Modeling and numerical simulation of the output spectrum of a broadband Vanadium-doped optical fiber light source

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Abstract: Preliminary results have been achieved in the study of rare-earth doped fiber amplifiers. Further studies on rare earth ion vanadium are discussed in this paper. Based on the rate equation and power propagation equation, a model for the variation of output spectrum with fiber length, doping concentration and pumping power is constructed and solved by MATLAB, ODE45 function to explore the variation of Vanadium-doped fiber output spectrum with control variables from experimental aspects. The numerical simulation results show that the variation is proportional and the output power spectrum is enhanced with increasing fiber length, doping concentration and pump power, respectively. It is observed from the experimental data that the fiber length and doping concentration vary similarly and the output power spectrum expands nearly three times when the optical length and pump power are increased by a factor of two. This model can provide some directions for selecting Vanadium-doped fiber amplifiers and designing vanadium-doped amplifiers.

Keywords: Vanadium-Doped Fiber Amplifier, Fiber Length, Pumping Power, Doping Concentration

1. Introduction

Fiber optic communication technology has large communication capacity, long relay distance, and freedom from electromagnetic interference in transmitting the information. Fiber optic resources are abundant, lightweight, and small. So it is widely used in various communication networks to meet the growing needs of people's life and business communication. But with the increase in demand, the traditional fiber optic communication technology can no longer meet. So the research trend on developing fiber optic communication systems gradually tends to become high-speed, ultra-large capacity, long-range fiber optic transmission systems and networks. Fiber lasers have a good reputation for their high spot quality and high power output, and ultrashort laser amplifiers are an important research direction in the laser field, especially fiber amplifiers based on rare-earth-doped ions [1].

Doped fiber amplifier, also known as rare-earth-doped OFA, makes optical fibers, a special process is used to dope the fiber core layer deposition with a very small concentration of rare-earth elements, such as bait, praseodymium, rubidium plasma. It can produce the corresponding Bait-doped, Praseodymium-doped, or Rubidium-doped fiber. Fiber optic communication in the 1. 55um band and 1. 31um band has a low loss window. The choice of different doping elements can make the amplifier work in different windows, so the study of rare-earth-doped fiber amplifiers has some significance.

In the 1980s, the University of Southampton, UK, made rare-earth doped fiber amplifiers more practical in bait-doped fiber, showing the prospect of application. in October 2001, Zhuo Zhongchang [2] et al. focused on the bait-doped fiber amplifier (Erbium-doped fiber amplifier, EDFA), showing people's development of optical amplifiers. In 2008, Xius et al. [3] used a new ratio-doped lead germanate glass and proposed that the 800 nm absorption band is associated with a bismuth center different from other absorption bands, giving that the addition of different elements can improve the lifetime of rare earth doped fiber amplifier. In 2014, Xiaozhe Han [4] et al. investigated Pr+3 doped phosphate glass, working in the fifth fiber communication window of 1. 38-1. 53um was investigated. Meanwhile, some rare earth ions, such as Bi^{+}, Ni^{+}, Cr^{+} doped glasses were reported, and their broadband emission has attracted a lot of attention in the development of ultra-wideband amplifiers and tunable lasers[4-11].

Nowadays, there are many studies on doping other rare-earth ions, but few studies on rare-earth ion vanadium, i. e. , Vanadium-doped fiber amplifiers. Hughes [12] et al. proposed that based on the available spectroscopic data, the Vanadium ion has a chemical valence of +3 and is in tetrahedral coordination. The results indicate the potential for its development as a laser or optical amplifier. The application principle of bait-doped optical fiber is to dope the bait element into the quartz fiber as a gain activator. When the pump light of a certain wavelength is coupled into the bait-doped fiber, most of the bait ions in the ground state are pumped to the excited state. The bait ions in the excited state undergo a rapid radiation-free transition from the excited state to the sub-stable state [13]. Similarly, since vanadium and bait are both rare earth ions, vanadium-doped optical fibers have the same application. Therefore, in this paper, the modeling and numerical simulation of the output spectrum of broadband Vanadium-doped fiber light source is constructed by combining the set of rate equations for the variation of the bulk density of ions located at each energy level with time. The set of power propagation equations, based on the output wavelength of 1200-1700nm. Vanadium ions considered under the three-energy level structure. The fiber length, vanadium ion concentration, pumping power, and MATLAB simulation are used to obtain the spectrum. Further research is done into the features of the vanadium-doped fiber amplifier, including how the output spectra vary with fiber length, vanadium-doped ion concentration, and pumping power.

2. Models

2.1 Three-energy leap model for vanadium ions

Hughes et al. proposed that the vanadium ion has a +3 valence and is in a tetrahedral coordination [12]. Meanwhile, the common chemical valencies of vanadium are +5, +4, +3, and +2. The electronic structure model of vanadium is shown in Figure $1-a,$ where the electronic configuration of vanadium is $1s^2 2s^2 2p^6 3s^2 3p^6 3d^3 4s^2$ with four energy levels and the fourth energy level in the outermost layer. The ionization energy required to excite to the third energy level is $2828kJ/mol$, whereas it takes $6294kJ/mol$ to thrill to the fourth energy level. To excite to the fourth energy level requires nearly three times the energy required to excite to the third energy level, so the spontaneous and excited radiation of pump light at the fourth energy level is not considered, and the vanadium ion is considered. The three-energy leap model, i. e. , the three-energy level system, is shown in Figure 1 (b).

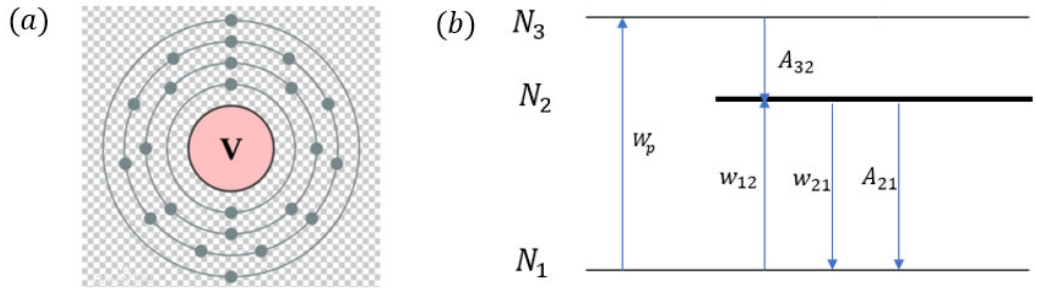


Figure 1 (a) Electronic configuration of vanadium. (b) Schematic diagram of a three-energy system leap

In Fig. 2, w_p indicates the absorption rate of pump light, w_{12}indicates the absorption rate of signal light, w_{21} indicates the excited emission rate of signal light, A_{32} indicates the no radiation jump rate, and A_{21} indicates the radiation jump rate. In order to better understand the absorption, spontaneous radiation and excited radiation of the three-energy level system, the absorption and spontaneous and excited radiation processes of the two-energy level system are as Figure 3. In Figure $2-a$, E_1 indicates the low state energy level, in the steady state, the electron is in at E_1. When the

photon hv is absorbed, the electron will jump from the low state to the excited state energy level E_2, this one process is absorption. Since the excited state energy level E_2 is extremely unstable, the electron will return to the E_1 energy level again, and this process is spontaneous radiation. In Figure $2-c$, the process with 2 photons in and 4 photons out is excited radiation This is an important theoretical basis for lasers as A. Einstein proposed that the interaction of light with matter should involve three processes: excited absorption, spontaneous radiation and excited radiation [14]. According to this hypothesis, when a particle of matter is exposed to a photon with an energy equal to the difference between two energy levels, it will transition into a lower energy state and produce two identical photons [15].

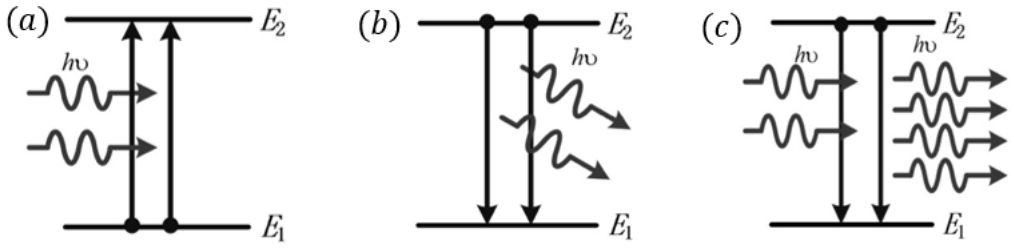


Figure 2 Schematic diagram of absorption and spontaneous and excited radiation processes in a two-energy level system. (a) Absorption, (b) Spontaneous launch. (c) Stimulated emission

2.2 System of rate equations

The light rate equation is obtained from the energy level structure.

$$\frac{\partial N_1(z)}{\partial t} = -\left[W_p(z) + W_{12}(z)\right]N_1(z) + A_{21}N_2(z) + W_{21}(z)N_2(z) \tag{1}$$

$$\frac{\partial N_2(z)}{\partial t} = W_{12}(z)N_1 - W_{21}(z)N_2(z) - A_{21}N_2(z) + A_{32}N_3(z) \tag{2}$$

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

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

The variation of ion bulk density (ions/m^3), $N_1, N_2, N_3$with time for electrons located at each energy level is called the rate equation. Where at different positions of the fiber, the ion bulk density is different, so equations (1-3) represent the variation of the ion bulk density at each energy level at different positions of the fiber with time. Equation (4)N represents the total number of ions

$$W_p(z) = \frac{\sigma_{13}P_p(z)}{hv_{13}A_{eff}} \tag{5}$$

$$W_{12}(z) = \frac{\sigma_{12}(v_{12})P_s(z)}{hv_{12}A_{eff}} \tag{6}$$

$$W_{21}(z) = \frac{\sigma_{21}(v_{21})P_s(z)}{hv_{21}A_{eff}} \tag{7}$$

$$A_{eff} = \pi r^2 \tag{8}$$

Since the model requires the establishment of rate equations, the density of electrons located at each energy level is related to the absorption rate of the pump light, the absorption rate of the signal light and the excited emission rate of the signal light, so it is necessary to establish. Eqs.5-8. The principle is shown in Fig.2. Calculated in Eqs. 5-8 are the absorption rates of pump light W_p, signal light W_{12}, emission rate of the signal light W_{21}. The purpose of calculating these three physical quantities is to combine the radiative leap rate A_{21} and the radiation-free leap rate A_{32} to calculate

the light rate equation for the ion concentration at different energy levels. where the absorption rate of the pump light W_p is related to the absorption cross section σ_{13} at the pump wavelength and the pump power P_p during the calculation, since the absorption of the pump light jumps directly from the ground state energy level to the third energy level. W_{12} and W_{21} are calculated for the same reason as W_p. Special note: σ indicates the absorption capacity, which is only related to the fiber material.

2.3 Set of power propagation equations

$$\frac{dP_p(z)}{dZ} = \left(-\sigma_p N_1(z) - \alpha_P\right)P_p(z) \tag{9}$$

$$\frac{dP_s(z)}{dz} = [\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_s]P_s(z) \tag{10}$$

$$\frac{dP_{ase}(z)}{dz} = [\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_s]P_s(z) + 2\sigma_{21}N_2(z)hv\Delta v \tag{11}$$

The propagation of pump power P_p across the fiber is related to the number of pump light absorbed in the ground state $\sigma_p N_1(z)$ and the loss coefficient of the pump light α_P. where σ_p denotes the pump light absorption power, N_1 denotes the number of vanadium ions in the ground state. Therefore it is necessary to establish Eqs 9-10.

The signal power P_s is used to indicate the absorption rate of the signal light W_{12} and the emission rate of the signal light W_{21}, so it consists of three parts. The first part is $\sigma_{21}N_2(z)$, which indicates the number of signal light emissions at the second energy level. Where σ_{21} denotes emission cross-section at the signal wavelength in $(/m^2)$, N_2 denotes the number of vanadium ions in the second energy level. The second part is $\sigma_{12}N_1(z)$, which indicates the number of signal light absorption at the second energy level. Where σ_{12} denotes absorption cross section at a signal wavelength in $(/m^2)$. The third part is loss factor of signal light α_s. When $\sigma_{21}N_2(z) > \sigma_{12}N_1(z)$, it indicates this equation is amplified, while $\sigma_{21}N_2(z) < \sigma_{12}N_1(z)$, it indicates this equation is attenuated.

The absorption rate of pump light w_p, the absorption rate of signal light w_{12}, and the excited emission rate of signal light w_{21} are obtained by calculating the pump power, the signal power, and the photon energy required to leap or radiate to each energy level. By combining the output wavelength range, energy level structure and electron leap process, can establish the modeling and numerical simulation of the output spectrum of broadband Vanadium-doped fiber light source. Also by MATLAB programming, the variation of the output spectrum with fiber length, doping concentration and pump power can be obtained.

3. Experimental

3.1 Experimental scenarios

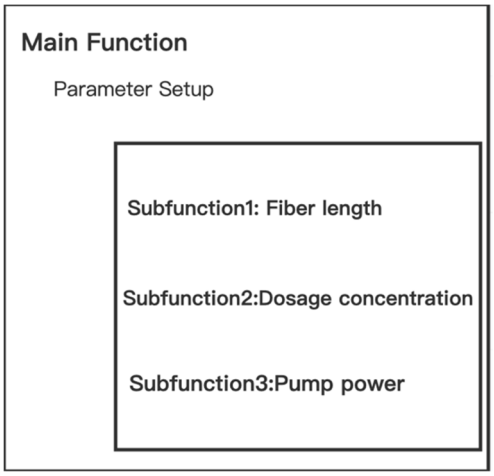


Figure 3 Experimental procedure diagram

The numerical model of the output spectrum of the broadband Vanadium-doped fiber light source is constructed by the power propagation equation and the rate equation of the three-energy-level structure system, and the experimental results are obtained by MATLAB simulation. The program is mainly divided into two parts. The first part is the main program, which includes the establishment of parameters, as shown in Table 2, and the representation of the power propagation equation and the rate propagation equation. The second part is the subroutine, i. e. The control variables fiber length, doping concentration and pumping power discussed in the experiment. The results required for the experiment can be discussed by calling the main function in the subfunction. Table 3 shows the values taken for each of the control variables. The experiments are mainly applied to the ode45 function, using the Runge-Kutta method with an algorithm of order 4-5, to solve the non-rigid problem where the unknown function changes more slowly with time.

Table 1 Creation of parameters

Parameters	Meaning	Numerical value
$\boldsymbol{c}$	Propagation rate of light	$3 * 10^8 m/s$
$\boldsymbol{h}$	Planck's constant	$6.626 * 10^{34}$
$\boldsymbol{\alpha}$	Background loss	$0.1/m$
$\boldsymbol{A_{21}}$	Radiation leap rate	$2000/s$
$\boldsymbol{A_{32}}$	Radiation-free leap rate	$10^4/s$
$\boldsymbol{T_s}$	Signal light overlap factor	0. 1
$\boldsymbol{T_p}$	Pump light overlap factor	0. 1
$\boldsymbol{r}$	Fiber radius	$2.5 * 10^{-6} m$
$\boldsymbol{\sigma_{13}}$	Absorption cross section at pump wavelength	$7 * 10^{-24}/m^2$
$\boldsymbol{\sigma_{31}}$	Emission cross section at pump wavelength	$0.8 * 10^{-24}/m^2$
$\boldsymbol{\lambda_p}$	Pump wave wavelength	$980nm$
$\boldsymbol{P_{p0}}$	Pump light initial power	$200mW$

Table 2 Control variables

Variables	Variable 1	Variable 2	Variable 3
Fiber length	2m	3m	4m
Doping concentration($\boldsymbol{ion/m^3}$)	$2 * 10^{24}$	$4 * 10^{24}$	$6 * 10^{24}$
Pump Power	100mW	400mW	800mW

3.2 Experimental results and analysis

3.2.1 Variation of output spectrum with fiber length

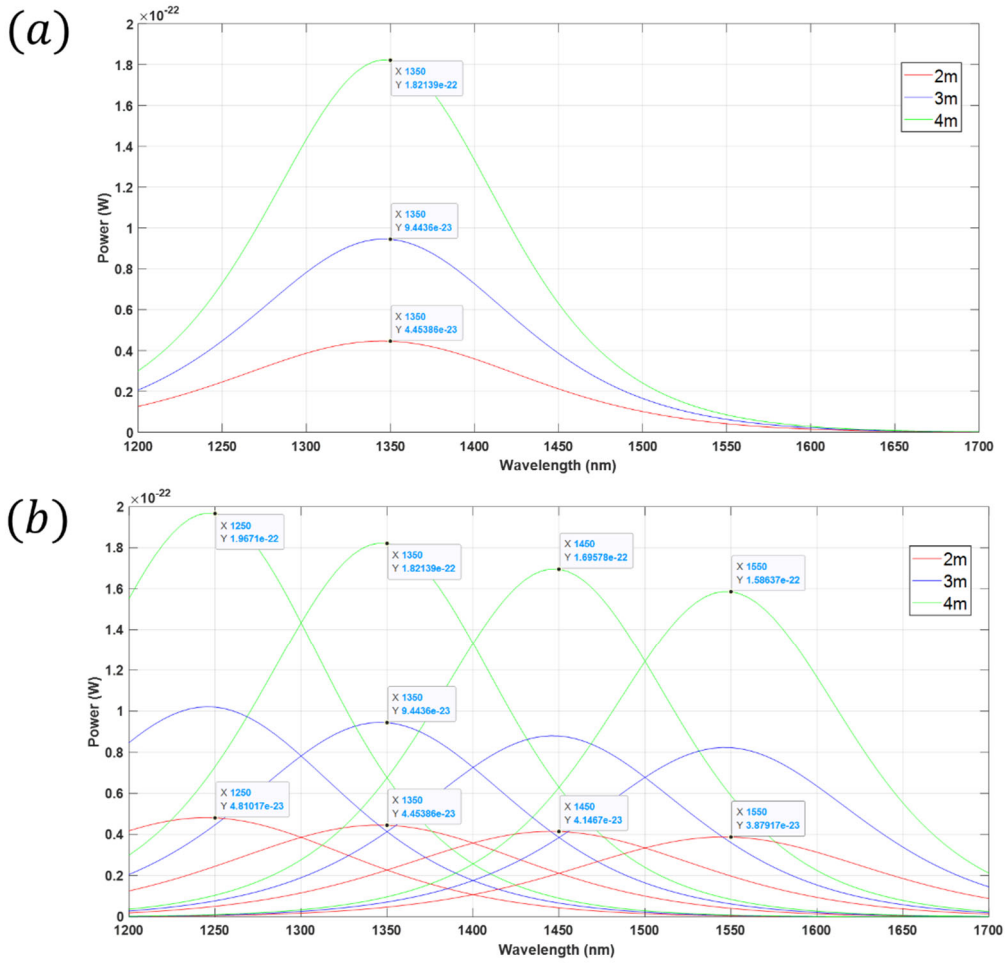


Figure 4 (a)Variation of output power spectrum with fiber length.(b)Variation of power spectrum with fiber length at different excitations

In the output wavelength range of 1200-1700nm, Figure 4 assumes excitation at 1350nm, and the output power spectrum varies with the fiber length. At 1350nm excitation, the output power of the fiber amplifier is $1.82 * 10^{-22}\ w$ for a fiber length of $4m$ and $4.45 * 10^{-23} w$ for a fiber length of $2m$, which is twice the length and nearly 2. 45 times the output power spectrum. According to the assumptions, the output power increases with the increase of the fiber length and reaches the peak at the excitation point for the control variables of $2m, 3m, 4m$. By observing Figure 5, the half-height width of the power spectrum of the fiber amplifier with a fiber length of $2m$ is about twice the half-height width of the power spectrum of the fiber amplifier with a fiber length of $4m$. According to the assumption that the fiber length of the control variable is $2m, 3m, 4m$, the half-height width is narrower as the fiber length increases, and the sensitivity of the fiber amplifier is higher. At the starting output wavelength, the output power spectrum of the Vanadium-doped fiber has an initial value. At the end output wavelength, the output power spectrum tends to zero. Figure 5 simulates the peak power of the fiber amplifier at 1250nm, 1350nm,1450nm, and 1550nm for different lengths of fiber amplifiers, and the peak power of the fiber amplifier at $4m$ length decreases from $1.96 * 10^{-22} w$ to $1.58 * 10^{-22} w$) w, which is 1. 24 times lower. The peak power of the fiber amplifier with a fiber length of 2m decreased from $4.81 * 10^{-23} w$ to $3.88 * 10^{-23} w$, a reduction of 1. 23 times. As the wavelength at the excitation increases, the output power decreases, and if the fiber length is larger, the output power decrease changes more obviously and sensitively. The closer to the starting position of the output wavelength, the greater the output power. And the greater the length of the fiber field, the greater the range of output power variation.

3.2.2 Variation of output spectrum with doping concentration

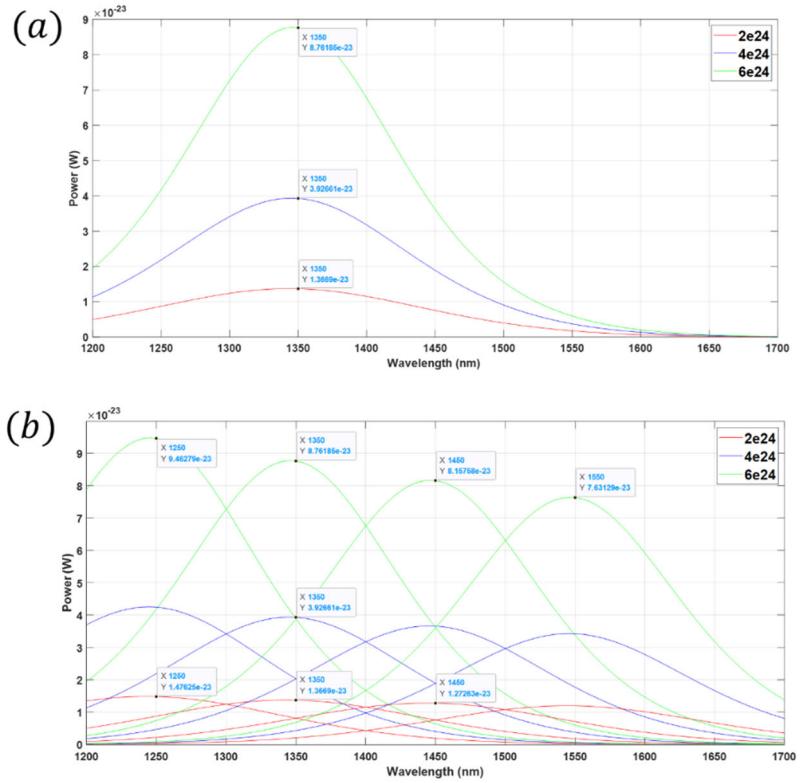


Figure 5 (a) Variation of output spectrum with doping concentration. (b) Variation of power spectrum with doping concentration at different excitations

In the output wavelength range of 1200-1700nm, Figure 7 assumes excitation at 1350nm, and the output power varies with the doping concentration. At 1350nm excitation, the output power is $3.93 * 10^{-23}\ w$ for a fiber amplifier with $4 * 10^{24}\ ion/m^3$ doping and $1.37 * 10^{-23} w$ for a fiber amplifier with$2 * 10^{24} ion/m^3$ doping. The doping concentration is increased by a factor of 2 and the output power spectrum is increased by a factor of nearly 3. The doping concentration is expanded by a factor of 2 and the output power spectrum is expanded by a factor of nearly 3. According to the assumption that the doping concentration of the control variables is $2 * 10^{24}, 4 * 10^{24}, 6 * 10^{24}\ ion/m^3$As the doping concentration increases, the output power increases and peaks at the excitation. The doping concentration on the output power of the fiber amplifier is greater than the fiber length's effect on the fiber amplifier's output power. By observing Figure 7, the half-height width of the power spectrum of the fiber amplifier with a doping concentration of $2 * 10^{24}\ ion/m^3$, is about twice the half-height width of the power spectrum of the fiber amplifier with a doping concentration of $6 * 10^{24}\ ion/m^3$. According to the assumption that the doping concentration of the control variable is $2 * 10^{24}, 4 * 10^{24}, 6 * 10^{24}\ ion/m^3$, as the doping vanadium ion concentration increases, the narrower the half-height width, the higher the sensitivity of the fiber amplifier. At the starting output wavelength, there is an initial value of the output power spectrum of the Vanadium-doped fiber, and the output power spectrum tends to zero at the end output wavelength. Figure 8 shows that the peak power of the fiber amplifier with a doping concentration of $6 * 10^{24}\ ion/m^3$ decreases from $9.46 * 10^{-23} w$ to $7.63 * 10^{-23} w$ for different lengths of fiber amplifier excited at 1250nm, 1350nm,1450nm and 1550nm, respectively, which is 1. 24 times lower. The peak power of the fiber amplifier with a doping concentration of $2 * 10^{24} ion/m^3$ decreases from $1.47 * 10^{-23} w$ to $1.19 * 10^{-23} w$, a reduction of 1. 23 times. As the wavelength at the excitation increases, the output power decreases. This may be due to the fact that when the wavelength of light increases, its frequency decreases, thus making the signal light absorption rate increase smaller and the volume density of ions located at each energy level becomes smaller, resulting in leading to a decrease in output power. As the wavelength increases, the output power changes more significantly when the doping concentration is larger, indicating a clear relationship between the output power and the

magnitude of the doping concentration. If the output power change is not obvious, then you can choose the case of lower doping concentration.

3.2.3 Output spectrum varies with pump power

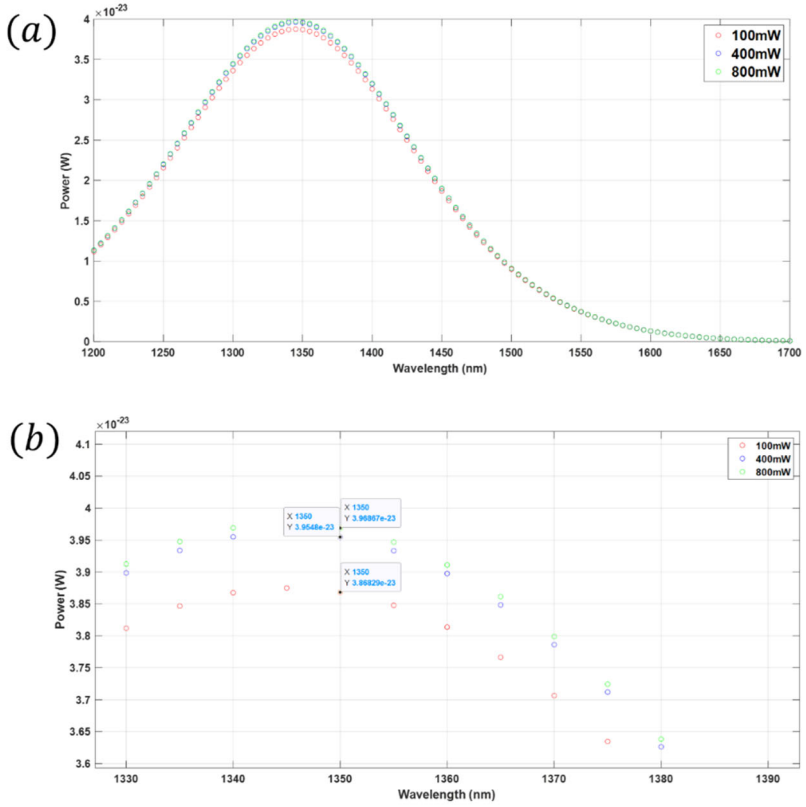


Figure 9 (a) Output spectrum varies with pump power.(b)Details of the output spectrum with pump power

In the output wavelength range of 1200-1700nm, Figure 9. 10. assume excitation at 1350nm. The output power spectrum is obtained with pumping, according to the assumption that the pumping power of the control variables are $100mW, 400mW, 600mW$. As the pumping increases, the output power increases and reaches a peak at the excitation. At the wavelength of 1350nm, the output power is $3.96 * 10^{-23}w$ when the pump power is $800mw$. While the output power of the pump power of 100mw is $3.86 * 10^{-23}w$. The difference between them is only about 10^{-24},At the starting output wavelength, the output power spectrum of the vanadium-doped fiber has an initial value, and at the end output wavelength, the output power spectrum tends to zero. However, the increase in pump power has little effect on the output spectrum, with only a small change. It was initially thought that the reason for this result might be because the pump powers were all relatively small, thus resulting in not much change, and then but the pump power changed by a factor of 1000 times with no significant change, so it shows that the pump power is not the main factor affecting the output power.

4. Conclusions

This paper studies and discusses the output spectrum of broadband Vanadium-doped optical fiber, and MATLAB is used for calculation and simulation. By combining the rate equation and power propagation equation of the three-energy system, the numerical model of the output spectrum of broadband Vanadium-doped fiber is constructed, and the relationship between the output spectrum and fiber length, doping concentration, and pump power is derived. The output power spectrum is wider, the half-height width is narrower, and the sensitivity is stronger when the light duration is the controlling variable. The output power spectrum is bigger, the half-height breadth is smaller, and the

sensitivity is stronger when the doping concentration is the controlling variable. If the pumping power is the control variable, the output power spectrum changes more when the pumping power is higher. Still, the change is less obvious compared to the light length and doping concentration. As observed by experimental data, the fiber length and doping concentration change similarly, and the output power spectrum expands nearly three times when both the light length and pump power are expanded by a factor of two. Due to the fiber material's specificity, the main component is silica, which is simple and inexpensive to obtain. At the same time, the price of vanadium is slowly decreasing. The future design of Vanadium-doped fiber can be mainly inclined to choose longer fiber length and higher doping concentration of Vanadium doped fiber amplifier.

References

[1] Li Lang, 2015. Research on novel rare-earth doped optical fiber amplifier, East China Normal University, MS thesis.

[2] Zhuo Zhongchang, Qin Li, 2001. Advances in optical fiber amplifiers, Journal of Natural Sciences, Jilin University.

[3] M. hughes, T. Suzuki, Y. Ohishi. Advanced bismuth-doped lead-germanate glass for broad band optical gain devices[J], Toyota Technological Institute, 2-12, Hisakata Tempaku, Nagoya,468-8511,Japan.

[4] Xiaozhe Han, Lifan Shen, Edwin Yue Bun Pun,etc. 2014. Pr^{3+}-doped phosphate glasses for fiber amplifiers operating at 1. 38-1. 53um of the fifths optical telecommunication window. School of Texitle and Material Engineering, 36(2014)1203-1208.

[5] B. B. Xu, S. F. Zhou, D. Z. Tan, Z. L. Hong, J. H. Hao, J. R. Qiu, J. Appl. Phys. 113 (2013) 0835031–0835038.

[6] V. O. Sokolov, V. G. Plotnichenko, E. M. Dianov, Opt. Lett. 33 (2008) 1488–1490.

[7] I. Razdobreev, L. Bigot, V. Pureur, A. Favre, G. Bouwmans, M. Douay, Appl. Phys.

[8] Lett. 5 (2007) 0311031–0311033.

[9] M. Y. Peng, J. R. Qiu, D. P. Chen, X. G. Meng, C. S. Zhu, Opt. Lett. 2005 2433– 2435.

[10] T. Suzuki, G. S. Murugan, Y. Ohishi, Appl. Phys. Lett. 86 (2005) 1319031– 1319033.

[11] Y. C. Huang, Y. K. Lu, J. C. Chen, Y. C. Hsu, Y. M. Huang, S. L. Huang, W. H. Cheng, Opt. Express 14 (2006) 8492–8497.

[12] M. Hughes, H. Rutt and D. Hewak. Specttoscopy of vanadium (III) doped gallium lanthanum sulphide chalcogenide glass, SO17 1BJ.

[13] Chen Jiangfeng, Huang Kun. 2013. Utility Analysis of optical Amplifier in Optical Fiber Communication [J]. Electronic Fabrication, 08):141.

[14] A.Einstein.1917. Zur quantentheorie der strahlung[J]. Physikalische Zeitschrift, 18.

[15] Chen Mina. 2020. Theoretical and experimental study of red light pumped Ho~(3+):ZBLAN fiber laser. Xiamen University,MA thesis.