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# *The Design of 1200-1250nm Fiber Laser*

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***Abstract.*** To address the demand for efficient and compact light sources in the 1200-1250 nm spectral range for applications in biomedical imaging and nonlinear frequency conversion, this paper proposes a theoretical design and performance simulation scheme of a bismuth-doped fiber laser. A steady-state rate-equation model based on a quasi-four-level system is established, which comprehensively describes the power evolution of forward and backward pump and signal light within a linear cavity structure. The resulting two-point boundary value problem is solved numerically using MATLAB's bvp4c solver. The simulation results indicate that the designed laser possesses excellent performance potential, clearly revealing the processes of pump attenuation and signal amplification within the cavity. The findings validate the effectiveness of the established model and quantitatively predict the feasibility of achieving high-efficiency operation from a 1200 nm bismuth-doped fiber laser. This work provides significant theoretical guidance and a design basis for the experimental fabrication, parameter optimization, and performance enhancement of fiber lasers in this spectral range.

***Keywords:*** Bismuth-doped fiber, 1200-1250 nm, Fiber laser

## 1. Introduction

Fiber laser technology, with advantages such as high conversion efficiency, excellent beam quality, a compact physical structure, and outstanding thermal performance, has undergone revolutionary development in fields like industrial processing, national defense and military, scientific research, and medical applications [1,2]. Traditional rare-earth-doped fiber lasers have achieved mature commercial applications in the 1μm and 1.55μm bands.

The 1200-1250 nm band is an important component of the spectral region, which holds scientific research value and application prospects. In the field of biomedical imaging, the light source of this band is an ideal excitation source for three-photon microscopy. Compared with traditional two-photon technology, the light source of this band has a deeper penetration depth and a higher signal-to-noise ratio into biological tissues, providing a powerful tool for cutting-edge research in neuroscience and other fields. In nonlinear frequency transformation, the fundamental frequency light of 1200-1250 nm can be efficiently doubled to the orange-red light band of 600-625 nm, which is in urgent demand in applications such as laser display, medical aesthetics, and sodium guide star [3]. In addition, this band also shows great potential in the field of optical communication. As an effective expansion of the existing optical communication window, it is expected to alleviate the

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'capacity contraction' problem [4]. Therefore, the development of high-performance fiber lasers in the 1200-1250 nm band holds significant theoretical and practical significance.

Researchers have explored various technical approaches, among which the technology based on bismuth-doped optical fibers (BDFs) has been proven to be the most promising solution [1]. Since Fujimoto et al. first reported the broadband near-infrared luminescence phenomenon of bismuth-doped quartz glass in 2001, BDFs has rapidly become a research hotspot in the field of laser materials. In 2005, the Dianov research group successfully fabricated the first bismuth-doped fiber by chemical vapor deposition and achieved laser output, marking the beginning of the BDF laser era [2,5].

Subsequent studies have shown that by co-doping different elements in the quartz matrix, such as aluminum, germanium, and phosphorus, the formation of bismuth active centers (BACs) can be regulated, which helps to achieve gain covering the ultra-wide band from 1150 nm to 1800 nm [2,4]. Research mainly focuses on BDFs of aluminosilicate and phosphorus-germanium silicate matrices for the 1200-1250 nm band. In 2007, Razdobreev et al. reported an all-fiber laser based on aluminosilicate BDF. They achieved slope efficiency as high as 24% at 1200 nm under a 1060 nm pump, laying an important foundation for the efficient operation of lasers in this band [3]. Subsequent studies have been continuously emerging. Through optimizing the pumping scheme and design parameters, the output power, efficiency and wavelength tuning range of the BDF laser in this band have been continuously improved [6]. In 2022, Mikhailov et al. systematically reviewed the optical amplification technology in the O-band and highlighted a high-performance wideband bismuth-doped fiber amplifier. This amplifier not only offers a gain of over 20 dB and a bandwidth greater than 60 nm, but also successfully supports the transmission of 400 Gb/s WDM signals over 50 km standard optical fibers, demonstrating its great application potential in the next-generation optical communication systems [7]. In 2024, Zhai et al. achieved a record gain of 1.33 dB/m per unit length and a total gain of nearly 40 dB in the E+S band by optimizing the germanium content in bismuth-doped germanium silicate fibers [8]. What is more notable is that the research on bismuth-doped optical fibers has expanded from the fields of light sources and amplifiers to brand-new application directions. In 2025, Huang et al. expanded their research perspective to the field of sensing. Based on the magneto-optical refraction effect of low-valent bismuth ions, they successfully developed a highly sensitive all-fiber magnetic field sensor, opening up a new direction for the application of bismuth-doped fibers in the field of precision sensing [9].

In this paper, by establishing a rate equation model, the theoretical design and performance simulation of bismuth-doped fiber lasers operating in the 1200-1250 nm band were carried out. The research results verified the validity of the established model and quantitatively predicted the feasibility of achieving high-efficiency operation of the laser. This work provides important theoretical guidance and design basis for the subsequent experimental development of high-performance lasers in this band.

## 2. Model simulation

To describe the evolution of the optical power inside the laser, a rate equation model based on steady-state operation is established. This model takes into account the forward pump light, backward pump light, forward signal light and backward signal light propagating along the axial direction z in the gain fiber. The distribution of optical power along the optical fiber is described by the following four coupled first-order ordinary differential equations:

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$$\frac{dP_p^+(z)}{dz} = (-\mathrm{G}_p s_{ap} N - \alpha_p) P_p^+(z) \quad (1)$$

$$\frac{dP_p^-(z)}{dz} = (\mathrm{G}_p s_{ap} N + \alpha_p) P_p^-(z) \quad (2)$$

$$\frac{dP_s^+(z)}{dz} = (\mathrm{G}_s (s_{es} N_2(z) - s_{as} N_1(z)) - \alpha_s) P_s^+(z) \quad (3)$$

$$\frac{dP_s^-(z)}{dz} = (-\mathrm{G}_s (s_{es} N_2(z) - s_{as} N_1(z)) + \alpha_s) P_s^-(z) \quad (4)$$

This simulation adopts a typical linear Fabry-Perot resonant cavity structure. The cavity is composed of a bismuth-doped optical fiber of length L, with two fiber Bragg gratings of different reflectance serving as cavity mirrors at both ends. The pump light is injected from the front end.

The boundary condition of this structure is mathematically described as follows: at z=0, the forward pump light power is equal to the total input pump power, and the forward signal light passes through the high reflector $R_1$ from the backward signal light. At z=L, it is assumed that no backward pump light is injected, and the backward signal light is reflected by the forward signal light through the output coupling mirror $R_2$. This set of boundary conditions, together with the above-mentioned system of differential equations, constitutes a two-point boundary value problem, which can be numerically solved through the bvp4c solver in MATLAB.

Dvoyrin et al. 's research employed an improved chemical vapor deposition method combined with solution doping technology to prepare optical fibers. This study provides the emission cross-section spectrum of the optical fiber in the range of 1000-1500 nm [10]. Based on this spectral line, 1200 nm is selected as the wavelength of the target signal light, and the corresponding stimulated emission cross-section is approximately $0.8 \times 10^{-24}$ m². Research shows that 1090 nm is an effective pumping wavelength. The fluorescence lifetime of bismuth-doped optical fibers at room temperature is approximately 880 μs, which is a core parameter determining the gain energy storage capacity and saturation characteristics.

The parameters of the simulation model are all set based on research or recognized physical models. For detailed parameters, please refer to Table 1.

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Table 1. Simulation parameters [10]

| Parameter symbol | Physical meaning | Numerical value | Units |
|---|---|---|---|
| $\lambda_p$ | Pump light wavelength | 1090 | nm |
| $\lambda_s$ | Signal light wavelength | 1200 | nm |
| $\tau$ | Fluorescence lifetime | 880 | μs |
| $\sigma_{es}$ | Signal light emission cross-section | $0.8 \times 10^{-24}$ | $m^2$ |
| $\sigma_{ep}$ | Pump light emission cross-section | $0.6 \times 10^{-24}$ | $m^2$ |
| $\sigma_{ap}$ | Pump light absorption cross-section | $1.1 \times 10^{-25}$ | $m^2$ |
| $\sigma_{as}$ | Signal light absorption cross-section | 0 | $m^2$ |
| $\lambda_p$ | Pump light wavelength | 1090 | nm |
| L | Gain fiber length | 55 | m |
| N | Bismuth ion concentration | $5 \times 10^{23}$ | $ions/m^3$ |
| $A_c$ | Core mold field area | $3.63 \times 10^{-11}$ | $m^2$ |
| $\alpha_p$, $\alpha_s$ | Inherent background loss | 0.003 | $m^{-1}$ |
| $\gamma_p$, $\gamma_s$ | Pattern overlap factor | 0.73, 0.82 | - |
| $R_1$ | High reflectivity of the mirror | 0.99 | - |
| $R_2$ | Output the reflectance of the coupled mirror | 0.50 | - |

## 3. Simulation results

In the simulation, the input pump power was increased from 0 W to 10 W, and the obtained 1200 nm laser output power was recorded. The simulation results are shown in Figure 1.

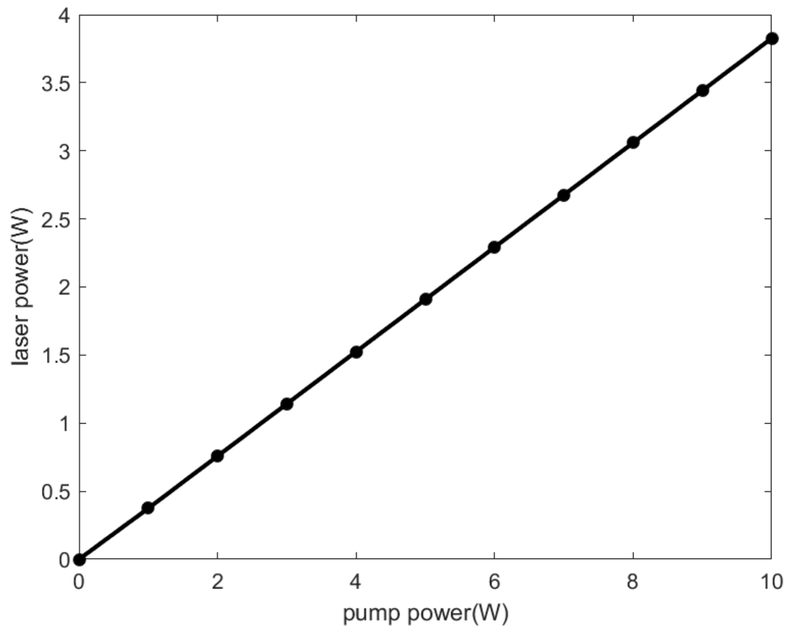


Figure 1. Simulation results of the output power of a 1200 nm bismuth-doped fiber laser varying with the pump power

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When the pump power is low, the gain is insufficient to compensate for the total loss in the cavity, and the laser has no laser output. As the pump power increases, when a specific value is reached, the laser begins to beam, and this point is the laser threshold. When the pump power exceeds the threshold, the output laser power shows an excellent linear relationship with the pump power. This indicates that within this power range, the laser operates in a stable gain saturation region, with no obvious thermal or nonlinear effects leading to a decrease in efficiency.

Analyze the power distribution of the forward pump light, backward pump light, forward signal light and backward signal light along the 55-meter gain optical fiber when the input pump power is 10 W. The simulation results are shown in Figure 2.

The blue curve represents the forward pump light. As can be seen from Figure 2, after the 10 W pump light is injected at z=0, it rapidly decays exponentially along the length of the optical fiber. This indicates that the pump light is efficiently absorbed by the gain medium to excite bismuth ions. At the end of the optical fiber, the power of the pump light has dropped to approximately 1 W, indicating that the 55-meter length of the optical fiber is effective in absorbing most of the pump power and avoiding the waste of pump light.

The green curve represents the backward pump light, whose power is almost zero throughout the cavity, which is completely consistent with the set single-ended forward pump boundary condition.

The red curve represents that the forward signal light propagating to the right starts from an extremely low value at z=0 and is continuously amplified as the energy of the pump light is injected, reaching its maximum value at z=55 m at the end of the optical fiber. This part of the light is partially transmitted at the output coupling mirror, forming the final laser output.

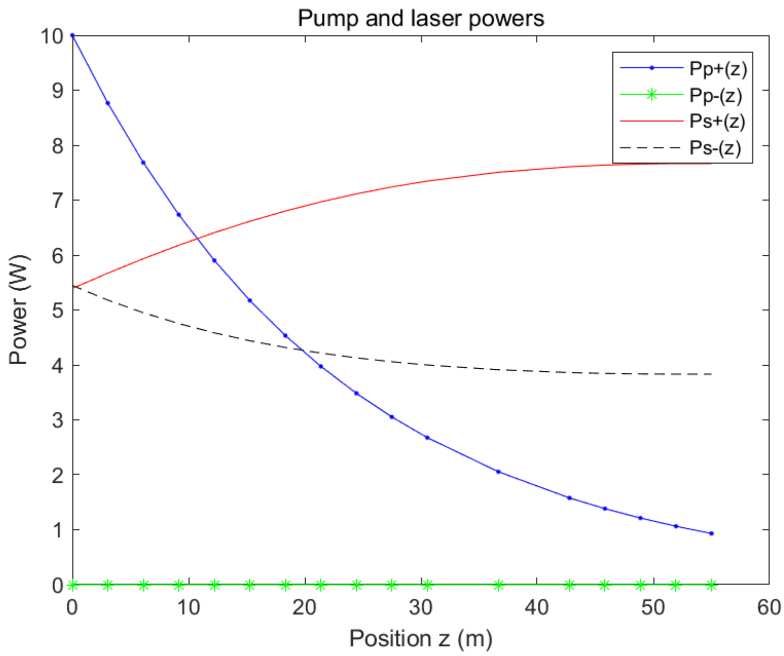


Figure 2. The distribution of the optical power of each path in the cavity along the length of the optical fiber when the pump power is 10 W

The black dotted line represents the backward signal light propagating to the left, which is generated by the reflection of the forward signal light at z=L through the output mirror $R_2$. It is amplified during the return process, but since the pump power has weakened in the rear section of the fiber, its gain slope is not as steep as that of the forward light. At z=0, it is almost completely

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reflected by the high reflectivity mirror $R_1$, forming a new round of forward signal light seed and constituting an oscillation loop.

By observing the growth slope of the forward signal light, it can be found that in the first half of the optical fiber, its growth rate is very fast because the pump power is the strongest and the gain is the highest here. In the latter half, as the pump power is consumed, the gain gradually decreases and approaches saturation, so the power growth of the signal light also slows down accordingly.

## 4. Discussion

The length of the gain fiber is one of the most direct parameters affecting the performance of the laser. It directly determines the total absorption of the pump light and the total loss in the cavity, thus forming a delicate balance between gain and loss. When the length of the optical fiber is too short, the pump light cannot be fully absorbed. A large amount of unused pump light directly penetrates the optical fiber, resulting in low pump efficiency and insufficient population inversion at the upper energy level. The laser may be in a high-threshold state or even fail to vibrate. As the length of the optical fiber increases, the pump absorption gradually becomes saturated and the gain increases accordingly. However, the total background loss within the cavity also increases in proportion to its length. When the length exceeds a certain optimal value, the additional loss caused by the increase in length will exceed the gain improvement it brings, resulting in a decrease in net gain, which in turn causes the slope efficiency and output power of the laser to start to decline.

The reflectivity of the output coupling mirror determines the average lifetime of photons in the resonant cavity and the proportion of laser energy extracted from the cavity, which is the key to optimizing the efficiency of the laser. When the reflectivity $R_2$ is too low, the threshold of laser oscillation will be very high because the intracavity loss during each round trip is extremely large. Although the photon extraction efficiency may be very high once the threshold is exceeded, an excessively high threshold will limit the overall efficiency and maximum output power of the laser. When the reflectivity $R_2$ is too high, the laser threshold is very low and it is prone to vibration. However, most of the energy is trapped within the cavity, and only a small amount of energy can be output, resulting in a low output power. At the same time, excessively high intracavity power may also cause unnecessary thermal or nonlinear effects.

The selection of the pump wavelength is directly related to the efficiency of the pump energy being absorbed by bismuth ions and affects the quantum efficiency of the laser. Pumping at the absorption peak can achieve the most effective pumping absorption with the shortest fiber length and maximize the gain coefficient.

By scanning and analyzing core parameters such as the length of the gain fiber and the reflectivity of the output coupling mirror, the underlying physical mechanism is clarified, and a theoretical basis and optimization direction are provided for designing bismuth-doped fiber lasers with higher performance in the 1200-1250 nm band.

## 5. Conclusion

The rate equation model adopted in this study successfully predicted the key performance indicators of bismuth-doped fiber lasers. Through the simulation of the internal optical power distribution of the laser, it is possible to clearly observe the process in which the pump light is efficiently absorbed along the length of the fiber, as well as the dynamic evolution of the signal light being continuously amplified during this process. The results show that the 55-meter optical fiber length has basically achieved full utilization of the pump light under a pump power of 10 W. The power growth of the

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signal light is more rapid in the front end of the optical fiber, while in the back end, it shows a gain saturation trend due to pump consumption. These analyses not only verified the rationality of the model design but also provided an intuitive picture for understanding the internal physical mechanism of the laser.

This simulation adopted an output coupling rate of 50% and achieved a relatively high slope efficiency. Generally, a higher output coupling rate is beneficial for extracting more energy at high pump power, thereby enhancing the slope efficiency, but it also increases the laser threshold. The low threshold obtained from the simulation indicates that the in-cavity gain remains very high even at 50% output. When designing higher-power lasers in the future, the ultimate output power can be further enhanced by adopting output coupling mirrors with lower reflectivity.

In the future, the established numerical model can be fully utilized as an efficient design platform to systematically study the comprehensive impact of key parameters on the performance of lasers. Through multi-dimensional parameter scanning, the optimal parameter combination for achieving the highest output power or the highest efficiency can be sought.

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