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Modeling and numerical simulation optimization of gain spectrum of thulium-doped broadband fiber amplifier based on cat swarm algorithm

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Abstract. With the development of light technology, especially the maturation of WDM/DWDM technology, the demand for optical amplification of the S-band and S+ band (1450nm~1520nm) is increasing day by day, and the energy level structure of Tm^{3+} has energy level transitions to meet the requirements of S-band and S+ band amplification. Although thulium ion has a very complex energy level structure, TDFA is one of the most promising optical fiber amplifiers for S and S+ bands. At the same time, with the continuous development of computer technology and mathematical theory, the optimization algorithm has been rapidly developed and widely used in recent decades, based on genetic algorithm, simulated annealing algorithm, and other traditional optimization algorithms that have been proved to get good convergence speed and optimization results. In this paper, the thulium-doped fiber amplifier's gain is optimized by using a cat swarm intelligent optimization algorithm to obtain the maximum fiber length and doping concentration.

Keywords: Fiber Optic Communication, Thulium-doped Fiber Amplifier, Cat Colony Optimization Algorithm, Amplification Gain.

1. Introduction

With the continuous development of information and communication technology, people's requirements for the network are getting higher and higher, which to a certain extent also promotes the development of fiber optic communication technology. At the same time, this also puts forward many new requirements for the optical amplification technology in the communication window band, for example, the effective optical amplification in the S-band (1450nm~1520nm) is one of the important optimization targets [1]. However, the erbium-doped fiber amplifier (EDFA), which has been used extensively in fiber optic communication systems, cannot effectively amplify the S-band signal. On the contrary, there are jumps in the energy level structure of thulium ion to meet the S-band amplification, which can realize the effective amplification of the S-band optical signal to meet the

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communication demand. Therefore, the thulium-doped fiber amplifier has become a new research hotspot for fiber optic communication devices and is the most promising laser amplifier device in S-band. Most of the studies on the gain of thulium-doped fiber amplifier (TDFA) start from the steady-state conditions of thulium ion particle rate equation and make reasonable approximations and modeling to derive the analytical expression of TDFA, to derive the effect of three parameters on the gain by the traditional calculation method.

With the continuous development of computer technology and mathematical theory, optimization algorithms have been rapidly developed and widely used in recent decades, providing powerful tools and methods for solving practical problems. In 2006, Shu-Chuan Chu et al. proposed the cat colony algorithm [2], a heuristic optimization algorithm based on the behavior of natural cat colonies, which finds the optimal solution by simulating the population intelligence of a cat colony. The algorithm can solve the function problem with a set number of iterations with a fast convergence rate to the maximum value. Therefore, it is feasible and innovative to use the cat swarm optimization algorithm as a tool to solve the problem of gain optimization of a thulium-doped fiber amplifier. This paper combines the optimization algorithm with the thulium-doped fiber amplifier's gain equation from the principle of the cat swarm intelligent optimization algorithm to derive the optimization results of fiber length and doping concentration at maximum gain.

2. Gain simulation and optimization

2.1. Research background

With the development of light technology, especially the maturation of WDM/DWDM technology, the demand for optical amplification of the S-band and S+ band (1450nm~1520nm) is increasing day by day, and the energy level structure of Tm^{3+} has energy level transitions to meet the requirements of S-band and S+ band amplification [3]. Although thulium ion has a very complex energy level structure, TDFA is one of the most promising optical fiber amplifiers for S and S+ bands [4]. At the same time, with the continuous development of computer technology and mathematical theory, the optimization algorithm has been rapidly developed and widely used in recent decades, based on genetic algorithm, simulated annealing algorithm, and other traditional optimization algorithms that have been proved to get good convergence speed and optimization results. At present, there are still many problems in Thulium-doped fiber amplifiers that need further study. Therefore, it is necessary to combine the optimization algorithm to model and optimize the thulium-doped fiber amplifier's gain.

2.2. Method

2.2.1. Energy-level modeling. This topic is to optimize the thulium-doped fiber amplifier's gain from 1450 to 1520nm. By consulting the relevant literature, the $^3H_4 \rightarrow {}^3F_4$ emission band of Tm^{3+}-doped ZBLAN is obtained as shown in figure 1 below, in which the pump wavelength is 790nm, so the three-level system model is abstracted according to the ion-doped level transition diagram (figure 2), where $E_3 \rightarrow E_2$ is the radiation transition (emitting photon) and $E_2 \rightarrow E_1$ is the radiation-free transition (heat generation) (as shown in figure 3).

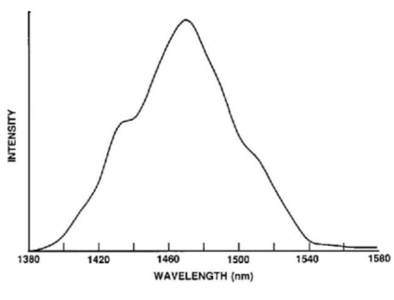

Figure 1. $^3H_4 \rightarrow {}^3F_4$ emission band for Tm^{3+}-doped ZBLAN [5].

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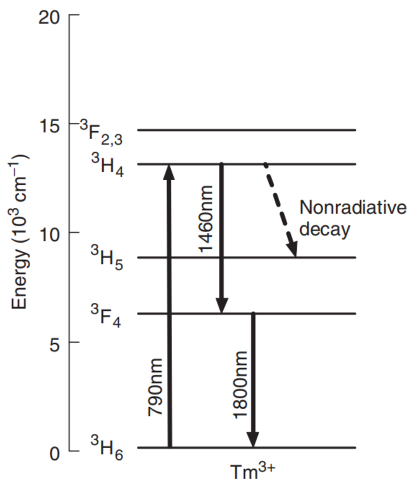

Figure 2. Energy level diagram of Tm^{3+} ion [6].

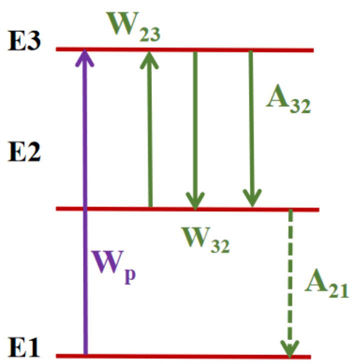

Figure 3. Energy level model.

According to the characteristics of the three-level system, the corresponding motion rate equation system(in equations (1)(2)(3)) and the power equation(in equations (4)(5)(6)) are constructed.

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

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

$$\frac{\partial N_3(z)}{\partial t} = W_p(z)N_1(z) + W_{23}(z)N_2(z) - [W_{32}(z) + A_{32}]N_3(z) \tag{3}$$

Where $W_p(z) = \frac{\sigma_{13}P_p(z)}{hv_{13}A_{eff}}$, $W_{23}(z) = \frac{\sigma_{23}P_s(z)}{hv_{23}A_{eff}}$, $W_{32}(z) = \frac{\sigma_{23}P_s(z)}{hv_{23}A_{eff}}$ are the upward transition rate after absorption of the pump photon, the transition rate after spontaneous forward transmission and the stimulated radiation rate respectively. $A_{eff} = \pi r^2$ is the fiber core cross-sectional area.

$$\frac{dP_p(z)}{dz} = \Gamma_p(-\sigma_p N_1(z) - \alpha_a)P_p(z) \tag{4}$$

$$\frac{dP_s(z)}{dz} = \Gamma_s[\sigma_{32}N_3(z) - \sigma_{23}N_2(z) - \alpha_s]P_s(z) \tag{5}$$

$$\frac{dP_{ase}(z)}{dz} = \Gamma_{ase}[\sigma_{32}N_3(z) - \sigma_{23}N_2(z) - \alpha_s]P_s(z) + \sigma_{21}N_2(z)hv\Delta v \tag{6}$$

2.2.2. Curve fitting. To find the maximum value of the emission interface in the studied band, fitting the emission interface as a function of wavelength is a key step. Figure 4 shows the fluorescence spectrum of thulium-doped ion glass. To find the emission spectrum as a function of wavelength, one of the curves was selected for preprocessing. The MATLAB curve fitter tool was used to fit the functions in the waveband range from 1450 to 1520nm. A multinomial Fourier expansion was chosen to obtain a functional relationship with high fitting accuracy. $y1 = a_0 + a_1\cos\omega x + b_1\sin\omega x + \ldots + a_6\cos6\omega x + b_6\sin6\omega x$ with constant parameters a_0, b_0, a_1, b_1, a_2, b_2, a_3, b_3, a_4, b_4, a_5, b_5, a_6, b_6, is chosen as the fitting function for subsequent amplification gain model simulation.

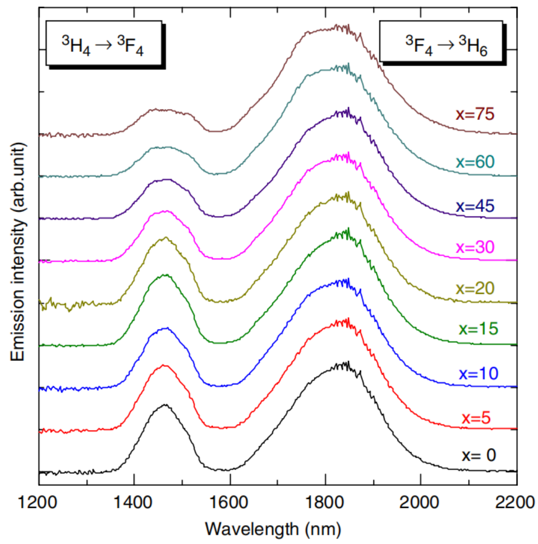

Figure 4. Fluorescence spectra of glasses [6].

Similarly, to obtain the absorption cross-section maximum, it is also necessary to fit the absorption cross-section versus the signal wavelength curve as a function. Figure 5 shows the absorption spectra of thulium-doped glasses. Between the ground state level of $^3H_6$ and the levels of $^1G_4$, $^3F_{2,3}$, $^5H_4$, $^3H_5$, and $^3F_4$, there are five bands of absorption. The fit function is still selected for the studied waveband (1450~1520nm) which uses a similar curve fitting method as the emission interface.

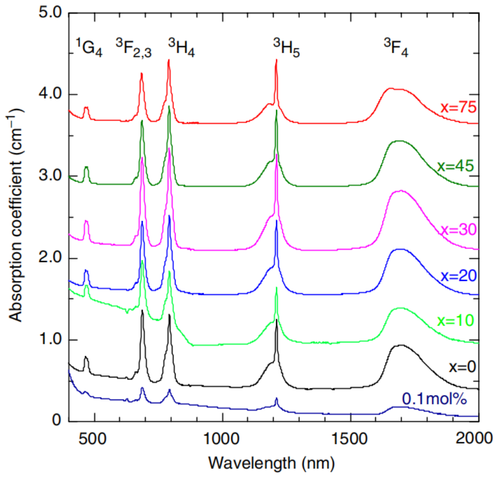

Figure 5. Absorption spectra of glasses [6].

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2.2.3. Fiber amplifier gain simulation. The rate and power equations derived from the above modeling of the system energy levels of thulium-doped fiber amplifiers in the 1450~1520nm signal band can be used to simulate the gain curves of fiber amplifiers under the influence of different variables (wavelength, doping concentration, and pumping power).

$$\mathrm{G}(\mathrm{P_p}(z), \mathrm{P_s}(z), \mathrm{N_2}, \mathrm{N_1}, z) = 10\log_{10}\left(\frac{\mathrm{P_s}(z)}{\mathrm{P_s}(0)}\right)(\mathrm{dB}) \quad (7)$$

The gain equation is obtained from the three-energy level power propagation equation as in equation (7). Write the code using MATLAB as the simulation environment. After parameter localization,

$$\mathrm{f}(1) = \mathrm{P}(1)\mathrm{T_s}(\sigma_{\mathrm{se}}\mathrm{N_3} - \sigma_{\mathrm{sa}}\mathrm{N_2}) - \alpha\mathrm{P}(1) \quad (8)$$

$$\mathrm{f}(2) = \mathrm{P}(2)\mathrm{T_p}(\sigma_{\mathrm{13pe}}\mathrm{N_3} - \sigma_{\mathrm{13pa}}\mathrm{N_1}) - \alpha\mathrm{P}(2) \quad (9)$$

$$\mathrm{f}(3) = \mathrm{P}(3)\mathrm{T_{ase}}(\sigma_{\mathrm{se}}\mathrm{N_3} - \sigma_{\mathrm{sa}}\mathrm{N_2}) + 2\sigma_{\mathrm{se}}\mathrm{N_3}\mathrm{T_s}\mathrm{hf_s}\Delta - \alpha\mathrm{P}(3) \quad (10)$$

Equation (8)(9)(10) is the power propagation equation, which is also the ordinary differential equation to be solved. The column vector P=[P_s; P_p; P_{ase}], where P_s is the signal power, P_p is the pump power, and Pase is the ASE power. After the parameters are determined, the above absorption cross section and emission cross section in the waveband is taken out of the maximum value of the amplitude to give σ_{sa} and σ_{se}. The wavelength range is defined as 1450~1520nm, and the number of wavelengths is measured as a function to determine the gain matrix dimension.

The signal light wavelength, σ_{21}, and σ_{21} are used as a function of wavelength, and the number of circular light wavelengths is solved by invoking the ordinary differential equation using ode45. The gain curves are plotted for different fiber lengths and doping concentrations, and the simulation functions are used as interface functions for the subsequent optimization process.

Table 1 below displays the TDFA's parameters. When uniform spreading is taken into account, the excited emission cross-sectional area of the 1460 nm band thulium-doped fiber amplifier is roughly equal to the exciting absorption cross-sectional area, which means σ_{se}=σ_{sa}=σ_s. In contrast, the spontaneous emission rate from energy level $^3H_4$ to $^3F_4$ is extremely tiny [7].

Table 1. Correlation coefficient of thulium-doped fiber amplifier.

Parameter	Value
Planck's Constant $\boldsymbol{h}$	6.626×10^{-34} J·s
Background Loss $\boldsymbol{\alpha}$	0.1 dB/m
the Velocity of Lightwave $\boldsymbol{c}$	3×10^{8} m/s
Spontaneous emission rate $\boldsymbol{A_{21}}$	108.6/s[8]
Wavelength of Main Pump $\boldsymbol{\lambda_p}$	790nm[5]
The wavelength of Signal $\boldsymbol{\lambda_s}$	1460nm
$\boldsymbol{\Gamma_p}$	0.45[9]
$\boldsymbol{\Gamma_s}$	0.45[9]
Fiber doping concentration N	1.6×1025/m^3

2.2.4. Cat group algorithm. The cat swarm optimization algorithm was selected for the optimization of the fiber amplifier gain curve, which can find the optimal value (extreme value) with a fast convergence rate.

2.2.4.1. Algorithm background. CSO is a heuristic optimization algorithm based on how a cat swarm behaves in the wild. The algorithm simulates the behavior of cats in foraging, hunting, and escaping, and simulates the group intelligence to find the optimal solution.

The cat group algorithm is mainly divided into two stages: the search stage and the aggregation stage. During the search phase, each cat moves randomly with a certain probability to search the new solution space and find the optimal solution through both local and global search. During the aggregation phase, each cat in the herd tries to move toward the optimal solution and gradually converges in the vicinity of the optimal solution. Compared with other heuristic algorithms, the cat group algorithm has the following characteristics [10]: (i) algorithm has strong global search ability and convergence speed. (ii) The algorithm is more robust to the selection of parameters such as initial population number, step size, and search space. (iii) The implementation of the algorithm is simple and easy to parallelize. (iv) The cat group approach has been utilized effectively to optimize a wide range of issues, including those in wireless sensor networks, power systems, image processing, and other areas.

2.2.4.2. Search mode. The principal flow of the search mode algorithm is described as follows [2]:

I. Copy j parts of the cat n, namely $j = SMP$, if SPC = TRUE, make $j = SMP$-1, and keep the current position as one of the candidates solutions.

II. Replace the previous value for each copy by adding or removing the *SRD* at random from the *CDC* 's current value:

$$\mathrm{X}_{cn} = (1 \pm SRD \times \mathrm{R}) \times \mathrm{X}_c \tag{11}$$

where X_c is the current location, X_{cn} is a new position, and R is an arbitrary value within the [0,1].

III. Find the fitness value *FS* for each potential option.

IV. The selection probability of each potential solution is determined from II if *FS* is not uniform; otherwise, the selection probability of each potential solution is set to.

$$|FS_i\text{-}FS_b| \tag{12}$$

$$P_i = FS_{max} - FS_{min}, \text{ where } 0 < i < j \tag{13}$$

where P_i is the selection probability of the current solution, FS_i is the fitness value of the cat, FS_{max} and FS_{min} are the maximum and minimum values of the fitness, respectively. For the maximization problem, FS_b=FS_{min}, for the minimization problem FS_b=FS_{max}.

V. From the candidate solution of the memory pool, replace the current cat *n*'s position by adhering to the selection probability.

2.2.4.3. Tracking mode. When the cat enters the tracking mode, it moves in accordance with the speed in each dimension, simulating the cat tracking the target [2].

I. Each cat *n* updates the speed of its current iteration following the following equation:

$$\mathrm{v}_{n,d}(t) = \mathrm{v}_{n,d}(t-1) + \mathrm{r}_1\mathrm{c}_1\left[\mathrm{x}_{\mathrm{B},d}(t-1) - \mathrm{x}_{n,d}(t-1)\right] \quad , d = 1,2,3\ldots,\mathrm{M} \tag{14}$$

Where $x_{B,d}(t\text{-}1)$ indicates the location with the highest fitness value from the most recent iteration, and $x_{n,d}(t\text{-}1)$ is the position of the last iteration *n*. c_1 is a constant and r_1 is the random number between[0,1].

II. Check the speed to see if it falls within the maximum speed range, if it does, take the boundary value.

III. Update the location of *n* by the following equation:

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$$\mathrm{x}_{n,d}(t) = \mathrm{x}_{n,d}(t-1) + \mathrm{v}_{n,d}(t) \tag{15}$$

2.3. Result and discussion

2.3.1. Result. The simulation curve obtained by running the simulation code is shown in the figure6,7,8 below.

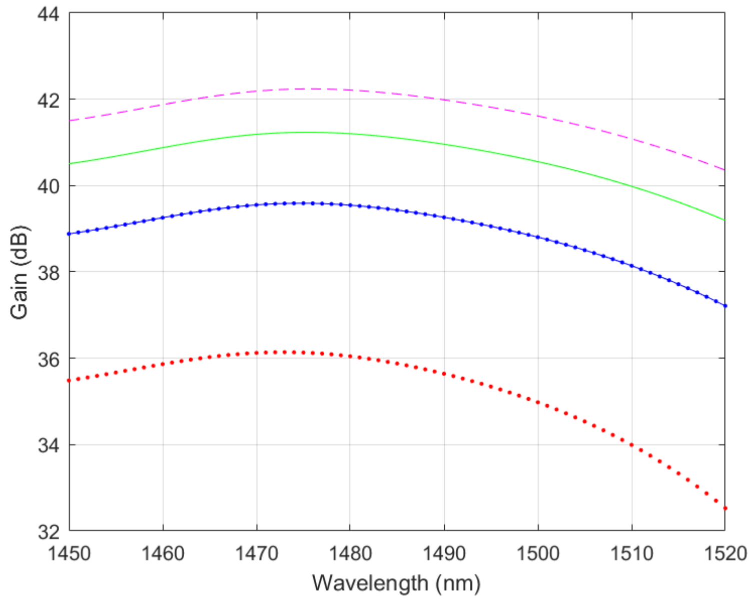

Figure 6. Simulation curve of amplifier gain regarding wavelength for various fiber lengths.

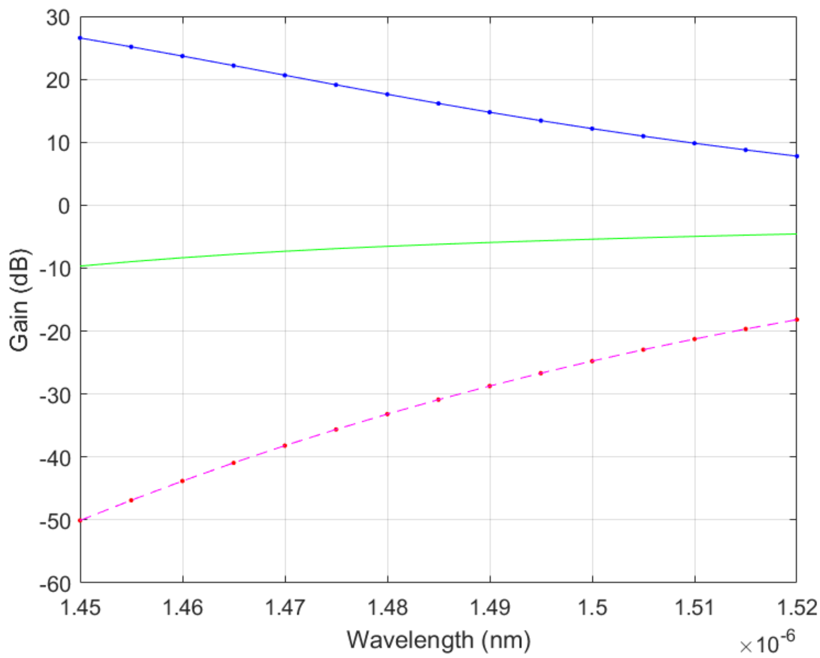

Figure 7. Simulation curve of amplifier gain with wavelength for various doping concentrations.

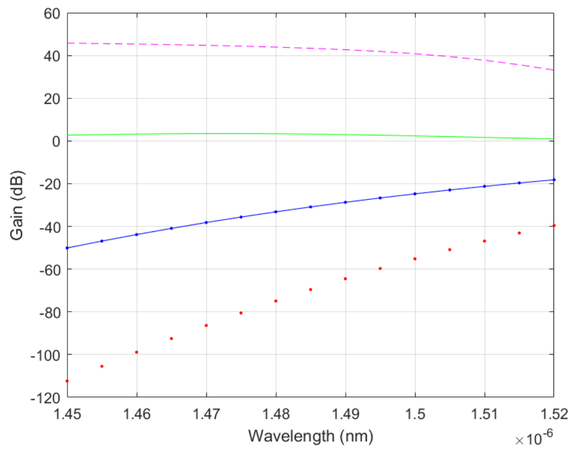

Figure 8. Simulation curve of amplifier gain with wavelength for various pump optical power.

The optimization results obtained by running the interface function by the cat colony algorithm are shown in figure 9 below.

```
      x: [9.7573 9.6556]
      v: [0.2598 0.1883]
   flag: 1
fitness: 540.8649
```

Figure 9. Optimization results.

Where x is a two-dimensional matrix, x(1) is the first optimization variable, namely the fiber length, and x(2) is the second optimization variable, namely the doping concentration. The optimization results show that when the gain is the maximum, the fiber length is 9.7m and the doping concentration is 9.6×1025mol/m³.

2.3.2. Discussion. After simulation and optimization, it is found that the cat colony optimization algorithm is feasible and effective in the gain optimization of the fiber amplifier. Based on the efficient function convergence rate and good optimization results of the cat colony optimization algorithm, the maximum value of the gain curve of the fiber amplifier can be obtained, which can be used in the design and application of a thulium-doped fiber amplifier.

3. Conclusion

After simulation and optimization, it is found that the cat colony optimization algorithm is feasible and effective in the gain optimization of the fiber amplifier. Based on the efficient function convergence rate and good optimization results of the cat colony optimization algorithm, the maximum value of the gain curve of the fiber amplifier can be obtained, which can be used in the design and application of the Tm^{3+}-doped fiber amplifier.

The simulation results show that the fiber length, doping concentration, and pump power have direct effects on the output signal gain characteristics of the Tm^{3+}-doped fiber amplifier.

The output signal gain of the fiber amplifier increases with the length of the fiber. The longer the fiber length, the more pump power that can be absorbed by the doped fiber, the higher the output signal power value, and the greater the signal amplification. The gain of the amplifier, however, will not increase indefinitely and will stop increasing once it reaches a particular level. There is an optimum length of fiber for the best performance of the amplifier's signal gain.

The doping concentration directly affects the absorption coefficient of pump light. The output light power increases with the doping concentration and the signal gain also increases correspondingly.

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When the signal gain and pump power are constant, the larger the ion doping concentration is, the shorter the fiber length is required, which is conducive to the development of miniaturization and modularization of the system. However, the doping concentration cannot be increased continuously, and the performance of Tm^{3+}-doped fiber amplifiers will be seriously affected when the doping concentration exceeds a certain range. In other words, there is an optimal doping concentration in optical fiber for the signal amplification of the amplifier to obtain the best performance.

Pump power is also an important influence parameter. When the signal gain and doping concentration are fixed, the larger the pump power, the shorter the fiber length required, which is also conducive to the development of miniaturization and modularization of the system. However, the pump power cannot be continuously increased. On the one hand, the high pump power may exceed the bearing capacity of the doped fiber and burn the fiber; on the other hand, it may cause the waste of pump power and reduce the power conversion efficiency of the system. In other words, there is an optimal pumping power for the signal gain of the amplifier in terms of signal gain.

Therefore, in a Tm^{3+}-doped fiber amplifier, there is a matching relationship among fiber length, doping concentration, and pump power, which can make the amplifier obtain the optimal signal gain characteristics under certain conditions.

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