Design of L^+Band Bismuth-doped Fiber Laser

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Abstract. At present, the development of new communication bands to meet the needs of large communication transmission capacity in the current era is one of the key research topics. The conventional erbium-doped laser is limited by its structure which has the problem of short luminous bandwidth and can not cover a large communication band. Therefore, there is growing interest in designing bismuth-doped glass and fiber with ultra-wide gain bandwidth for fiber laser applications. By utilizing its ultra-wide gain bandwidth characteristics, important communication devices such as broadband fiber amplifiers and broadband tunable fiber lasers can be designed to operate in the L+band, thereby solving the problem that the ultra-wide bandwidth of the optical communication window cannot be achieved in the future high-speed communication systems. In this study, the 1550nm pump source is used to excite the bismuth-doped fiber, and the MATLAB numerical simulation modeling is used to design a bismuth-doped fiber laser with a central wavelength of 1650nm and a threshold power of 10W. To a certain extent, this design addresses the research gap in L^+ band bismuth-doped fiber lasers.

Keywords: Fiber laser; Bi; L^+ band.

1. Introduction

Optical fiber communication is a mode of communication that utilizes light as the carrier and optical fiber as the transmission medium. In comparison to traditional communication modes, it possesses characteristics such as high transmission capacity, wide frequency band, low loss, strong anti-interference capability, robust confidentiality, and long service life [1]. With the advent of the 5G era, there has been a rapid increase in demand for information transmission speed and capacity in communication systems. Consequently, achieving ultra-large capacity information transmission has become a primary challenge in the development of optical communication systems. The research on fiber lasers capable of operating within new communication bands has emerged as an important approach to enhancing the transmission capacity of these systems.

In 1985, the University of Southampton successfully developed an erbium-doped fiber laser (EDFA), which has excellent spectral performance due to the 4F electron transition, and its emission peak is located at 1550nm in the near-infrared band. Since then, EDFA has gradually become the mainstream application in optical fiber communication systems. However, due to the shielding of 5S2 and 5P6 electrons, the emission of erbium ions is very little affected by environmental changes. The emission peak position is stable and the broadband is very narrow, which can only support the amplification of optical signals at 1535-1565nm. According to the loss spectrum of quartz fiber, the theoretical loss of the 1300-1700nm band is less than 0.4db/km[2]. Limited by the current development and research of fiber lasers, a large part of the ultra-low loss window of quartz fibers has not been effectively utilized. In 1999, K Murata et al. Found that bismuth-doped quartz glass can emit a wide near-infrared emission with a central wavelength of 1150nm and a half-height width of 150nm under the excitation of 500nm. Its emission range is much larger than that of rare earth ions, which can effectively cover the low-loss window of quartz fiber [3]. Therefore, more and more researchers focus on the research of bismuth-doped quartz glass. Although the research of bismuth-doped fiber laser has made breakthroughs in recent years, there are still problems of low laser efficiency, fiber loss can be further reduced, and the research in L^+band is relatively blank [4-6]. At the same time, up to now, the research on the energy level spectrum and absorption coefficient of bismuth ion also has some defects, which also affect the realization of bismuth-doped fiber laser in the L^+band.

The purpose of this study is to design a bismuth-doped silica salt fiber laser with the center wavelength of the signal light at 1650nm, which can cover the low loss region of quartz fiber loss spectrum, fill the blank of L+band bismuth-doped fiber laser research to a certain extent, and apply it to the field of optical fiber communication, effectively increasing the transmission capacity of optical fiber communication system.

2. Method

For the design of bismuth-doped silicate optical fiber light source, it is necessary to consider the energy level structure of bismuth-related active center and the related transitions between the corresponding energy levels of absorption and emission, as shown in Fig 1.

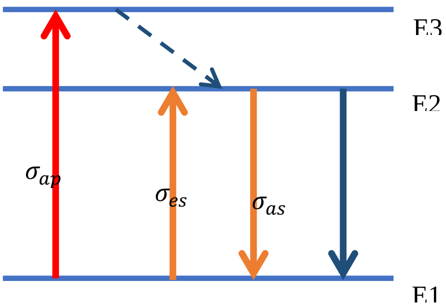

Fig 1. Energy level diagram of bismuth related active centers.

σ_{ap}: The absorption cross-section of the pump light; σ_{as}: The absorption cross-section of the signal light; σ_{es}: The emission cross-section of the signal light.

In the related reports of bismuth ion doped silicate glass, under the excitation of 1550nm pump light, the emission spectrum will produce a peak at 1730nm[7].

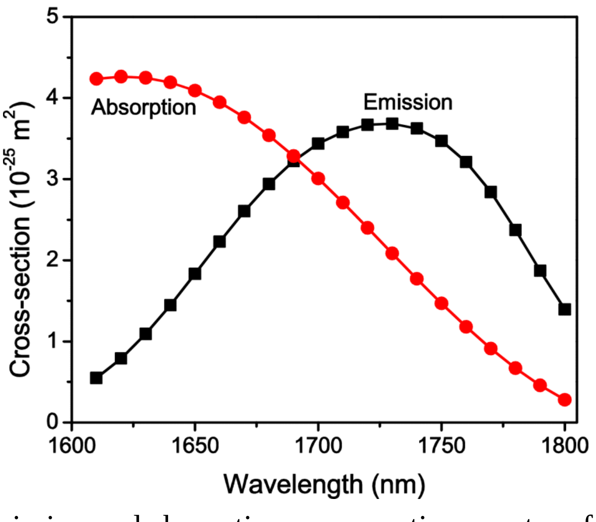

Fig 2. Emission and absorption cross-section spectra of BAC [7]

To obtain a better amplification effect after the fiber light source passes through the resonator, the Bragg grating composed of two different refractive index materials in the same direction of the periodic arrangement is selected in Fig 2. The front cavity mirror consists of a three-layer structure refractive index where $n_0 = 1.0$ (air), $n_{A1} = 1.45$, and $n_{B1} = 2.25$, the thickness were $d_{A1} = 259\mu m, d_{B1} = 167\mu m$, the number of cycles for 10, reflectivity of 0.99. The back-cavity mirror has the same structure as the front-cavity mirror and different media refractive indices and media thicknesses. The refractive index is $n_0 = 1.0$ (air), $n_{A2} = 1.05$, $n_{B2} = 1.50$, the thickness was $d_{A2} = 259\mu m, d_{B2} = 105\mu m$, and the reflectivity are 0.035.

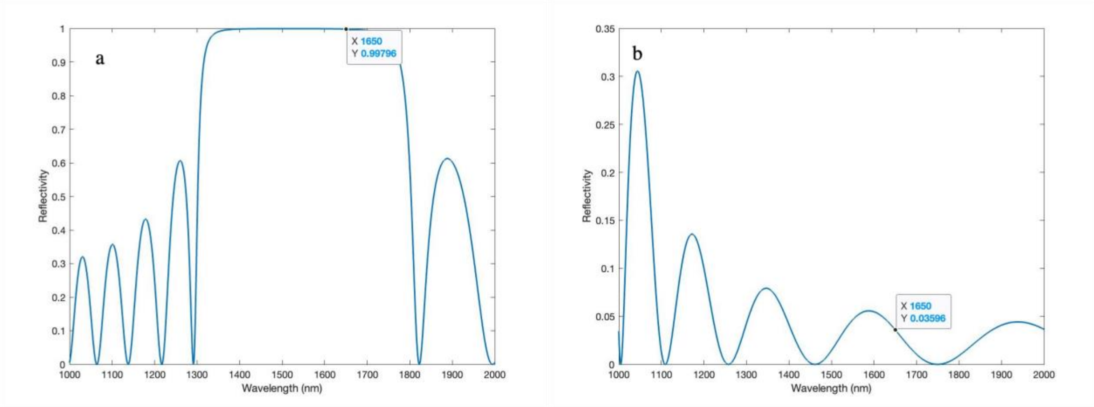

Fig 3. Wavelength versus reflectance in Bragg grating structures.

a The front cavity mirror b The back-cavity mirror

As shown in Fig 3, Matlab is used to simulate the bismuth-doped fiber laser. The specific use of the model is shown in Table 1.

Table 1. Main Parameters for Matlab Operation Modeling

Symbol	Physical parameters	Value	Unit
λsp	Pump wavelength	1550	nm
λs	Laser wavelength	1730(1650)	nm
τ	Emission lifetime[4]	500	μs
σap	Absorption cross section at 1.55μm	3×10^{-25}	m^2
σas	Absorption cross section at 1.65μm	4×10^{-25}	m^2
σes	Emission cross section at 1.65μm	1.6×10^{-25}	m^2
Ac	The cross-sectional area of the fiber core	3.1416×10^{-10}	cm^2
N	Doping concentration of bismuth ions in the fiber core	1×10^{26}	m^3
αp	Loss of pump light in double clad optical fibers	2×10^{-5}	cm^{-1}
αs	The Loss of Double Clad Fiber on Laser	4×10^{-6}	cm^{-1}
L	The length of double clad optical fibers	1	m
Γp	Pump light power fill factor	0.0024	/
Γs	Laser power filling factor	0.82	/
R1	Front cavity mirror reflectivity	0.99	/
R2	Back-cavity mirror reflectivity	0.035	/

3. Result and Discussion

The model of the bismuth doped fiber laser can be established by MATLAB simulation, and the relationship between the pump power and the laser power (Fig 4.) and the internal power propagation diagram of the fiber laser (Fig 5.) can be obtained.

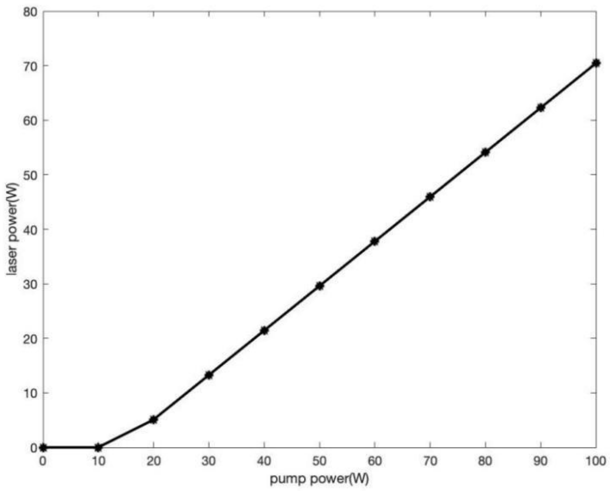

Fig 4. The relationship between pumping power and output power of Bismuth-doped optical fibers

It can be seen from Fig 4 that the threshold power of the bismuth-doped fiber laser is about 10W. At this time, the population inversion density of the upper and lower levels of the laser is reversed, and the laser gain generated can just compensate for the total loss of transmission in the laser. When the pump power is greater than 10W, the population inversion density in the bismuth ion level is saturated, that is, the laser gain is saturated, and a stable light intensity is formed in the laser to emit laser. When the pump power reaches 100W, the laser luminous efficiency is 70.44%.

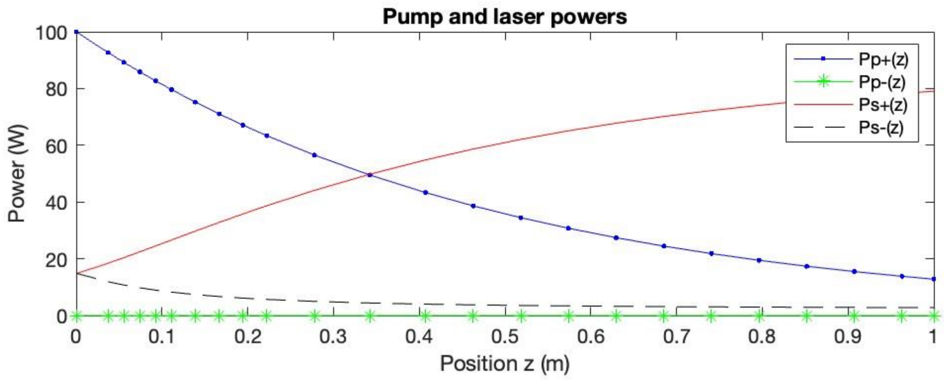

Fig 5. Power distribution in optical fiber

According to the internal power propagation diagram of the fiber laser in Fig 5, the forward propagation power of the pump light continues to decrease from 100W to 12.79W, while the forward propagation power of the signal light continues to increase from 14.866W to 79.032W; At the same time, the back-propagation power of signal light decreases with its forward propagation.

It can be seen that the threshold power of the bismuth-doped fiber laser model is low, and larger laser emission power can be obtained in the shorter fiber waveguide, with higher laser emission efficiency.

4. Conclusion

This study uses a quasi-three-level system to solve the rate equation and power propagation equation of bismuth-doped fiber laser and give the relationship between the pump power and the luminous power of bismuth-doped fiber laser, as well as the distribution of pump power and signal light luminous power in the fiber. Matlab numerical simulation results show that when the pump power is greater than 10W, the laser produces a laser, and increases with the increase of pump power.

When the pump power reaches 100W, the laser power reaches 70.439W, and the laser luminous efficiency reaches 70%.

This research is based on the existing research and design of bismuth-doped fiber laser. Through MATLAB numerical simulation, the experimental results can only represent the theoretical laser power and luminous efficiency that can be achieved under the design scheme. In the practical application design, the problem of the 1550nm laser pump cost and the industrial design standard of Bragg grating still need to be considered. Up to now, the research on bismuth-doped fiber lasers is still in its infancy. The excellent laser development effects of bismuth ions, such as 1000-1600nm ultra wide-band radiation, high gain, and low noise, continue to attract the attention of various researchers. It is believed that with the improvement of social demand for the quality of optical fiber communication transmission, there will be more and more high-quality fiber lasers with high luminous efficiency and ultra-low loss that meet the diversified requirements.

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