Optimization of the Peak Power of the Output Spectrum of Spontaneous Emission Spectrum Amplified by O-Band Fiber

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Abstract. As the demand for information and communication continues to increase, the optimization and improvement of optical fiber communication has been a key focus of scientific research, with profound impacts on multiple fields, including military, aerospace, industrial, and daily communications. Based on the in-depth understanding and establishment of the rate equation and power propagation equation of each energy level system, this study explores the influence of fiber length and doping concentration on amplifying spontaneous emission spectrum under certain pump power. With a comprehensive understanding of its characteristics, analog annealing algorithms are employed to optimize the length and doping concentration of the fiber to maximize the peak power of the output spectrum. This research provides an important contribution to the further development and efficiency improvement of optical fiber communication in the future. It is concluded that for the O-band, the output peak of high power can provide greater signal strength, thereby increasing the transmission distance and bandwidth capacity of the signal. This is essential for applications such as long-distance communications, high-speed data transmission, and multi-channel transmission.

Keywords: Rate equation, pump power, analog annealing algorithms, peak power.

1. Introduction

With the increasing demand for efficient information communication among humans, the enhancement and optimization of fiber optic communication systems have remained a central focus of scientific research. These efforts have far-reaching implications, spanning various domains such as military applications, aerospace technology, workplace productivity, and everyday communication needs [1]. They also influence the establishment of industry standards and the assurance of communication quality.

In pursuit of these objectives, this study delves into the rate equation and power propagation equation for each energy level system within fiber optic communication. It comprehensively examines the amplified spontaneous emission spectrum, observing how it evolves in response to variations in fiber length and doping concentration while keeping a certain pump power constant. With a thorough understanding of these spectral characteristics, the study employs a simulated annealing algorithm. This algorithm optimizes both the fiber length and doping concentration, ultimately maximizing the peak power of the output spectrum. The findings of this research are poised to make significant contributions to the ongoing development and efficiency enhancement of future fiber optic communication systems.

2. Overview of the basic theory of optical fiber

2.1. Fundamentals of laser principles

Since the 1960s, lasers have been a revolutionary human invention, often referred to as "the sharpest cutting tool," "the most precise measuring tool," and "the brightest source of light" due to their unique characteristics. These lasers have found extensive applications in scientific research, industry, agriculture, the military, and various other sectors [2]. The term "laser" stands for "Light

Amplification by Stimulated Emission of Radiation," a name that aptly reflects the primary process involved in laser production.

In the laser production process, atoms absorb energy, transitioning from lower to higher energy levels, and subsequently return to lower energy levels, emitting photons as they release energy. These emitted photons form an intense and highly coherent photon beam. Consequently, lasers outperform standard light sources in terms of monochromaticity, directionality, and overall brightness.

According to the principles of quantum mechanics, atoms can only exist stably in a series of energy-discontinuous states, and absorption or radiation in atoms can only occur between two states [3]. If an atom interacts with an alien photon and absorbs this photon and excites itself into a high-energy state, this process is also called atomic absorption. It should be noted that if you want to complete this process, the energy carried by the foreign photon needs to meet the difference in energy between the low and high energy levels before the atom can absorb the photon.

Spontaneous radiation This process does not require external action for this process. Atoms are extremely unstable at high energy levels, so their stay in the excited state is very short (about 10-8s). Its spontaneous transition from high energy level to low energy level will release a photon, then this process is called spontaneous radiation [4]. Spontaneous radiation has nothing to do with the external role, so the radiation of each atom is also independent of each other and independent of each other. Then, the frequency, initial phase, polarization state, propagation direction, etc. emitted by each atom will be arbitrary.

A luminescent atom in an excited state is subjected to the action of an alien photon, and the energy is exactly the difference between the two energy levels of the atom before spontaneous radiation occurs. After this, the atom can switch from an excited state to a low energy state and emit photons that are identical to foreign photons. This process is also known as stimulated radiation. The photons emitted by the stimulated radiation have the same state as the incident photons, and in this process, one photon will output two photons in the same state, and the output photons can continue to act on other atoms, thereby obtaining a large number of photons with the same characteristics, which is stimulated radiation light amplification. Therefore, stimulated radiation is a necessary condition to produce lasers.

2.2. Energy level system rate and power propagation equation

2.2.1 Two-level system rate and power propagation equation

The bulk density (pcs/m^3) of ions with electrons at each energy level, N_1, N_2 changes with time is called the rate equation. W_P, W_{12}, W_{21}, A_{21} are pump light absorption rate, signal light absorption rate, signal light stimulated emission rate, radiation transition rate, the above units are /s. The two-level system workflow diagram is shown in the figure 1 below.

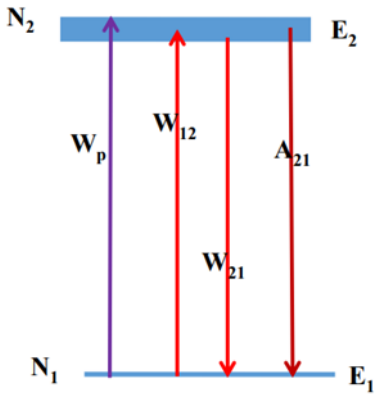


Fig. 1 The two-level system workflow diagram (Photo/Picture credit: Original)

W_P, W_{12}, W_{21}, A_{21}, respectively, pump light absorption rate, signal light absorption rate, signal light stimulated emission rate, radiation transition rate, the above units are /s. The first and second

energy level is represented by N1 and N2, while the first and second energy level energy is represented by E1 and E2.

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

$$\frac{\partial N_2(z)}{\partial t} = [W_p(z) + W_{12}(z)]N_1(z) - W_{21}(z)N_2(z) - A_{21}N_2(z) \quad (2)$$

$$N = N_1(z) + N_2(z) \quad (3)$$

Pump light absorption rate:

$$W_p(z) = \frac{\sigma_p P_P(z)}{h v_p A_{eff}} \quad (4)$$

Signal light absorption rate:

$$W_{12}(z) = \frac{\sigma_{12}(v_{12}) P_S(z)}{h v_{12} A_{eff}} \quad (5)$$

Signal light stimulation emission rate:

$$W_{21}(z) = \frac{\sigma_{21}(v_{21}) P_S(z)}{h v_{21} A_{eff}} \quad (6)$$

The change of pump power, signal power, ASE power (P_P, P_S, P_{ase}) with propagation length is called the power propagation equation. This can be obtained from the figure 2 below.

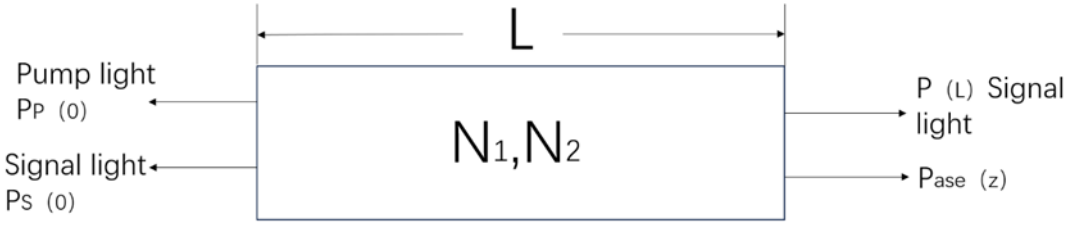


Fig. 2 Power propagation equation (Photo/Picture credit: Original)

N_1, N_2, L, P are energy level 1, energy level 2, propagation length, and signal power, respectively.

$$\frac{dP_P(z)}{dz} = \Gamma_p(-\sigma_p N_1(z) - \alpha_a)P_P(z) \quad (7)$$

$$\frac{dP_s(z)}{dz} = \Gamma_s[\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_s]P_s(z) \quad (8)$$

$$\frac{dP_{ase}(z)}{dz} = \Gamma_{ase}[\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_s]P_{ase}(z) + \sigma_{21}N_2(z)h v \Delta v \quad (9)$$

$$\Delta v = \frac{2\pi}{\lambda^2}\Delta\lambda\Delta\lambda = 1e^{-9} \quad (10)$$

α Δv are the loss factor (/m) and frequency half-height full width (Hz) of the fiber material, respectively.

$$G(P_p(z), P_s(z), N_2, N_1, z) = \frac{P_s(z)}{P_s(0)}(100\%)$$
$$G(P_p(z), P_s(z), N_2, N_1, z) = 10 * \log 10(\frac{P_s(z)}{P_s(0)})(dB) \quad (11)$$

2.2.2 Three-level system rate and power propagation equation

The three-level system workflow diagram is shown in the figure 3 below.

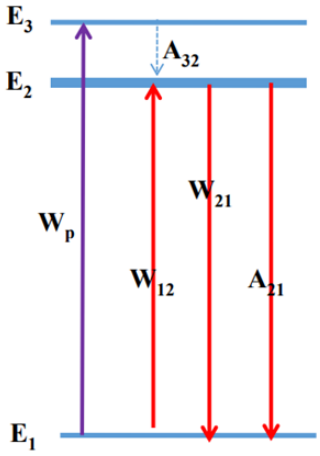


Fig. 3 The three-level system workflow diagram (Photo/Picture credit: Original)

In Figure 3, W_P, W_{12}, W_{21}, W_{32}, and A_{21} are respectively pump light absorption rate, signal light absorption rate, signal light stimulated emission rate, no radiation transition chance, and radiation transition rate.

$$\begin{aligned}\frac{\partial N_1(z)}{\partial t} &= -[W_p(z) + W_{12}(z)]N_1(z) + A_{21}N_2(z) + W_{21}(z)N_2(z)\\ \frac{\partial N_2(z)}{\partial t} &= W_{12}(z)N_1(z) - W_{21}(z)N_2(z) - A_{21}N_2(z) + A_{32}N_3(z)\\ \frac{\partial N_3(z)}{\partial t} &= W_p(z)N_1(z) - A_{32}N_3(z)\\ N &= N_1(z) + N_2(z) + N_3(z)\end{aligned} \tag{12}$$

The above units are /s. E_1, E_2 and E_3 are the energy of the first energy level, the energy level of the second level, and the energy level of the third level, respectively pump:

Light absorption rate:

$$W_p(z) = \frac{\sigma_{13}P_P(z)}{h\nu_{13}A_{eff}} \tag{13}$$

Signal light absorption rate:

$$W_{12}(z) = \frac{\sigma_{12}(\nu_{12})P_S(z)}{h\nu_{12}A_{eff}} \tag{14}$$

Signal light stimulated emission rate:

$$W_{21}(z) = \frac{\sigma_{21}(\nu_{21})P_S(z)}{h\nu_{21}A_{eff}} \tag{15}$$

The change of pump power, signal power, ASE power (P_P, P_S, P_{ase}) with propagation length is called the power propagation equation. This can be obtained from the figure 4 below.

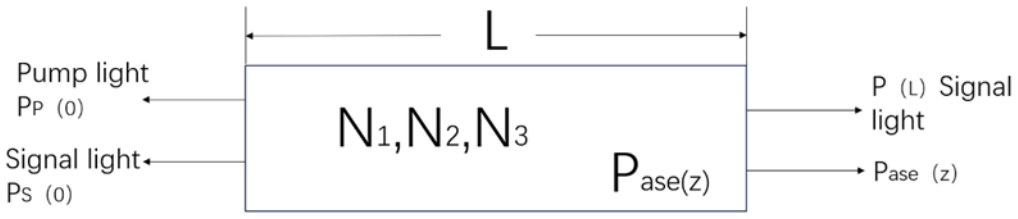


Fig.4 The power propagation equation (Photo/Picture credit: Original)

N_1, N_2, N_3, L, and P are energy level 1, energy level 2, energy level 3, propagation length, and signal power, respectively.

$$\begin{aligned} \frac{dP_P(z)}{dz} &= \Gamma_p(-\sigma_p N_1(z) - \alpha_a)P_P(z) \\ \frac{dP_s(z)}{dz} &= \Gamma_s[\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_s]P_s(z) \\ \frac{dP_{\text{ase}}(z)}{dz} &= \Gamma_{\text{ase}}[\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_s]P_s(z) + \sigma_{21}N_2(z)h\nu\Delta\nu \end{aligned} \tag{16}$$

α $\Delta\nu$ are the loss factor (/m) and frequency half-height full width (Hz) of the fiber material, respectively.

$$\begin{aligned} G(P_p(z), P_s(z), N_2, N_1, z) &= \frac{P_s(z)}{P_s(0)}(100\%) \\ G(P_p(z), P_s(z), N_2, N_1, z) &= 10 * \log 10(\frac{P_s(z)}{P_s(0)})(dB) \end{aligned} \tag{17}$$

3. Optimization algorithm and model analysis of peak power of O-band optical fiber output spectrum

3.1. Simulated annealing algorithm

The concept of the first simulated annealing algorithm was introduced by N. Metropolis et al. in 1953 [1]. S. Kirkpatrick et al. successfully applied annealing principles to the realm of combinatorial optimization in 1983. Stochastic methods are effective for addressing large-scale combinatorial optimization problems, as they enable the exploration of global optimization solutions by probabilistically escaping local optima [5]. Simulated annealing algorithms, being a versatile optimization approach, offer the potential for achieving probabilistic global optimization performance. In various engineering applications, such as VLSI design, production scheduling, control engineering, and signal processing, simulated annealing has gained widespread adoption. The simulated annealing algorithm comprises three essential components: the solution space, the objective function, and the initial solution.

The fundamental concepts of simulated annealing: The initial temperature at which annealing begins is represented by the shilling $T = T_0$ in the first step. An initial solution x_0 is generated randomly, and the corresponding objective function value $E(x_0)$ is calculated. In the second step, let$T = kT$, where k is between 0 and 1, which is the rate of temperature decrease. For the current solution x_t.Applying random perturbation to generate a new solution x_{t+1} in its neighborhood $E(x_{t+1})$, and calculate the corresponding objective function value $E(x_{t+1})$, calculate $\Delta\text{E} = E(x_{t+1}) - E(x_t)$. Accept the new solution as the current solution if $\Delta E < 0$. Alternatively, evaluate whether to accept the new solution based on the probability $e^{-\Delta E/kT}$. To verify that temperature T has reached the termination temperature level, repeat L perturbations and acceptance processes at temperature T. In the event that is the case, terminate the algorithm, otherwise proceed to the second step [6].

The initial temperature needs to be set first. Then, during the iteration process, the temperature decreases based on the cooling coefficient to determine whether the new state obtained is better: yes, accept the new state; no, accept it with a certain probability, which decreases as the temperature decreases. The program is stopped if the temperature drops below the set lower limit.

In conclusion, the simulated annealing algorithm is capable of surpassing local optimal and attaining global optimal. A feasible solution is obtained instead of an exact solution, which is not completely correct optimal solution that depends on the algorithm's parameters.

3.2. Corresponding variables based on the algorithm

The absorption and emission cross-sections are very important parameters for evaluating the laser performance of materials and are also one of the most critical parameters in the simulation experiment

of the O-band fiber output spectrum optimization algorithm. To assess the laser performance of materials, the absorption and emission cross-section is a crucial parameter. The Beer-Lambert equation and McCumber (MC) theory can be utilized to calculate them as follows:

$$\sigma_a(\lambda) = \frac{2.303OD(\lambda)}{Nd} \tag{18}$$

$$\sigma_e^{MC}(\lambda) = \sigma_a(\lambda)\frac{Z_L}{Z_U}exp\left[\frac{hc}{\mathcal{K}_B}T\left(\frac{1}{\lambda_{ZL}}-\frac{1}{\lambda}\right)\right] \tag{19}$$

In this experiment, the signal light wavelength and pump cross-section are also important parameters. In order to seek the conditions for maximizing the peak output spectrum, the simulation experiment calculates the variation of the amplified spontaneous emission spectrum with fiber length and doping concentration under the premise of 200mW and optimizes the fiber length and doping concentration through the simulated annealing algorithm to maximize the peak power of the output spectrum.

3.3. Optical fiber spontaneous emission spectrum output power calculation model

3.3.1 Four-level system rate equation

The ion energy levels and energy transfer diagram in a four-level system are shown in the figure 5.

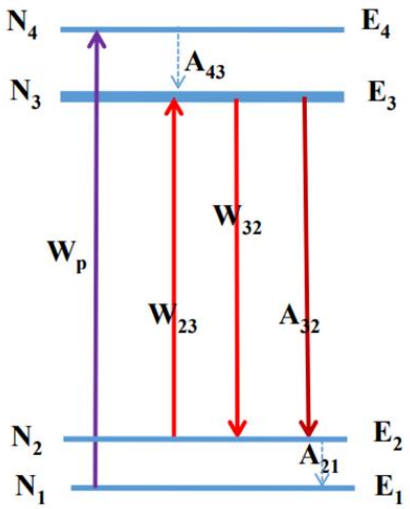


Fig. 5 Four level system (Photo/Picture credit: Original)

In Figure 5, WP, W23, W32, A32, A43, and A21are pump light absorption rate, signal light absorption rate, signal light stimulated emission rate, radiation transition probability and no radiation transition rate, respectively. The above units are /s [7].

$$\begin{gathered}\frac{\partial N_1(z)}{\partial \mathrm{t}} = -W_{\mathrm{p}}(z)N_1(z) + A_{21}N_2(z) \\ \frac{\partial N_2(z)}{\partial t} = -A_{21}N_2(z) - W_{23}(z)N_2(z) + W_{32}(z)N_3(z) + A_{32}N_3(z) \\ \frac{\partial N_3(z)}{\partial t} = W_{23}(z)N_2(z) - W_{32}(z)N_3(z) - A_{32}N_3(z) + A_{43}N_4(z) \\ \frac{\partial N_4(z)}{\partial \mathrm{t}} = W_{\mathrm{p}}(z)N_1(z) - A_{43}N_4(z) \\ N = N_1(z) + N_2(z) + N_3(z) + N_4(z)\end{gathered} \tag{20}$$

Pump light absorption rate:

$$\mathrm{W}_p(z) = \frac{\sigma_{14}P_P(z)}{h\nu_{14}A_{eff}} \tag{21}$$

Signal light absorption rate:

$$W_{23}(z) = \frac{\sigma_{23}(v_{23})P_S(z)}{hv_{23}A_{eff}} \tag{22}$$

Signal light stimulated emission rate:

$$W_{32}(z) = \frac{\sigma_{32}(v_{32})P_S(z)}{hv_{32}A_{eff}} \tag{23}$$

3.3.2 Four-level system power propagation equation

The change of pump power, signal power, ASE power (P_P, P_S, P_{ase}) with propagation length is called the power propagation equation. It can be obtained from Figure 6.

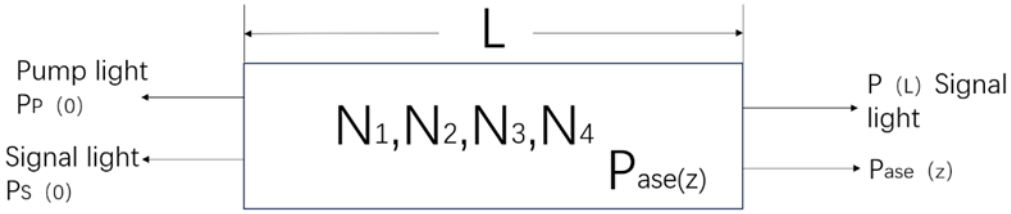


Fig. 6 Power propagation equation (Photo/Picture credit: Original)

$$\begin{aligned}
\frac{dP_P(z)}{dz} &= \Gamma_p(-\sigma_p N_1(z) - \alpha_a)P_P(z) \\
\frac{dP_S(z)}{dz} &= \Gamma_s[\sigma_{32}N_3(z) - \sigma_{23}N_2(z) - \alpha_s]P_s(z) \\
\frac{dP_{ase}(z)}{dz} &= \Gamma_{ase}[\sigma_{32}N_3(z) - \sigma_{23}N_2(z) - \alpha_s]P_s(z) + \sigma_{32}N_3(z)hv\Delta v
\end{aligned} \tag{24}$$

α Δv are the loss factor (/m) and frequency half-height full width (Hz) of the fiber material, respectively.

$$\begin{aligned}
G(P_p(z), P_s(z), N_2, N_1, z) &= \frac{P_S(z)}{P_S(0)}(100\%) \\
G(P_p(z), P_s(z), N_2, N_1, z) &= 10 * \log\ 10(\frac{P_S(z)}{P_S(0)})(dB)
\end{aligned} \tag{25}$$

4. Literature research analysis

This section aims to analyze and evaluate the conclusions in the literature and the output peak power of O-band fiber under different parameter conditions. By varying the parameters such as the pump power, fiber length and polarization of the laser, as well as the specifications and losses of the fiber connector, the effect of lasers on the output peak power is explored. In 2019, the State Key Laboratory of Luminescent Materials and Devices at the South China University of Technology, within the Institute of Optical Communication Materials, conducted a research study focused on Nd3+ doped TeO2–MoO 3–Zn O tellurite glass for diode-pumped 1.06 μm laser systems. In this investigation, the "thermodynamic method" played a key role in predicting the glass formation region. Additionally, the Beer-Lambert equation and McCumber (MC) theory were employed to calculate the maximum values of the absorption and stimulated emission sections, yielding results of 1.04 ± 0.03×10−20 cm and 3.12 ± 0.09×10−20 cm, respectively. Through several experimental iterations, it was ultimately determined that Nd3+TMZ glass holds substantial promise for enhancing the performance of high-power 1.06μm lasers [8].The Center for Optics and Photonics of the National University (CEPOF), the Center for Engineering, Modeling and Applied Social Sciences of the ABC Federal University in Brazil, and the Ministry of Defense of the Federal Technical University of Santo André Paraná, Brazil, have also studied Pr 3+/Yb 3+ co-doped tellurite tungstate glass, and proved through multiple sets of experiments that when the pump wavelength changes from 474 nm to 980 nm, the emission FWHM of Pr3+/Yb3+ co-doped tellurium tungstate glass changes from the E-S band (1370~1530 nm) becomes O-E band (1250~1400 nm) [9].

According to the analysis and comparison of the results of these two experimental items, the change trend of output peak power under different parameters is understood. Appropriately increasing the pump power and fiber length of the laser can increase the output peak power. At the same time, reasonable selection of fiber polarization and fiber optic connector specifications and losses is also crucial to maintain the stability of output peak power [10].

5. Conclusion

Through the above research, the conclusions obtained in this paper are as follows: O-band optical fiber output peak power is a key parameter in optical fiber communication system, which is of great significance to ensure the quality and stability of signal transmission. The output peak of high power can provide greater signal strength, thereby increasing the transmission distance and bandwidth capacity of the signal. This is critical for applications such as long-distance communications, high-speed data transmission, and multi-channel transmission.

However, in practical applications, there are still challenges in achieving high-power O-band fiber output peaks. First, fiber nonlinear effects and losses affect the transmission and stability of peak power. Fiber optic nonlinear effects such as self-phase modulation and optical clock comb effects can cause distortion and dispersion of the signal, reducing peak power. In addition, the quality and loss of fiber optic connectors also affect the transmission efficiency of output peak power.

Secondly, achieving high power output peaks also faces the pump power limitations of the laser and the optical characteristics of the fiber material. In order to obtain high power output peaks, lasers with high power and stability are required, and suitable fiber materials and structures are selected to achieve optimal power transfer and nonlinear characteristics.

Therefore, studying and optimizing the output peak power of O-band fiber has important theoretical significance and practical application value. Breaking through current challenges and improving the stability and transmission efficiency of output peak power will help further expand the performance of optical fiber communication systems and meet the growing communication demand.

References

[1] Mao Hu. Research on transmission technology and application of optical fiber communication network. Light Industry Standards and Quality, 2022(04): 117-119.

[2] "Research on China's Laser Technology and Application 2035 Development Strategy" project comprehensive group. Research on the development strategy of laser technology and application in China 2035. Engineering Science, 2020, 22(03): 1-6.

[3] LIU Jinhong. Study on quantum interference and chiral edge state of cesium atomic system. Shanxi University, 2020.

[4] Ma Rui. Research on all-optical quantization method based on fiber nonlinear effect. Beijing University of Posts and Telecommunications, 2021.

[5] LI Qiong, LIU Haifeng, ZHANG Gongmu, et al. Application of simulated annealing algorithm in chemical free energy model. Journal of Computational Physics, 2019, 36(03): 259-264.

[6] ZHAO Jinghe, XIE Ling. Simulated annealing algorithm for TSP problem based on LabVIEW simulation. Electronic Design Engineering, 2011, 19(17): 31-33+36.

[7] Wang Feng. Quantum coherent imaging of N-type four-level systems. University of Shanghai for Science and Technology, 2018.

[8] Belançon M P, Marconi J D, Ando M F, et al. Near-IR emission in Pr3+ single doped and tunable near-IR emission in Pr3+/Yb3+ codoped tellurite tungstate glasses for broadband optical amplifiers. Optical materials, 2014, 36(6): 1020-1026.

[9] Liu J L, Wang W C, Xiao Y B, et al. Nd3+-doped TeO2–MoO3–ZnO tellurite glass for a diode-pump 1.06 μm laser. Journal of Non-Crystalline Solids, 2019, 506: 32-38.

[10] Rong Xiaofeng. Research on neodymium-doped all-fiber pulsed laser. Xiamen University, 2021.