Proceedings of the 2nd International Conference on Mathematical Physics and Computational Simulation
DOI: 10.54254/2753-8818/38/20240527

Principle and design of vanadium-doped fiber laser under simulation

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Abstract. Due to the low efficiency of traditional communications and many problems, the development of optical fiber communications is currently necessary. Among them, fiber laser is the core of fiber communication, and the higher the output band of a fiber laser, the more information it carries, and the information that can be transmitted increases accordingly. Therefore, the primary goal is to develop a fiber laser with high-band output. At present, research on high-band output fiber lasers is being carried out at home and abroad. Domestic research focuses on the selection of fiber media; foreign research focuses on random fiber lasers. This article adopts the domestic research route, based on the premise that vanadium ions can emit laser wavelengths that include the L+ band when performing energy level transitions. At the same time, vanadium-doped gallium lanthanum sulfide glass has good functions of absorbing pump light and emitting lasing light. Therefore, this article mainly discusses the design of vanadium-doped fiber lasers using vanadium-doped gallium sulfide as the gain medium under simulation conditions to achieve high-band output of fiber lasers.

Keywords: Optical fiber, energy level transitions, vanadium, fiber laser, pump power, laser power.

1. Introduction

Because there are a series of problems in traditional communication methods, such as insufficient bandwidth, signal interference, and security to meet the growing communication needs, the above-mentioned deficiencies are modified, and optical fiber communication is developed. Optical fiber is a very transparent and weak glass filament. so its structure consists of a protective jacket, a cladding, and a three-level structure of the core. The difference in refractive index between the core and the cladding is less than 0.5%, so the structure ensures that the way it carries information can be transmitted stably and at high speed with the help of optical media [1].

In fiber optic communications, optical signals are transmitted through optical fibers, and light of different wavelengths can transmit multiple signals in the same optical fiber. Higher wavelength fiber lasers can provide a larger wavelength range, allowing fiber optic communication systems to transmit more data and signals, increasing communication capacity and speed, so this is why L+ band fiber lasers are studied.

Domestic experts are researching fiber lasers. The Shanghai Institute of Optics and Precision Mechanics of the Chinese Academy of Sciences successfully manufactured a nitrogen fiber laser for the first time in China, laying the foundation for subsequent fiber laser research and development. The Changchun Institute of Optics, Precision Mechanics, and Physics of the Chinese Academy of Sciences successfully manufactured the first fiber laser in China. As a result, China's fiber laser technology has developed rapidly and gradually achieved industrialization. In the current research, one of the main achievements is the fiber laser using mid-infrared fluoridise-based glass as the gain medium. By borrowing the characteristics of relatively low neutron energy and wide mid-infrared transmission window of fluor indium-based glass, it can Significantly increase the output power of mid-infrared fiber laser in the 3~4 μm band [2].

Foreign experts are also continuing to promote research on fiber lasers, among which random fiber lasers are the current mainstream research direction. Different from traditional fiber lasers, random fiber lasers do not rely on ions to oscillate in the left and right cavity mirrors to emit lasers. Instead, they use the random scattering or gain fluctuations encountered when light propagates in the fiber to simulate the left and right cavity mirrors. internal gain space. The most important advantage of random fiber lasers is that they are no longer limited by the small variety of gain media or the difficulty of finding a suitable gain medium [3]. Nowadays, the latest random fiber laser abroad is the Raman random fiber laser. It is a complex physical system produced by combining the inherent randomness of Raman distribution and fiber scattering. Raman random fiber laser is important for studying the interaction of light wave function [4].

At present, the research and development of fiber lasers is still on the rise, and there are still many technical problems waiting to be solved, such as how to increase the output power and power density of fiber lasers, and how to achieve longer transmission distances and greater bandwidth capacity and so on.

The research goal of this article is to calculate the relevant experimental parameters and simulate the physical characteristics and output results of the L+ band fiber laser under simulation conditions. The following will focus on the important processes of the above experiments and the corresponding experimental results and charts. Finally, the above experimental results will be synthesized phenomena and diagrams for discussion and analysis.

2. Research method

This article uses numerical simulation methods to study vanadium-doped fiber lasers. Because the laser band of the fiber laser to be designed is between 1600nm and 1650nm, in the search for ions, vanadium ions were finally chosen to achieve this function, because the output band of vanadium ions after energy level transition is 1100nm to 2000nm, including the research institute The required L+ band (1600nm to 1650nm) is shown in Fig 1.

Before starting the formal simulation experiment, it is first necessary to use MATLAB to perform the ion rate equation (1)-(4) and the power propagation equation (5)-(8)[5]to conduct more accurate simulation experiments. In formulas (1)-(4), Wp, $W12$, $W21$, $A32$, $A21$ are the pump light absorption rate, signal light absorption rate, signal light stimulated emission rate, radiative transition probability and non-radiative transition rate respectively; in formulas (5)-(8), αp, αs, σ12, and σ21 are the loss coefficient of the fiber material at the pump wavelength and lasing wavelength, the laser absorption cross section (m2) and the laser emission cross section (m2) respectively.

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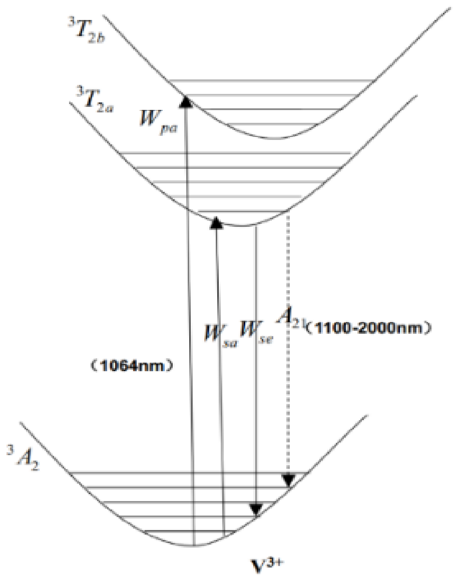

Figure 1. Vanadium ion energy level transition (Photo/Picture credit: Original)

$$\frac{\partial N_1(z)}{\partial \mathrm{t}} = -W_\mathrm{p}(z)N_1(z) - w_{21}N_1(z) + A_{21}N_2(z) + w_{21}N_2(z) \tag{1}$$

$$\frac{\partial N_1(z)}{\partial \mathrm{t}} = -W_\mathrm{p}(z)N_1(z) - w_{21}N_1(z) + A_{21}N_2(z) + w_{21}N_2(z) \tag{2}$$

$$\frac{\partial N_3(z)}{\partial \mathrm{t}} = W_\mathrm{p}(z)N_1(z) - A_{32}N_3(z) \tag{3}$$

$$N = N_1(z) + N_2(z) + N_3(z) \tag{4}$$

$$\frac{dP_p^+(z)}{dz} = \Gamma_p\big(-\sigma_p N_1(z) - \alpha_p\big)P_P{}^+(z) \tag{5}$$

$$\frac{dP_p^-(z)}{dz} = -\Gamma_p\ (-\sigma_p N_1(z) - \alpha_p)P_P{}^-(z) \tag{6}$$

$$\frac{dP_s^+(z)}{dz} = \Gamma_s[\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_s]P_s^+(z) \tag{7}$$

$$\frac{dP_s^-(z)}{dz} = -\Gamma_s[\sigma_{21}N_3(z) - \sigma_{12}N_2(z) - \alpha_s]P_s^-(z) \tag{8}$$

In order to facilitate the understanding of the above formula, Fig.4. and Fig.5 are used to visually display the energy level transition process of ions and the power propagation within the optical fiber. Taking the pump power propagation process in Fig.5. as an example, after the pump light enters the optical fiber from the left cavity mirror, it propagates to the right cavity mirror in the optical fiber of length L, because the reflectivity of the left cavity mirror is close to 99%. The reflectivity of the right cavity mirror is only about 70%, so part of the laser light propagated to the right cavity mirror is emitted to form a signal light; the light that is not emitted is reflected by the right cavity mirror and then re-transmitted to the left cavity mirror, and the above action is repeated. Part of the laser light emitted from the right cavity mirror is reflected by the right cavity mirror again and propagates to the left cavity mirror.

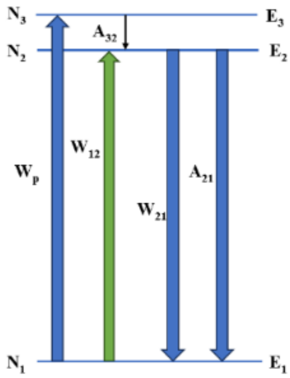

Figure 2. Energy level transition (Picture credit: Original)

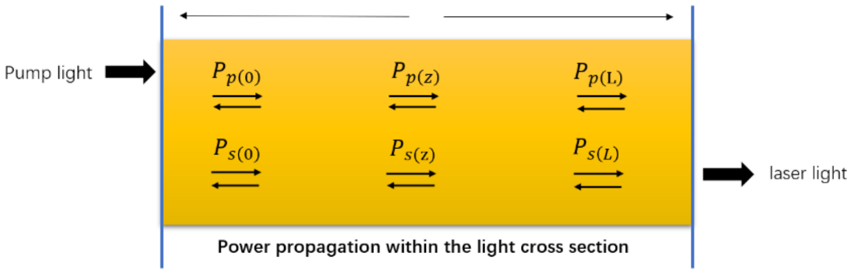

Figure 3. Power propagation within the light cross section (Picture credit : Original)

After the pump light propagates in the optical fiber, the simulation system can obtain the threshold power (9), gain coefficient (10) and saturated signal light output power (11) [5][6].The relevant parameters required to calculate (9), (10), (11) and this simulation experiment are all in Table 1.

$$p_{th} = \frac{(\mathrm{N}\Gamma_s\sigma_{12} + \alpha_s)L + \ln\left(\frac{1}{\sqrt{R_1R_2}}\right)}{1 - \exp(-\beta)} \cdot \frac{v_p}{v_s} \cdot p_{s,sat} \tag{9}$$

$$\beta = \frac{(\sigma_{31} + \sigma_{13})\Gamma_p}{(\sigma_{21} + \sigma_{12})\Gamma_s}\left[(N\Gamma_s\sigma_{12} + \alpha_s)L + \ln\left(\frac{1}{\sqrt{R_1R_2}}\right)\right] - \left(N\Gamma_p\sigma_{13} + \alpha_p\right)L \tag{10}$$

$$p_{s,sat} = hv_sA_c/\tau\Gamma_s(\sigma_{12} + \sigma_{21}) \tag{11}$$

Table 1. Experimental parameters[6]

physical parameter	numerical value	units
Center wavelength of pump light	$1064*10^{-9}$	m
center wavelength of fiber laser	$1625*10^{-9}$	m
fluorescence lifetime	$33*10^{-6}$	s
absorption cross section of pump light	$3.3626*10^{-25}$	m^2
emission cross section of pump light	$3.3626*10^{-25}$	m^2
absorption cross section of fiber laser	$2.3954*10^{-25}$	m^2
emission cross section of fiber laser	$3.326*10^{-22}$	m^2
The cross-sectional area of the core	$3.1416*10^{-6}$	cm^2

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Table 1. (continued)

Doping concentration of vanadium ions in the fiber core	10^{24}	cm^2
Loss of pump light by double clad fiber	$2*10^{-5}$	cm^{-1}
Loss of fiber laser by double clad fiber	$4*10^{-6}$	cm^{-1}
Length of double-clad optical fiber	3	m
Pump optical power fill factor	0.0024	
Laser power filling factor	0.82	
Reflectance of front cavity mirror	0.99	
Reflectance of posterior cavity mirror	0.35	

In Table 1, the parameters of the laser emission cross section can be obtained from formula (12) [7].

$$\sigma_{em} = \sqrt{\frac{ln2}{\pi}\frac{A}{4\pi cn^2}\frac{\lambda_0^4}{\Delta\lambda}} \tag{12}$$

In formula (d), n is the GLS refractive index [8]; A is the Einstein coefficient, whose size is equal to 1260 and the unit is s-1; C is the speed of light in vacuum; λ0 is the wavelength corresponding to the maximum emission coefficient; Δλ is the full width at half maximum [7].

From the above discussion, it can be known that in order to realize a fiber laser with an output in the L+ band, it is necessary to keep the vanadium ions in an excited state so as to emit laser light of the corresponding wavelength during the energy level transition. However, no suitable material has been found. Fiber optic gain medium. After reviewing many papers, this article decided to use vanadium-doped gallium lanthanum sulfide as the gain medium for the following reasons.

First, the atomic mass of chalcogenide glass is large and the phonon mass is small, especially gallium lanthanum sulfide; secondly, due to the small molecular weight of gallium lanthanum sulfide, many transitions in the active vanadium ion dopant can emit laser light [6], which ultimately leads to the fact that gallium lanthanum sulfide glass can be used as an optical fiber material to effectively observe energy transitions. At the same time, optical transitions in dopants cannot be observed in other traditional glasses such as silica [8]. Therefore, gallium lanthanum sulfide glass is a suitable gain material to realize a fiber laser with an output in the L+ band

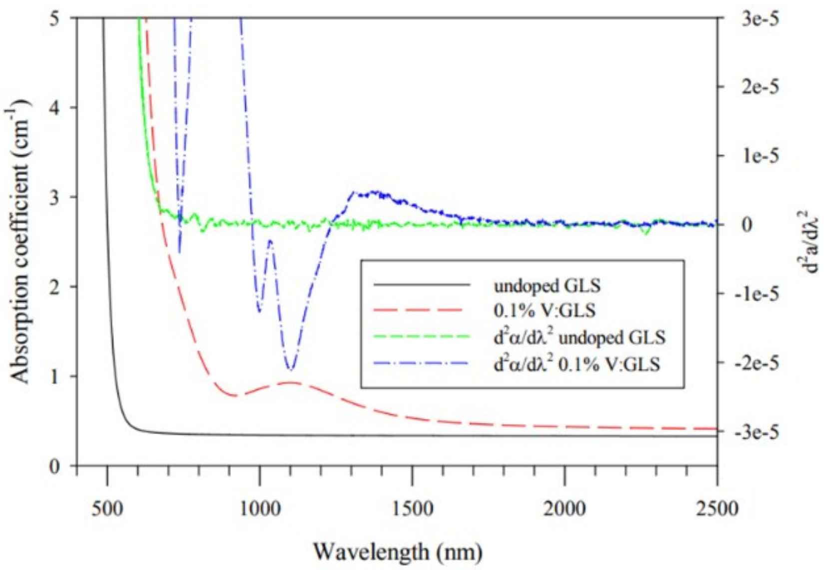

Figure 4. Absorption coefficient versus wavelength curve [8]

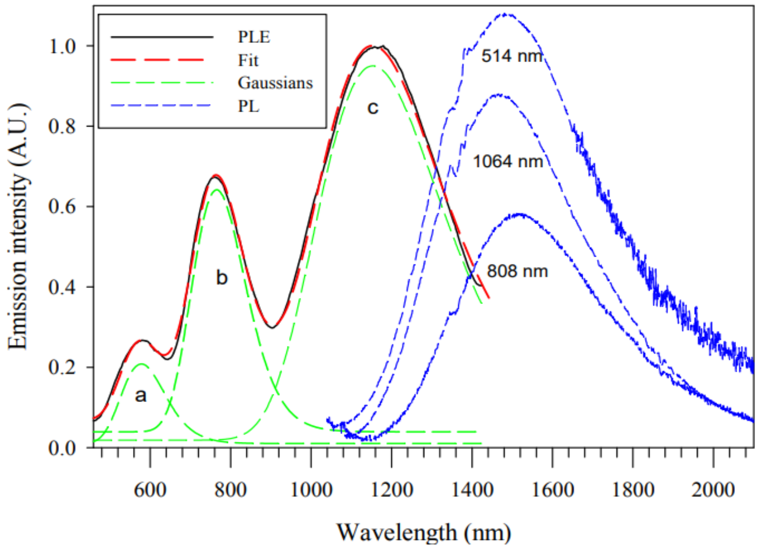

Figure 5. Emission coefficient versus wavelength curve [8]

It can be seen from Fig 4 that the absorption spectral coefficient of gallium lanthanum sulfide doped with 0.1% vanadium is significantly higher than that of undoped vanadium. of gallium lanthanum sulfide. In spectral analysis, mathematical differentiation is often used as a resolution-enhancing technique to facilitate the detection and localization of poorly resolved spectral components, including peaks that appear only in the shoulders, and their separation from interfering large background absorptions peak point[9]. In the second-order differential spectrum, the absorption band corresponds to the negative peak below $d\alpha^2/d\lambda^2=0$. In the $d\alpha^2/d\lambda^2$ spectrum of 0.1% V: GLS in Fig 4., the absorption band of gallium lanthanum sulfide doped with 0.1% vanadium at a wavelength of 1100 nm is clearly visible, as is the 750 nm absorption band, which can now be more precisely specified as 737nm. However, the absorption band that is not evident in the absorption spectrum is clearly visible in the differential spectrum at 1000 nm. The second-order differential of the undoped GLS absorption spectrum does not show any features, with no obvious shoulder peaks and shoulder valleys [10].

Based on the above first-order and second-order differential spectrum results, it can be considered that the size of the absorption spectral coefficient of gallium lanthanum sulfide is only related to whether it is doped with vanadium.

3. Results and discussion

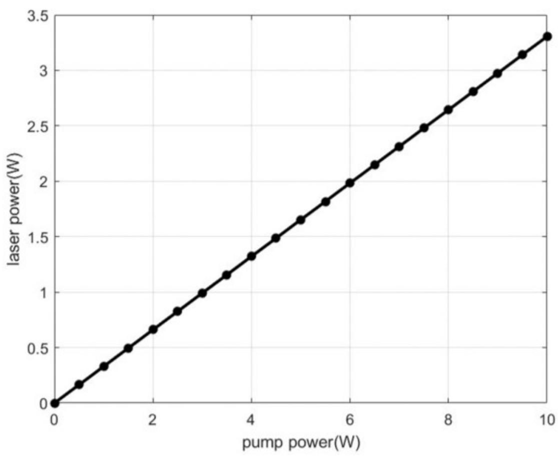

Figure 6. Pump power and output power diagram of vanadium-doped fiber laser (Picture credit: Original)

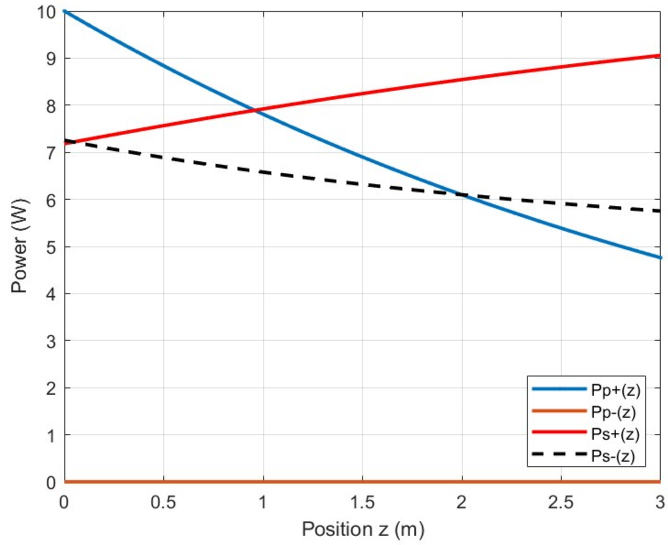

Figure 7. Relationship between pump power and lasing power as a function of length (Picture credit: Original)

It can be seen from Fig 6 that the greater the pump power of the vanadium-doped fiber laser, the greater the final output power. The reason for this situation can be explained in Fig 7. It can be seen from Fig 7 that as the vanadium ions propagate from the left cavity mirror to the right cavity mirror, the forward pump power gradually decreases, and this lost power is transferred to the forward lasing power, thus making the forward lasing power gradually increase.

4. Conclusion

The current part of the experiment that can be improved is the gain medium. This experiment only uses vanadium-doped gallium lanthanum sulfide, a type of sulfide glass. In the following experiments, different types of sulfide glasses can be doped with vanadium to conduct experiments on absorption spectral coefficients. Through comparison, we can determine which type of vanadium-doped sulfide glass has the strongest ability to absorb and emit light.

In addition, one thing that can be improved in this experiment is the size of the fiber core in the optical fiber. The experiment can be carried out using the core cross-section as the independent variable, the fiber's absorption power of the pump light, and the emission efficiency of the laser light as the dependent variables. Analysis Effect of core cross-section on optical fiber.

Since the above experimental deficiencies and improvements all appear in optical media, future research can focus on random fiber lasers. Because random fiber lasers are not limited by gain media, there is no need to conduct experiments to compare the advantages and disadvantages of different fiber media. Moreover, due to its unique working characteristics, random fiber lasers have strong stability, high anti-interference performance, and are more practical.

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