Simulation of Bismuth on-doped Fibre Lasers in the 1250-1300 nm Band

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Abstract. Optical fiber transmission has become the predominant mode of transmission in modern communication systems. The extensive bandwidth potential of optical fiber makes it crucial for achieving high-capacity transmission. With the successful development of anhydrous peak fiber, the issue of harmonic absorption caused by OH molecules has been effectively resolved. This novel fiber establishes a low-loss window within the wavelength range from 1280 nm to 1625 nm, thereby providing enhanced transmission capacity for fiber optic communication systems. By increasing WDM density, which involves the simultaneous utilization of multiple light signals with different wavelengths in the fiber, higher transmission capacity can be achieved. This paper presents a comprehensive simulation study on bismuth-doped fiber lasers operating within the 1250-1300nm band. Specifically, this study investigates the numerical relationship between laser power, threshold power, and pump power. The simulation results demonstrate that a threshold power level of approximately 1.5W is required for laser generation; no laser emission occurs below this threshold. Once the pumping power surpasses this threshold value, laser operation commences and output power increases proportionally with further increments in pumping power.

Keywords: Bismuth-doped fiber laser; emission cross-section; absorption cross-section; output power.

1. Introduction

In the field of optical communication, driven by the exponential growth in information demand, there is an increasing requirement for higher transmission capacity in optical fiber communication systems. This escalating need for enhanced transmission capacity has fueled continuous innovation and development in optical communication technology. Currently, efforts to increase single-channel transmission rates and reduce channel intervals have approached the Shannon limit. Therefore, expanding transmission bandwidth and increasing the number of channels has emerged as a more advantageous approach. However, traditional rare-earth doped fiber amplifiers have limited operating bandwidth mainly concentrated in the C+L band (1530-1620nm), which fails to cover the entire low-loss transmission window of fibers. It has been discovered that bismuth-doped glass exhibits ultra-wideband near-infrared emission encompassing the complete optical fiber communication window. Hence, investigating bismuth-doped fiber lasers holds immense significance for harnessing all-band fiber communication windows.

Due to its unique optical properties, bismuth-doped fibers can be utilized for developing novel fiber amplifiers, prompting numerous scholars to conduct research in this domain. M. Hughes et al.'s study revealed that enhancing the PbO ratio improves glass transparency while significantly reducing bismuth absorption intensity enhances quantum efficiency and emission lifetime[1]. The research team also compared the spectral characteristics of bismuth-doped lead-aluminum-germanium glass and bismuth-doped yttrium-aluminum-silicate glass [2] and found that with the increase of PbO and Y2O3 content, the absorption strength of bismuth in both glasses decreased. Cheng Mingsheng measured the spontaneous radiation spectra of bismuth-doped fiber with three different components[3] and deduced the luminescence center of bismuth ion by exciting the bismuth-doped fiber with two pump sources. Cheng et al. found that the gain coefficient of the independently developed bismuth-doped fiber was greater than 1.5 dB/m the noise coefficient was close to 5 dB in the band of

1384~1480 nm when the wavelength was 830 nm and the power was 200 mW [4]. V.M. Paramonov et al. built a new BI-doped tunable continuous fiber laser using a 65 cm germanium silicic acid fiber with an operating range of 1360~1510 nm and output power of 25~50 mW[5]. S.V. Firstov et al. developed a new bismuth-doped fiber amplifier (B

DFA) with an operating band of 1640-1770nm and pumped with a laser diode of 1550nm[6]. The BDFA has a maximum gain of 23dB at 1710nm wavelength and a 3dB bandwidth of 40nm. The gain efficiency is 0.1 dB/mW and the minimum noise factor is about 7 dB. Teppo et al. studied a tunable, mode-locked fiber laser that can produce subpicosecond pulses in the 1700-1800 nm wavelength range[7]. YAN et al. achieved a broadband Bi-doped fiber amplifier (BDFA) from 1325 nm to 1441 nm with a gain of more than 23 dB and a flatness of less than 3 dB by using a 250 mW single-wavelength pump source (1256 nm) and a low-OH bismuth-doped fiber containing two kinds of bismuth-active centers[8]. The noise factor is less than 6.8 dB. S. V. FIRSTOV et al. studied a 1.7μm band bismuth-doped fiber laser based on nonlinear self-phase modulation (NPEM)[9]. By using a bismuth-doped fiber amplifier as the main oscillator power amplifier, the output pulse energy reached 5.7nJ. Jiang et al. proposed for the first time the energy class[10], transition configuration, and numerical model of the bismuth ion-doped fiber amplifier. The research shows that under excitation in the wavelength range of 800-900 nm, the amplifier can achieve ultra-wideband gain in the range of 1.2-1.62 microns, covering the low-loss window of the full-wave fiber.

This paper plans to design a new type of bismuth ion-doped fiber laser. By using the numerical simulation method, through the application and derivation of physical theory and formula. MATLAB software is used for code simulation, and the relationship between laser power, threshold power, and pump power in the target wavelength range is studied and analyzed.

2. Methods and Modelling

2.1. Energy Level Systems and Electron Transition Processes

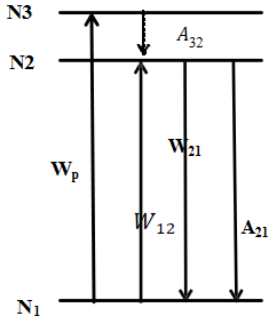


Fig 1. Schematic diagram of the bismuth ion energy level system and electron-leaping process

Fig. 1 and the rate equations for a three-energy-level system describe the rate at which a bi atom jumps between energy levels after being externally excited. In this system, a ground state, an excited state, and a metastable level are included. The rate equations can describe the rate of jump between these states, including the processes of excited radiation, spontaneous radiation, and non-radiative jumps.

Wp,W12,W21 represent pump light absorption rate,signal light absorption rate, and signal light stimulated emission rate,respectively; A32, A21 represent radiative leap rate and non-radiation leap rate; and N is the total number of particles, N1, N2, N3 are the number of particles in each energy level.

2.2. Power Propagation Equation

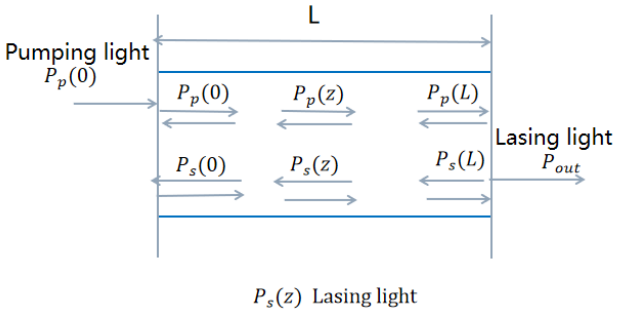


Fig 2. Schematic of the propagation of pumped and excited light in an optical fiber

As shown in Fig. 2, the power of pumped and excited light changes at different locations in the optical fiber. The power propagation equation describes the variation of pump and signal light power at each point of propagation in the resonant cavity. It includes the variation of pump power Pp and excitation power Ps with the propagation length.

2.3. Power Calculation

2.3.1. Saturation power of signal and pump light

$$P_{s,sat} = h\nu_s A_c/\tau\Gamma_s(\sigma_{12} + \sigma_{21}) \tag{1}$$

$$P_{p,sat} = h\nu_p A_c/\tau\Gamma_p(\sigma_{23} + \sigma_{32}) \tag{2}$$

Ps,sat indicates the saturation power of signal light. Pp,sat indicates the saturation power of the pump light. h represents Planck's constant, νs and νp represent the frequency of the signal light and the frequency of the pump light, respectively. These frequencies can be obtained from the speed of light c, as well as the wavelengths of the signal light λs and the pump light λp. Ac represents the excitation cross-sectional area of the laser.The symbolτ represents the average energy level lifetime of bismuth ions.

2.3.2. Fibre laser pump power threshold

$$\beta = \frac{(\sigma_{31} + \sigma_{13})\Gamma_p}{(\sigma_{21} + \sigma_{12})\Gamma_s}\left[(N\Gamma_s\sigma_{12} + \alpha_s)L + \ln\left(\frac{1}{\sqrt{R_1R_2}}\right)\right] - (N\Gamma_s\sigma_{13} + \alpha_p)L$$

$$P_{th} = \frac{(N\Gamma_s\sigma_{12}+\alpha_s)L+\ln\left(\frac{1}{\sqrt{R_1R_2}}\right)}{1-\exp(-\beta)} \cdot \frac{\nu_p}{\nu_s} \cdot P_{s,sat} \tag{3}$$

β is an intermediate parameter of the laser .Pth denotes the threshold power, N represents the concentration of dopant ions in the fibre, R1 and R2 are the front cavity mirror reflectivity and rear cavity mirror reflectivity of the laser, respectively.

2.3.3. Fibre laser output power

Finally, the output power of the fibre laser is calculated by the following equation:

$$P_{out} = (1 - R_2)P_s^+(L) = \frac{(1-R_2)\sqrt{R_1}\cdot P_{p,sat}}{(1-R_1)\sqrt{R_2}+(1-R_2)\sqrt{R_1}} \cdot \left[(1 - \exp(-\beta)) \cdot \frac{P_p^+(0)+P_p^-(0)}{P_{p,sat}} - (N\Gamma_s\sigma_{12} + \alpha_s)L - \ln\left(\frac{1}{\sqrt{R_1R_2}}\right)\right] \tag{4}$$

Consider the output power at threshold power:

$$P_{lout} = [P_{out} - P_{th} + abs(P_{out} - P_{th})]/2 \tag{5}$$

2.4. Relevant Parameter Additions

In Table 1, the relevant parameters for the simulations carried out in this paper are given.

Table 1. Parameters Used for Numerical Calculation [10]

Symbol	Parameter	Value	Unit
1	456	456	123
λp	Pump light centre wavelength	808	nm
λs	Fibre laser centre wavelength	1300	nm
τ	Average energy level lifetime on bismuth ions	5×10^{-4}	s
σap	Absorption cross section of pumped light	1.3×10^{-24}	m^2
σep	Emission cross section of pumped light	0.2×10^{-24}	m^2
σas	Absorption cross section of fibre laser	1×10^{-24}	m^2
σes	Emission cross section of fibre laser	9.31×10^{-25}	m^2
Ac	Cross-sectional area of fibre core	3×10^{-10}	m^2
N	Doping concentration of bismuth ions in the fibre core	7×10^{-24}	$ions/m^3$
αp	Loss of pump light by a double-clad fibre	2×10^{-5}	cm^{-1}
αs	Loss of laser light by a double-clad fibre	4×10^{-6}	cm^{-1}
L	Length of the double-clad fibre	1	m
Γp	Pump light power fill factor	0.5	
Γs	Laser power fill factor	0.8	
R1	Front mirror reflectivity	0.99	
R2	Rear mirror reflectivity	0.035	

The emission cross section and absorption cross section of bismuth ion are calculated and drawn by MATLAB: as shown in Fig.3, the wavelength is 1300nm, and the value of the emission cross section of bismuth ion is 9.31×10-25 m^2, and the value of absorption cross section is1×10-24 m^2.

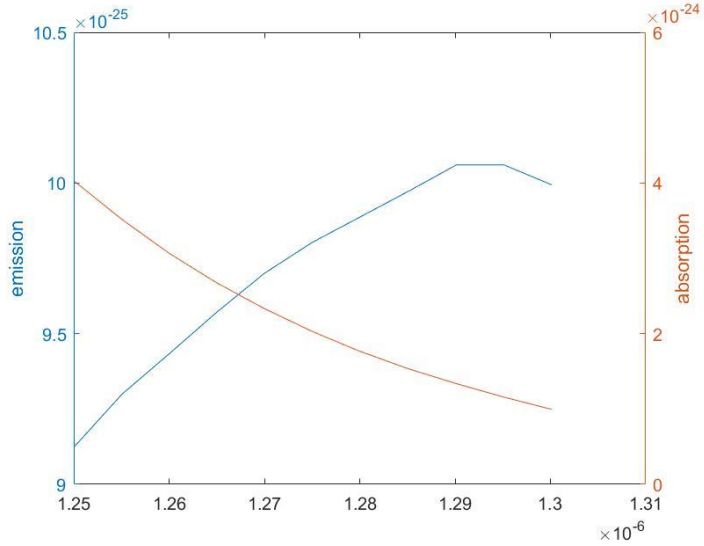


Fig 3. Bismuth ion emission cross section and absorption cross section versus wavelength

The front and rear mirror structures are designed in this paper using MATLAB via the transfer matrix method.

At a wavelength of 1300 nm, the front cavity mirror reflectivity of 0.99 was selected. The mirror consists of two layers of waveguides with refractive indices of 1.03 and 1.7, thicknesses of 299 nm and 166 nm respectively, and a period of n = 7. The relationship between reflectivity and wavelength is shown in Fig. 4.

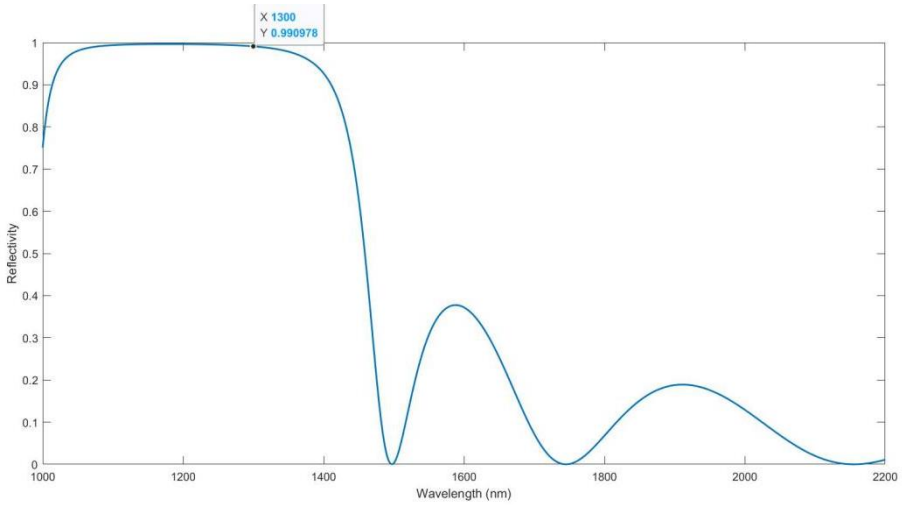


Fig 4. Front cavity mirror simulation

The rear cavity mirror chosen has a reflectivity of 0.035. It consists of two layers of waveguides with refractive indices of 1.025 and 1.148, and thicknesses of 351 nm and 168 nm respectively. The period is n=11. Fig 5 below illustrates the relationship between the reflectivity and the wavelength.

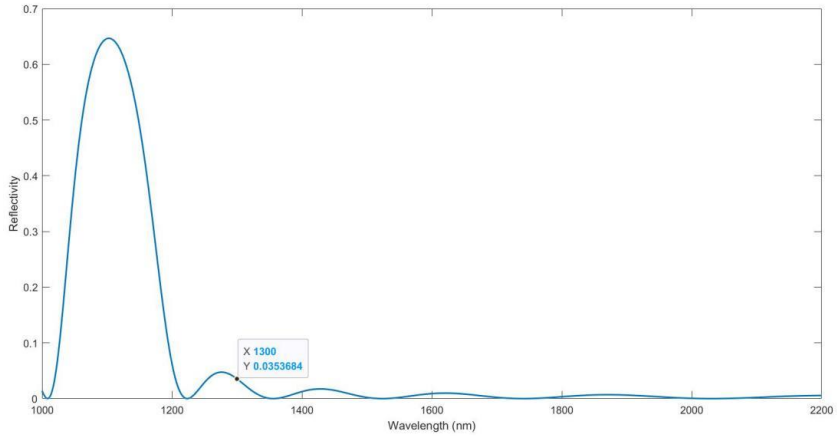


Fig 5. Rear cavity mirror simulation

The laser cavity design is shown in Fig. 6.

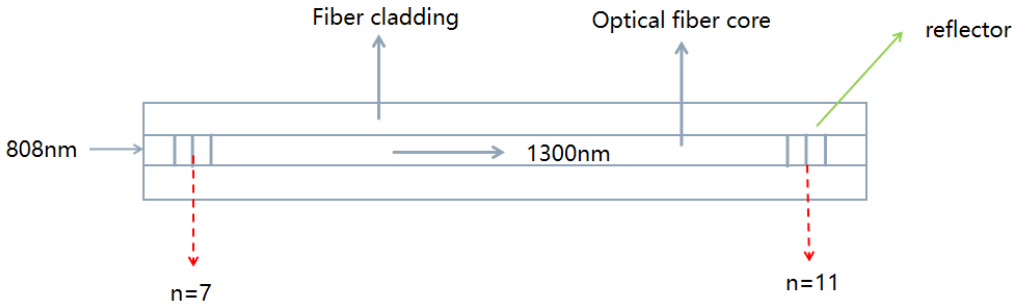


Fig 6. Laser resonant cavity

3. Results and Discussion

In this paper, the following results were obtained by numerical simulation of the above equations and data parameters in MATLAB programming software.

As can be seen from the simulation results in Fig. 7, the threshold power of the laser is 1.5 w. When the pump power is 0w-1.5w, the N2 energy level is not much larger than N1, which does not produce the particle number inversion, and the laser cannot be produced; when the pump power is larger than 1.5w, up to 25w,the output power of the laser will start from 0 to increase to 10.1w, which produces the laser.

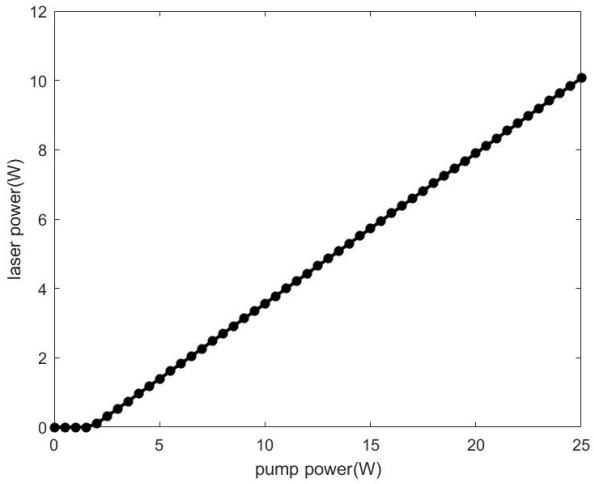


Fig 7. Plot of laser pump power and laser output power

Fig.8 illustrates the distribution of laser light in a 1 m long fibre. The pump power gradually decreases from left to right, from 25 W to 7.5 W, while the signal light power increases gradually from left to right, from 0 W to 10.1 W. This occurs due to the interaction between the pump light and the gain medium (e.g. the laser material or the fibre) within the FP cavity through multiple reflections within the cavity. The gain medium is excited, causing atoms or molecules to release energy and enhance the power of the signal light.

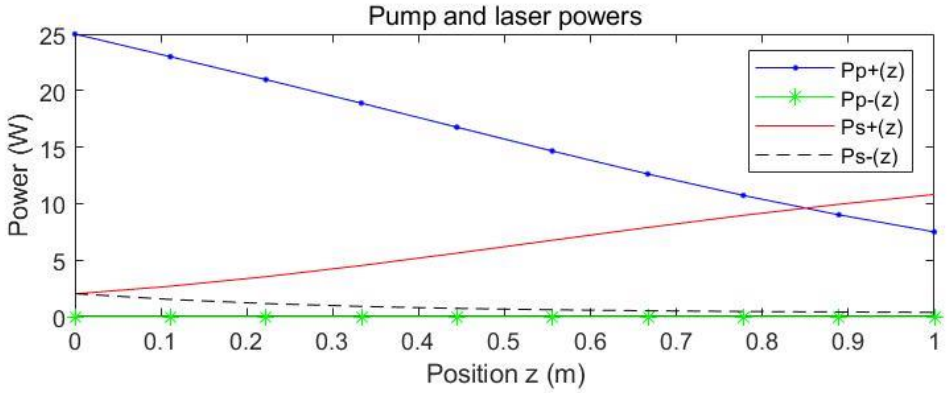


Fig 8. Laser power distribution at each position in a 1m long fibre

4. Conclusion

This paper presents the design of a bismuth-doped fibre laser in the 1250-1300nm band. The laser's parameters and corresponding power were simulated to demonstrate its superior performance. The design of this type of fibre laser fills the wavelength range not covered by conventional lasers, particularly in the near-infrared spectral region. This provides new options for light sources in various applications. There are still deficiencies in the design, and researchers should continue to improve it in the future to achieve higher gain and lower threshold power. This will broaden the application value of the bismuth-doped fibre laser.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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