Nd^{3+}-doped Fiber Laser at 1000-1100nm

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Abstract. Fiber optic amplifiers have revolutionized telecommunications by enabling efficient signal amplification over long distances. Their development stems from the increasing demand for high-speed data transmission and the limitations of traditional electronic amplifiers. Fiber amplifiers utilize rare-earth-doped fibers to boost optical signals, offering advantages in bandwidth, reliability, and cost-effectiveness. Nd^{3+}-doped fiber laser is one of the focal topics of current research. Researchers have found advancements in the application of Nd^{3+}-doped fiber laser at wide wavelengths. However, there still exist uncertainties in applying Nd^{3+}-doped fiber laser at 1000-1100nm. Therefore, this paper aims to design a Nd^{3+}-doped fiber laser at 1000-1100nm. The research methodology of this paper is as follows: using numerical simulation via Matlab. Research finds that Nd^{3+}-doped fiber laser at 1000-1100nm is theoretically applicable. The results of this research will promote the development of optical fiber. Through an in-depth exploration of new materials and application technologies, it will bring breakthroughs in optical fiber communication, optical sensing, laser technology, and other fields. This will promote the improvement of laser performance and provide a more reliable and efficient basis for future scientific research and engineering applications.

Keywords: Fiber laser; Nd^{3+}; 1000-1100nm.

1. Introduction

Nd3+ has gained significant attention as one of the most sought-after rare earth ions due to its vast potential across various applications. These include optical amplifiers, waveguide lasers, fiber optics, optical data storage systems, and communication optics within the infrared wavelength range.[1]. Nd^{3+} is also closely associated with the development of fiber lasers. Up to now, the research on neodymium-doped fiber lasers has seen numerous recent advancements. For example, a mode-locked all-polarization-maintaining Nd^{3+}-doped fiber laser near 910nm has proved to be a promising alternative to the Ti: Sapphire technology for two-photons microscopy in the 800-1000nm band[2]. An additional instance arises in the 900 nm wavelength domain, where Nd3+-doped phosphate fiber exhibits superior efficiency over silica fiber counterparts in short-length three-level fiber laser setups.[3]. Despite extensive research on Nd^{3+}-doped fiber lasers, there exists a significant research gap in Nd^{3+}-doped fiber lasers at 1000-1100 nm. In this paper, a Nd^{3+}-doped fiber laser at 1000-1100nm is designed.

2. Methods and Modeling

The Neodymium-doped fiber laser at 1000-1100nm is designed based on the four-level $^4F_{3/2}\rightarrow{}^4I_{11/2}$ transition of neodymium[4]. To calculate the output power, according to its theoretical derivation is shown below, its rate equations shown below represent the temporal variation of the volume density N1, N2, N3, N4 of ions at each energy level where electrons reside.

$$\frac{\partial N_1(z)}{\partial t} = -W_p(z)N_1(z) + A_{21}(z)N_2(z) \quad (1)$$

$$\frac{\partial N_2(z)}{\partial t} = W_{32}(z)N_3(z) - W_{23}(z)N_2(z) - A_{21}(z)N_2(z) + A_{32}N_3(z) \quad (2)$$

$$\frac{\partial N_3(z)}{\partial t} = W_{23}(z)N_2(z) - W_{32}(z)N_3(z) - A_{32}(z)N_3(z) + A_{43}(z)N_4(z) \quad (3)$$

$$\frac{\partial N_4(z)}{\partial t} = W_p(z)N_1(z) - A_{43}(z)N_4(z) \tag{4}$$

$$N = N_1(z) + N_2(z) + N_3(z) + N_4(z) \tag{5}$$

$W_p, W_{23}, W_{32}, A_{32}, A_{32}, A_{21}$ respectively correspond to pump light absorption rate, signal light absorption rate, signal light stimulated emission rate, non-radiative transition rate, radiative transition probability, and the unit of each is second,as shown in Fig 1.

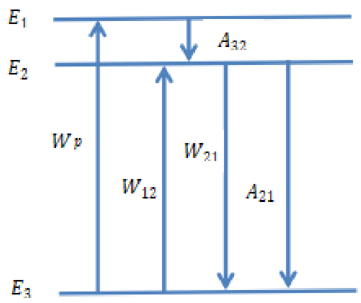

Fig 1. The four-level 4F3/2→4I11/2 transition of neodymium

In steady state, $\frac{\partial N_1(z)}{\partial t} = \frac{\partial N_2(z)}{\partial t} = \frac{\partial N_3(z)}{\partial t} = \frac{\partial N_4(z)}{\partial t} = 0$. To determine N1, N2, N3, N4, P_p, P_s ,which refer to pump power and lasing power, need to be determined first.

The power propagation equation is the variation of pump power and lasing power with respect to the propagation length, by which P_p, P_s are determined.

$$\frac{dP_p^+(z)}{dz} = \Gamma_p\left(-\sigma_p N_1(z) - \alpha_p\right)P_p^+(z) \tag{6}$$

$$\frac{dP_p^-(z)}{dz} = -\Gamma_p\left(-\sigma_p N_1(z) - \alpha_p\right)P_p^-(z) \tag{7}$$

$$\frac{dP_s^+(z)}{dz} = \Gamma_s[-\sigma_{32}N_2(z) - \sigma_{23}N_2(z) - \alpha_s]P_s^+(z) \tag{8}$$

$$\frac{dP_p^-(z)}{dz} = -\Gamma_s[\sigma_{32}N_3(z) - \sigma_{23}N_2(z) - \alpha_s]P_s^-(z) \tag{9}$$

σ_p, α_p, $\alpha_s$respectively correspond to the absorption coefficient of the pump wavelength, the loss coefficient of fiber material at pumping wavelength and lasing wavelength(/m). As shown in Fig 2, mirrors are located at z=0 and z=L. The pump light enters at z=0 and propagates to the right mirror at z=L. The direction from z=0 to z=L is considered positive, hence P_p^+ denotes the pump power propagating in the positive direction. L=1m. P_p^- denotes the pump power propagating in the negative direction. Γ_p represents the overlap integral between the pump power and the fiber core. When the mode field diameter of the pump light exactly matches the diameter of the fiber core, all the energy of the pump light can interact with the emitting ions, and in this case, Γ_p equals 1. When the mode field diameter of the pump light is smaller than the diameter of the fiber core, Γ_p is less than 1.

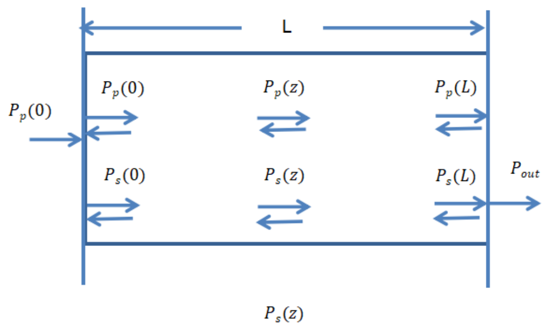

Fig 2. Abstract fiber laser

The threshold pump power of a fiber laser then can be calculated through the following expressions.

$$p_{th} = \frac{(N\Gamma_s\sigma_{12}+\alpha_s)L+\ln(\frac{1}{\sqrt{R_1R_2}})}{1-\exp(-\beta)}\frac{v_p}{v_s}\ p_{s,sat} \quad (10)$$

$$\beta = \frac{(\sigma_{41}+\sigma_{14})\Gamma_p}{(\sigma_{23}+\sigma_{32})\Gamma_s}\ [(N\Gamma_s\sigma_{23}+\alpha_s)L+\ln(\frac{1}{\sqrt{R_1R_2}})] - (N\Gamma_p\sigma_{14}+\alpha_p)L \quad (11)$$

$$p_{s,sat}=\frac{hv_sA_c}{\tau\Gamma_s(\sigma_{23}+\sigma_{32})} \quad (12)$$

p_{th} is threshold power,β is lasing power,$p_{s,sat}$ is signal saturation power,R_1、R_2respectively refer to reflectance of the left and right mirror,N is total doping concentration.

The output power then can be calculated through the following expressions.

$$p_{out} = (1-R_2)p_s+(L) = \frac{(1-R_2)\sqrt{R_1}.p_{p,sat}}{(1-R_1)\sqrt{R_2}+(1-R_2)\sqrt{R_1}} = [(1-\exp(-\beta))] \quad (13)$$

$$\frac{v_s}{v_p}\frac{p_p^+(0)+p_p^-(L)}{p_{s,sat}} - (Nl_s'\sigma_{23}+\sigma_s)L - \ln\left(\frac{1}{\sqrt{R_1R_2}}\right) \quad (14)$$

$$p_{p,sat} = \frac{hv_pA_c}{\tau\Gamma_p(\sigma_{13}+\sigma_{31})} \quad (15)$$

$$p_{s,sat} = \frac{hv_sA_c}{\tau\Gamma_p(\sigma_{12}+\sigma_{21})} \quad (16)$$

τ is Ion lifetime, $p_{p,sat}$ is saturation power of signal light, $p_{s,sat}$ is saturation power of pump light.

The main spectral parameters are λ_p=802nm, λ_s=1060nm, σ_{ap}= 3.01×10^{-24} m^2, σ_{as}= 1.57×10^{-24} m^2, τ_s=461.4μs, all from a Nd^{3+}-doped phosphate laser glass[5].

The results are obtained via numerical simulation.

3. Experimental Results

The simulation results are shown in the following figure. As shown in Fig3, it can be seen that below a power of 10W, the laser threshold has not yet been reached. Although laser generation has begun, there is no population inversion. Laser generation starts only after pump power exceeds 10W. This graph reflects the distribution of laser power in various parts of a one-meter-long optical fiber. Fig4 shows that as z increases from z=0 to z=L, Pp+ and Ps- exhibit a decreasing trend, while Ps+ shows an increasing trend, and Pp- remains essentially unchanged.

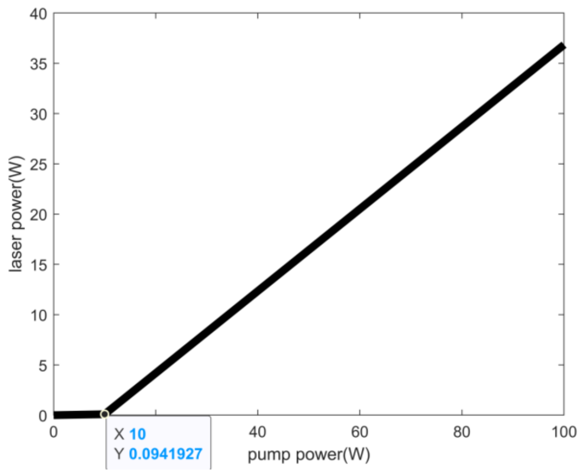

Fig 3. Output power

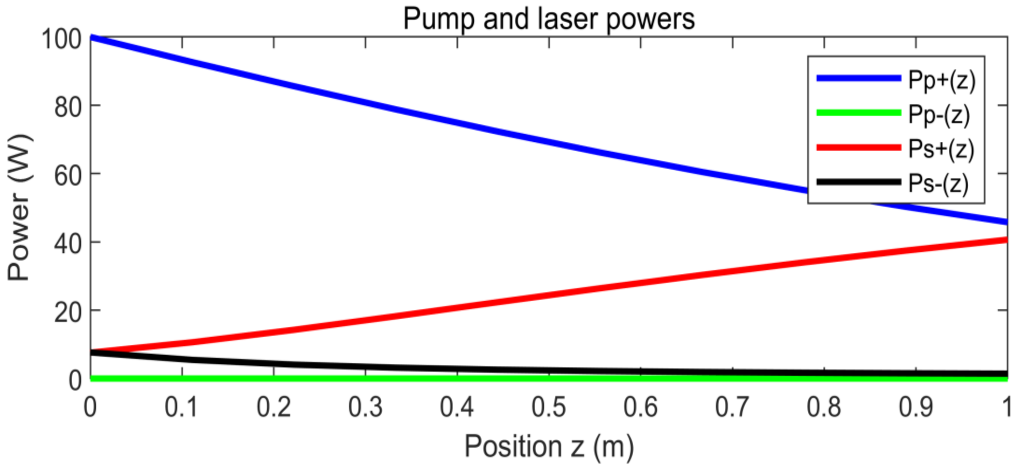

Fig 4. Pump and laser powers

4. Conclusions

This study focused on several aspects. Firstly, it conducted an analysis of the level structure based on rate equations, power propagation equation and so on. The design involved utilizing spectral parameters to the given system. Data processing was carried out using Matlab. The results indicated that at 1000-1100nm, laser power positively correlated to pump power. It can be inferred that theoretically, Nd3+-doped fiber laser at 1000-1100nm are potentially applicable.

Moving forward, in terms of future research prospects, it is recommended to further validate the results obtained from theoretical simulations through experimentation to ensure their accuracy and reliability. Systematic experimental designs and practical implementations can verify the applicability of simulated results in real-world environments and identify and address disparities between model assumptions and actual conditions.

Additionally, future studies are advised to prioritize rigor and reproducibility in experimental design and data collection to ensure the credibility of research findings. By employing such methodologies, future research will be able to address the empirical validation gap observed in the current study, thus providing a more reliable foundation for further advancements in the relevant field.

It's essential to acknowledge some limitations of the current study. For instance, there may have been constraints related to experimental validation. The present study, while successful in theoretical simulation, lacked experimental validation. This absence of empirical testing restricts the robustness of the findings. To improve future research endeavors, it would be beneficial to complement theoretical frameworks with rigorous experimental verification.

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