 1310 nm Raman fiber laser as the pump source and achieved a fiber length of 125 m with a signal power of -20 dBm. A fiber amplifier doped with Bismuth has the best gains of 24 dB and 30 dB at 1427 nm at 65 mW and 100 mW pump power, respectively [9]. In 2015, Firstov et al. prepared a new Bismuth-doped fiber with 100-300 ppm of Bismuth doping in the core and a high concentration of Ge doping with more than 50 mol% to achieve 1600- 1800 nm luminescence finally. Using a 1565 nm erbium-doped fiber laser as a pump, a laser near 1700 nm was obtained with an output power of 1.5 W and a slope efficiency of 33% [10]. In 2016, Russian researchers Sergei V. Firstov, Sergey V. Alyshev, Konstantin E. Riumkin, and others successfully operated a Bismuth-doped fiber amplifier in the 1700 nm region. In 2018, Taengnoi N et al. observed that Bismuth-doped phosphosilicate fiber produced ~22 dB gain at 1340 nm pumping, 720 mW power, 15.7 dBm saturation output power, and 42 nm gain bandwidth [11]. Dianov E M et al. used 1568 nm pumped light at 300 mW power to achieve 25 dB maximum gain at 1725 nm for BGSF (50GeO2-50SiO2) with 3 dB bandwidth of 50 nm for amplification in the 1600-1750 nm band (L+U)[12]. In 2019, Thipparapu N K et al. observed that the input signal power - 10 dBm, 152 m BPSF, pump wavelength of 1270 nm/1240 nm, the peak gain of 31 dB at 1360 nm at 500 mW of pump power, the power conversion efficiency up to 11%, and gain coefficient of 0.06 dB/mW [13].

The working model and theory of the fiber-optic amplifier will be presented first, followed by a discussion of the variables influencing the amplifier's gain. In contrast, this research examines the relationships between gain and fiber length, gain and dopant particle concentration, and gain and pump optical power using the controlled variable approach and MATLAB's numerical simulation method. The maximum gain of the fiber and the optimal operating conditions will be investigated.

2. Models and Methods

The Bismuth ion doped in the fiber is a triple-energy structure. The three-energy level structure, as the name implies, consists ofE_1,E_2 and E_3 three energy levels. The ground state energy level, or E_1, is where the majority of particles are in thermal equilibrium,E_3 the pumping high energy level, and E_2, the sub-stable energy level. When excited by an external photon (the energy of the external photon is$h\nu = E_3 - E_1$), the atom in the E_1 energy level takes in the photon's energy and moves up to the E_3 energy level, a process called excited absorption. (As in Fig. 2(a)), due to the instability of the E_3 energy level, some atoms will leap back to the E_2 energy level, releasing photons with a photon energy of$h\nu = E_3 - E_2$. This process does not require external photon excitation, called spontaneous radiation (as in Fig. 2(b)). The excited emission (see Fig. 2(d)) not only does not absorb the photon but also releases it, thus amplifying the light, and the particle jumps back to the E_1 energy level from the E_2 energy level. (As shown in Fig. 2)

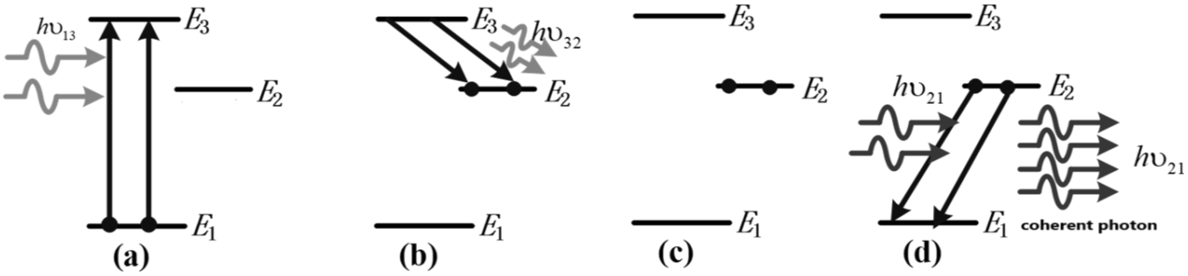

Fig 2. Schematic diagram of three-energy level structure.

We model and simulate primarily using the rate equation and the power propagation equation to investigate the relationship between fiber length, particle concentration, and pumping optical power and the gain of the fiber.

The process of particle leap between the three energy levels is shown in Fig. 3. In response to the external pump source's stimulation, the particles in the ground state are pumped down to the pump energy level, and the probability of pumping is Wp ($E_1 \rightarrow E_3$). Wp is the fraction of the total amount of particles in the volume that are pushed by the external pump source from the ground state to the pump energy level per unit volume of time., because the particles jump from E_1 to E_3 energy level, and the number of particles in the E_1 state decreases.

The E_3 energy level has a very short lifetime and is unstable. Most of the particles are rapidly transferred to the sub-stable energy level in the form of radiation-free jumps with a radiation probability of S_{32}, while a small number of the particles will return to the ground state energy level with spontaneous radiation and radiation-free jumps with probabilities of A_{31}, S_{31} (because the order of magnitude of A_{31} and S_{31} is too small to be negligible).

When the quantity of particles in the E_2 energy level does not exceed the quantity of particles in the E_1 energy level, some particles in the E_1 energy level will spontaneously radiate and make a radiation-free leap back to the ground state; the probability is A_{21},S_{21} (S_{21} is very small, negligible).The majority of particles stay between E_1 and E_2 energy level, once the formation of the inversion particle number situation, the excited radiation between E_1 and E_2 energy level and the excited Once the inversion particle number condition is formed, the excited radiation between E_1 and E_2 energy levels and the excited absorption will be absolutely dominant (mainly W_{12} and W_{21}). The rate equation represents the transformation of the particle number at each energy level with time in a three-energy system.

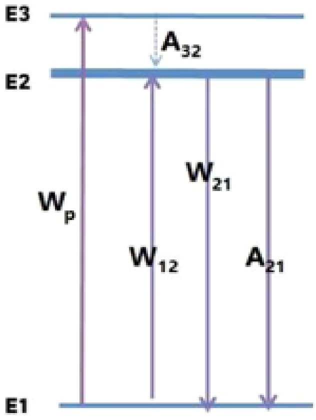

Fig 3. Particle leap process.

The signal light strength changes from $P_{S(0)}$ to $P_{(L)}$ as soon as the pump light enters the fiber core for excitation, as in Fig. 4(b).

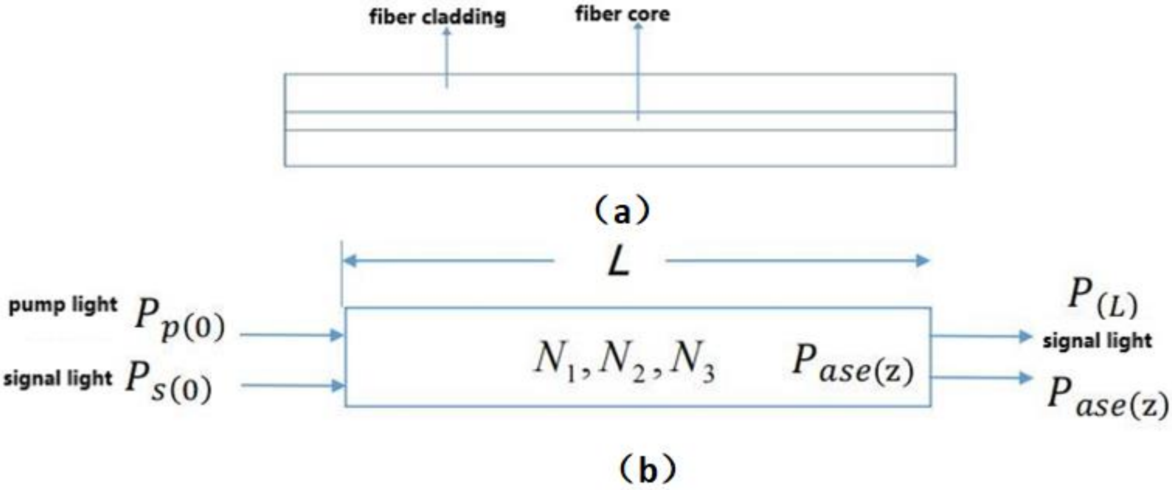

Fig 4. (a) A brief diagram of an optical fiber.
(b)The change of pump and signal light after entering the fiber.

In the simulation, the meaning of some parameters is essential, such as α indicates the fiber material loss coefficient (dB/m), is how many decibels per meter reduction of light in the fiber. Δν Indicates the frequency half-height full width (in Hz), Γ indicates the effective light into the fiber core of each light as a percentage of each light, the minimum value is 0, the maximum value is 1. σreveals the cross-section of light's absorption and emission. The fibre gain value in relation to the signal light is obtained by replacing the power after the signal light leaves the fiber and the power before the signal light enters the fiber into the gain formula.

3. Results and Discussion

3.1. Parameters

It finds the parameters required in the rate equation and the equation for power propagation, from which the pump light power and the pump light wavelength were learned [14, 15]. For obtaining the light absorption and emission sections of the pump and the absorption and emission sections of the signal light, the plots in the literature (Fig. 5) were fitted (replaced by the normal distribution function approximation) to roughly determine the signal light's emission and absorption cross sections. The pertinent characteristics were used to determine the rough values of the pump light's absorption and emission cross-sections. The obtained parameters are listed in the following table.

Table 1. Parameter table.

Material parameters	Material: BDFA (Bi: 50GeO2-50SiO2, fiber 232 in the literature)
Pumping power	300mw
Concentration of Bi wt(%)	4.5×10^{-3}
Numerical aperture	0.45
Peak wavelength	1650nm0
Pump light wavelength	1550nm
Pump light absorption cross-section	$1.17\times10^{-24}m^2$
Pump light emission cross-section	$1.8063\times10^{-25}m^2$
Signal light absorption cross-section	$1\times10^{-2}m^2$ (approximate value from fitting)
Signal light emission cross-section	$1\times10^{-2}m^2$ (approximate value from fitting)
Material loss coefficient α	0.1dB/m
A_{21}	2000 pcs/s
A_{32}	10000 pcs/s (assumed)

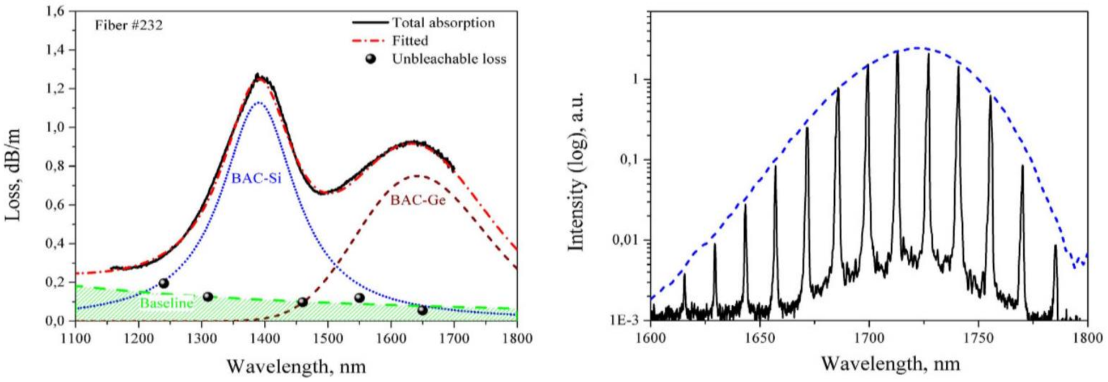
(a) **(b)**

Fig 5. Spectrum of the fiber's absorption (a).
Spectrum of the input signal (solid line) and the fiber source (dashed line) (b).

3.2. Results graph and analysis

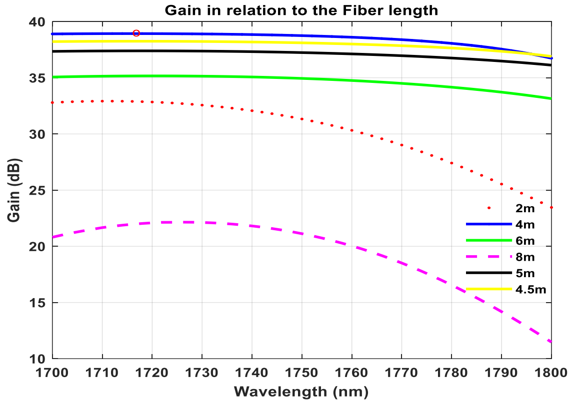

Fig 6. Exploring the relationship between gain and fiber length.

In the Fig. 6, the red dotted line, blue line, green line, purple dotted line, black line and yellow line represent the fiber lengths of 2m, 4m, 6m, 8m, 5m and 4.5m, respectively. The horizontal coordinate of the red circle in the Fig. is the wavelength of the signal light at this time, and the vertical coordinate is the gain value. In order to investigate the relationship between gain and fiber length (Fig. 6), the particle concentration and the pumping optical power (300mw) were controlled first. Then the fiber lengths of 2m, 4m, 6m, and 8m were selected first. The maximum gain is 38.9294dB at 4m, which is about 1.77 times of the gain at 2m, when the signal light wavelength is 1716nm. The strength of the signal light is likely to be diminished by secondary absorption. The pump light output in the fiber also decreases with fiber length. As a result, fewer particle inversions will eventually result in more particles at lower energy levels than higher ones. According to the above explanation, the longer length is not always better for a given pump power fiber. The loss factor and fiber noise are both connected. When the length is 4 meters, the noise may be reduced. So the maximum gain is achieved when the fiber length is 4m.

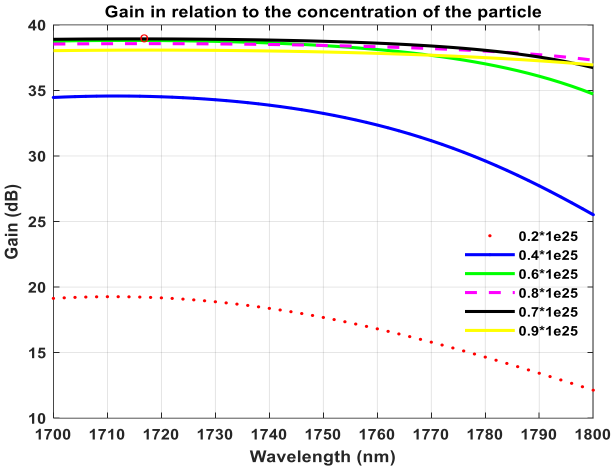

Fig 7. Exploration of the relationship between gain and particle concentration.

The red dashed line, blue line, green line, purple dashed line, black line and yellow line represent the particle concentration of $0.2 \times 10^{25}\, pcs/m^3$, $0.4 \times 10^{25}\, pcs/m^3$, $0.6 \times 10^{25}\, pcs/m^3$, $0.8 \times 10^{25}\, pcs/m^3$, $0.7 \times 10^{25}\, pcs/m^3$, $0.9 \times 10^{25}\, pcs/m^3$. The horizontal coordinate of the red circle in the Fig. is the wavelength of the signal light at this time, and the vertical coordinate is the gain value. When the total number of particles was selected to investigate the relationship between gain and particle concentration (Fig. 7), the fiber length was set to 4 m, and the pumping power was 300 mW. It was found that the gain decreased gradually with the increasing wavelength of the signal light for different particle concentrations. The particle concentration was set to $0.2 \times 10^{25}\, pcs/m^3$, $0.4 \times 10^{25}\, pcs/m^3$, $0.6 \times 10^{25}\, pcs/m^3$ and $0.8 \times 10^{25}\, pcs/m^3$, and the gain was found to be maximum at $0.8 \times 10^{25}\, pcs/m^3$. When the new particle concentration is set to $0.9 \times 10^{25}\, pcs/m^3$ and $0.7 \times 10^{25}\, pcs/m^3$, the gain is very close to that of $0.7 \times 10^{25}\, pcs/m^3$ and $0.8 \times 10^{25}\, pcs/m^3$, and the maximum gain is 38.9294dB. We speculate that a larger pumping power is required to form the reversed particles when the particle concentration is larger than a certain value. The gain will tend to be saturated when the particle concentration increases gradually from 0. When it exceeds $0.7 \times 10^{25}\, pcs/m^3$, the particles excited by the pump optical power will start to decrease, which leads to the decrease of the gain, so the optimal particle concentration is about $0.7 \times 10^{25}\, pcs/m^3$.

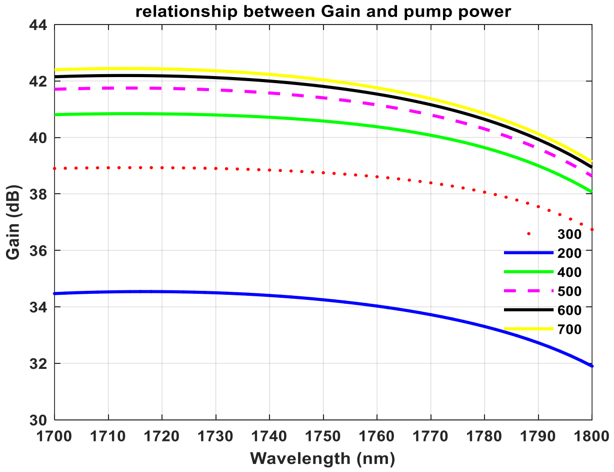

Fig 8. Investigating the connection between gain and pump optical power.

Firstly, the fiber length was set to 4m, the particle concentration was 0.7×10^{25}pcs/m^3, and the pumping optical power was selected to different values. It was found that the gain was larger when the pumping optical power was larger (Figure 8). However, when the pump power exceeds 500mw, the gain amplitude decreases and may have tended to gain saturation. And do not choose a large pump power may not only because of gain saturation but also may be the fiber material in the high-power pump light irradiation will be damaged. Therefore, the pump power should not take a too large value.

4. Conclusion

The experimental simulation takes the control variable method, we found that when the particle concentration and the pump optical power (300mw) are certain, the fiber length with the maximum gain is about 4m, and the gain is 38.83dB. When the length is 4m and the pump optical power is certain (300mw), the particle concentration with the maximum gain is about 0.7×10^{25} particles/m^3, and the maximum gain is 39.1746dB. The wavelength around 1716 nm is the best wavelength for signal light. The continuous wave laser can use Bismuth-doped fiber as a new active medium, and the 1700–1800 nm spectral range is suitable for the Bismuth–doped fiber amplifier.

This experiment explored the feasibility of Bismuth-doped fiber working in the 1700-1800nm band and explored the fiber working conditions at a pump optical power of 300mw. However, the experiments were not conducted with the actual material but with the relevant parameters and then modeled and simulated, and the absorption and emission cross sections, as well as the values of τ, were not assessed using the actual substance. The emission and cross-sectional absorption values were adjusted with the normal distribution function. Therefore there will be a certain amount of error.

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