Design of U-Band Fiber Amplifying Spontaneous Emission Spectra and Optimization of Output Spectral Peak Power

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Abstract. Optical communication is an important way of information transmission. At present, most of the optical fiber amplifiers on the market can only work in the wavelength range of 1530-1610m. The higher band, U-band is less used. Therefore, optical fiber amplifiers can extend the communication frequency range, provide more bandwidth, and meet the demand for higher rates and greater bandwidth optical communication with the continuous growth of network traffic. The paper is about the design of U-band (1650-1700m) fiber amplifying spontaneous emission spectrum and the optimization of output spectral peak power, and to find out the possibility of realizing efficient U-band fiber amplifiers. By establishing rate equation and power propagation equation, we simulate and calculate the variation of amplifying spontaneous emission spectrum with fiber length and doping concentration, and use genetic algorithm to optimize fiber length and doping concentration, so as to maximize the peak power of output spectrum. The experimental results show that the bismuth-doped high germanium silicate fiber can achieve effective amplification in the U-band range, and higher output spectral peak power can be obtained through optimization.

Keywords: U-band; amplifiers; fiber length; doping concentration.

1. Introduction

With the development of times and technology, optical fiber amplifiers have been widely used in signal processing and transmission [1]. At present, researchers have developed U-band fiber amplifiers with wide gain bandwidth. These amplifiers can provide high gain and maintain a wide operating bandwidth in the U-band range, so as to achieve high-speed data transmission and broadband wide communication. Besides, by improving the design of U-band fiber amplifiers and signal amplification mechanism, their gain and power output are improved which allows U-band fiber amplifiers to provide higher signal amplification and transmission capabilities.

However, there is still a long way to go to make full use of the broadband resources of U-band. First of all, the selection of optical materials in U-band is limited, including fiber materials and amplification media. The current material selection limits the performance and application range of -band fiber amplifiers, so it is still a challenge to find optical materials that are more suitable for U-band. Secondly, the U-band light is easily affected by the loss of scattering and absorption in the fiber transmission, resulting in the weakening of the signal strength and the limitation of the transmission distance. Solving the scattering and loss problems is the key to realize the efficient U-band fiber amplifier. In recent years, researchers have found that bismuth ion doped fiber has the ability to amplify in the U-band range [2]. So, in this experiment, bismuth-doped silica germanium dioxide fiber is used as the amplification medium [1]. Intensity of the absorption band at 1650 nm grows with an increase of GeO2 content in the glass matrix [3]. Taking the three-level bismuth ion system as the model, the rate equation and power propagation equation were established, and the ion concentration and absorption and emission cross section area of each level were calculated, respectively. The three-dimensional image of the output power changing was obtained by MATLAB modeling and drawing

the parameters to find the doping concentration and fiber length corresponding to the highest output power.

Then, this paper also put the equation parameters into the genetic algorithm to optimize the bismuth-doped fiber to amplify the peak power of the spontaneous emission spectrum [4]. The code iterates to find the optimal doping concentration and fiber length corresponding to the highest output power. The two results can be mutually corroborated to get as much as possible.

2. Energy level structure of bismuth ion

Bismuth ion is an important amplification medium in the study of U-band fiber amplifier. Bi-doped optical fibers exhibit broadband luminescence spanning from 1000 to 2000 nm [5]. Bismuth ions can absorb pumping energy and transition from a basic state to a high pumping state. Bismuth ions jump to different energy levels at different pump wavelengths is shown in figure 1.

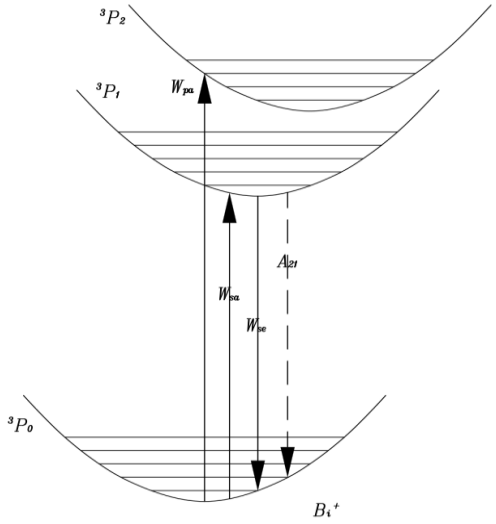


Fig. 1 Bismuth ions jump to different energy levels at different pump wavelengths [5]

As is shown, when pumping at 1550m is used, bismuth ions change from basic state to P2. Due to the short carrier lifetime at the pump level, the electrons quickly return to the unstable state of P1 at the pumping energy level. At the metastable level, the carrier has a long lifetime and accumulates under constant pumping, thus realizing the population inversion distribution. When the 1550m signal light passes through the activated doped fiber, the particles are converted to basic states under the induction and radiation of the signal light. Each jump generates a photon, similar to an induced photon, thus continuously amplifying the signal during the bismuth-doped fiber diffusion process. During the amplification, metastable particles will also jump to the basic state in the form of spontaneous radiation. The amplified spontaneous radiation power is the object of our study.

3. Equation and analysis

3.1. Rate Equations

To describe the behavior of spontaneous emission spectra in bismuth-doped fiber amplifiers, we utilize rate equations. Based on the energy level structure of bismuth ions, the rate equations for bismuth-doped fibers can be derived, and their general forms are as follows [6].

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

$$\frac{\partial N_2(z)}{\partial \mathrm{t}} = W_2(z)N_1(z) + W_{21}(z)N_2(z) - A_{21}N_2(z) + A_{32}N_3(z) \quad (2)$$

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

These equations represent the variation of the particle number densities of the metastable state, excited state and ground state bismuth ions with respect to the length. $W_p(z)$ represents the pumping rate, $W_{21}(z)$ represents the non-radiative transition rate from the ground state to the metastable state, A_{21} represents the stimulated emission rate from the metastable state to the ground state, $W_{21}(z)$ represents the spontaneous emission transition rate from the metastable state to the ground state, $W_2(z)$ represents the pumping rate from the ground state to the metastable state, A_{21} represents the stimulated emission rate from the metastable state to the ground state, and A_{32} represents the stimulated emission rate from the metastable state to the excited state. The pumping rate $W_p(z)$ plays a crucial role in the variation of the ground state and metastable state particle number densities. By adjusting the pump power and wavelength, pump rate can be controlled to influence the particle number densities of the excited and metastable states. The stimulated emission rates A_{21} and A_{32} play important roles in the variation of the particle number densities. They describe the transition processes of particles from the metastable state to the ground or excited state. By altering the stimulated emission rate, the particle number transfer between the metastable and excited states can be influenced. The spontaneous emission rates $W_{12}(z)$ and $W_{21}(z)$ describe the spontaneous emission transition processes between the metastable and ground states. Spontaneous emission affects the variation of particle number densities and is related to the spontaneous emission power $P_{ase}(z)$.

For the calculation of the pumping rate, spontaneous emission transition rate, and spontaneous emission transition rate in the optical fiber, the following formulas are used:

$$W_p(z) = \frac{\sigma_{13} P_p(z)}{h v_{13} A_{eff}} \quad W_{12}(z) = \frac{\sigma_{12}(v_{12}) P_{ase}(z)}{h v_{12} A_{eff}} \tag{4}$$

$$W_{21}(z) = \frac{\sigma_{21}(v_{21}) P_{ase}(z)}{h v_{12} A_{eff}} \quad A_{eff} = \pi r^2 \tag{5}$$

In the above equation，σ_{13} represents the absorption cross-section of bismuth ions, $P_p(z)$ is the pumping power, A_{eff} is the effective area of the bismuth-doped fiber, σ_{12} is the spontaneous emission cross-section of bismuth ions, v_{12} is the transition rate, $P_{ase}(z)$ is the spontaneous emission power.

3.2. Absorption and emission cross-sections calculation

The absorption cross-sectional area and emission cross-section area of bismuth-doped fibers at specific wavelengths or frequencies can be calculated using the following parameters and formulas, and the picture is shown in figure 2 [7].

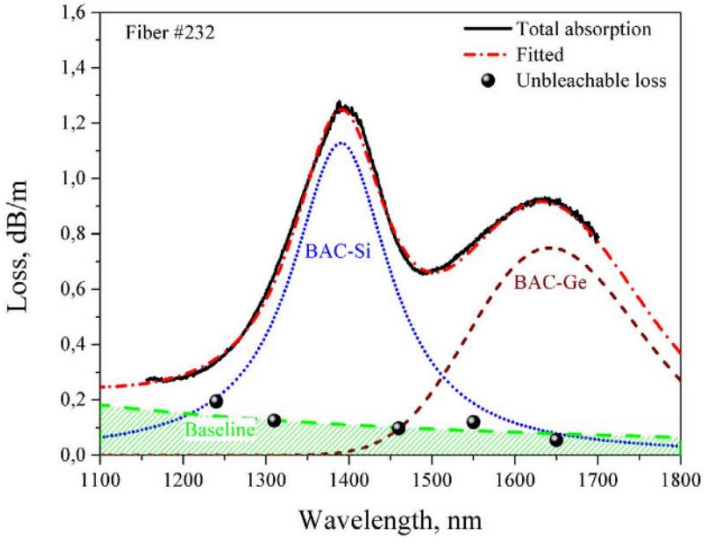


Fig. 2 Absorption cross-sectional area and emission cross-section area [7]

$$Loss=10lg(ab)/L \tag{6}$$

$$mol_{Bi_2O_3} = d * Wt_{Bi_2O_3}/M_{Bi_2O_3} \tag{7}$$

$$N_{Bi} = 2 * mol_{Bi_2O_3} * A_V \tag{8}$$

$$\sigma_{ab}(n) = ab(m^{-1})/N_{Bi}(m^{-3}) = ab/N_{Bi} \tag{9}$$

$$\upsilon = c^{*}1e9/n \tag{10}$$

$$\sigma_{em}(u) = \sigma_{ab}(\nu)\exp\left(\frac{\varepsilon_0 - h\upsilon}{\kappa T}\right) \tag{11}$$

Here, $\sigma_{ab}(n)$ represents the absorption cross-section area at a wavelength of n nanometers. Based on the given data, $\sigma_{ab}(1550)$ = 1.19m⁻¹ and $\sigma_{ab}(1650)$= 1.23m⁻¹. $M_{Bi_2O_3}$ is the molar mass of bismuth trioxide (Bi2O3) in bismuth-doped fibers, which is 465.96g/mol. $Wt_{Bi_2O_3}$ represents the weight percentage of bismuth trioxide in bismuth-doped fibers, with a value of 18 × 10⁻³%. d is the density of bismuth-doped fibers, which is 3.715g/cm³. $mol_{Bi_2O_3}$ is the molar quantity of bismuth trioxide in bismuth-doped fibers, and A_V is Avogadro's constant. $\sigma_{em}(u)$ represents the emission cross-section area at a frequency of u, ε_0 means vacuum permittivity, h means Planck's constant, υ means frequency, κ means Boltzmann constant, T means temperature, and u means unit obtained by multiplying the speed of light c by 1e9 and dividing by the value of n in nanometers. It is used to calculate the emission cross-section, considering the population distribution of energy levels at a specific frequency.

Using these parameters and formulas, the absorption section area and discharge section area can be calculated at specific wavelengths or frequencies. And the stimulated emission cross-sectional area of the signal is determined to be 4.13*e-24/m, signal absorption area is 6.76*e-25/m, pump absorption area is 6.99*e-25/m. The excitation emission cross-sectional area of the signal reflects the bismuth-doped fibers' gain characteristics, indicating the amplification of signal light through stimulated radiation. By solving the excitation emission cross-sectional area, the gain performance and amplification effect of the fiber can be evaluated. The signal absorption cross-section reflects the absorption loss in the fiber which is the energy lost by the signal light due to absorption by bismuth ions during transmission. Solving the signal absorption cross-section helps evaluate the transmission efficiency and loss characteristics. The pump absorption cross-sectional area reflects the energy lost due to absorption by bismuth ions during the transmission of the signal light, thereby indicating the transmission and loss characteristics of the fiber.

3.3. Power propagation equation

In optical fibers, the optical signal attenuates as the fiber length increases [8]. Taking into account the absorption loss, attenuation loss, gain effect of the fiber, and spontaneous emission of bismuth ions in the doped fiber, the power propagation equation describes the variation of optical power along the propagation direction in bismuth-doped fibers [9].

$$\frac{dP_z(z)}{dz} = -\Gamma_p(\sigma_p N_1(z) + \alpha_a)P_p(z) \tag{12}$$

$$\frac{dP_s(z)}{dz} = \Gamma_s[\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_s]P_s(z) \tag{13}$$

$$\pm\frac{dP_{ase}(z)}{dz} = \pm\Gamma_{ase}[\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_s]P_s(z) \pm 2\sigma_{21}N_2(z)hu\Delta u \tag{14}$$

$$G(P_p(z), P_s(z), N_z, N_1, z) = \frac{P_s(z)}{P_s(0)}(100\%) \tag{15}$$

$$G(P_p(z), P_s(z), N_z, N_1, z) = 10 * \log\ 10(\frac{P_s(z)}{P_s(0)})(dB) \tag{16}$$

The term $\frac{dP_z(z)}{dz}$ represents the power gradient along the propagation direction z of the fiber, which indicates the rate of change of power density. Γ_p, Γ_s, and Γ_{ase} represent the gain coefficients for pump, signal, and spontaneous emission, respectively. σ_p, σ_{12}, and σ_{21} denote the absorption cross-sections for pump light, signal light, and stimulated emission of signal light, respectively. $N_1(z)$ and $N_2(z)$ represent the particle number density distribution functions for pump and signal light, with their magnitudes varying with the fiber length z. α_a and α_s represent the absorption loss coefficient of the fiber material and the attenuation loss coefficient of the signal light, respectively. $P_z(z)$, $P_s(z)$, and $P_{ase}(z)$ are the power distribution functions for pump and signal light, and spontaneous emission, respectively. Δu represents the half-width of the frequency. $G(P_p(z), P_s(z), N_z, N_1, z)$ denotes the gain function that describes the gain relationship between pump light and signal light, expressed as a power ratio or a logarithmic ratio in decibels.

The above equations demonstrate the variation of optical power along the propagation direction in bismuth-doped fibers. These equations incorporate factors such as the absorption of pump light, absorption and radiation of signal light, and losses in the fiber material [10]. Consequently, the power distribution of pump and signal light, and spontaneous emission can be derived as a function of the fiber length, enabling the characterization of the transmission and gain properties of light in bismuth-doped fibers. This facilitates the amplification and transmission of optical signals. The power propagation equation allows for the optimization of the structure and parameters of bismuth-doped fibers. By adjusting factors such as material parameters, fiber length, and pump power, it becomes possible to predict and optimize the transmission characteristics, gain properties, and loss properties of optical signals. These advancements contribute to the realization of more efficient and stable optical fiber transmission systems and play a crucial role in the design, modeling, solving, and optimization using MATLAB [11].

3.4. MATLAB simulation and analysis

First, this paper uses the exhaustive modeling method to define the signal power Ps_0; Pump optical power Pp_0; Signal bandwidth power Pase_0; Doping concentration N; Signal stimulated emission cross section sig_se; The absorption cross section of signal sigma_sa; Pumped stimulated emission cross section sigma_13pe; The absorption cross section of the pump sigma_13pa. The result is shown in figure 3.

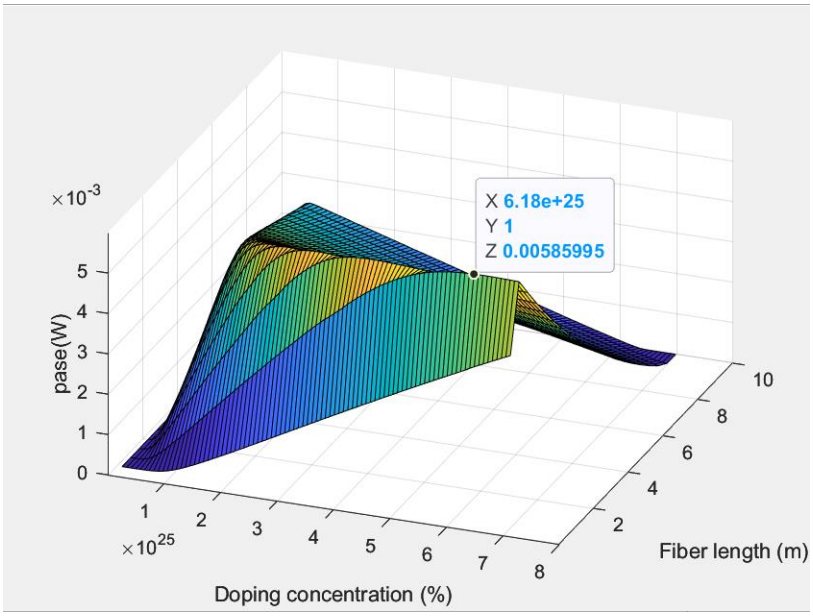


Fig. 3 MATLAB simulation result (Photo/Picture credit: Original)

The X axis represents the doping concentration, the Y axis represents the fiber length, and the Z axis represents output power. This three-dimensional image with the peak power and its

corresponding fiber length and doping concentration are obtained by the exhaustive method. It can be found that the output power first increases and then decreases with the rise of fiber length, while output power first rises with the increase of doping concentration and finally tends to a relatively stable value and then decreases.

4. Genetic algorithm optimization

Then, in order to acquire maximum output spectral peak value, we use genetic algorithm to optimize the fiber length and doping concentration. Genetic algorithm is an optimization algorithm based on the principles of natural selection and genetics, which can quickly find the best solution in the search space [7]. In this experiment, using MATLAB programming language to realize the genetic algorithm and optimize the calculation.

4.1. Genetic algorithm flow chart

In the pursuit of optimizing controller parameters using a genetic algorithm, a systematic workflow is essential. This process involves several critical steps, each contributing to the refinement of the controller. The following figure 4 outline these steps in detail.

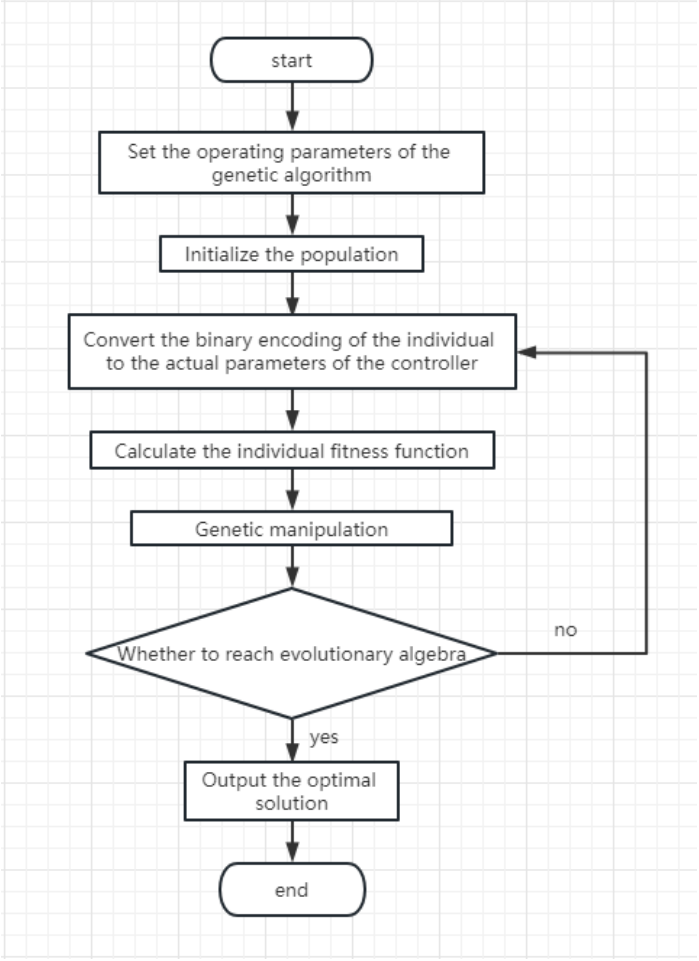


Fig. 4 Genetic algorithm flow chart (Photo/Picture credit: Original)

To begin, the genetic algorithm's operating parameters must be set. This crucial step establishes the framework within which the optimization process will unfold. Properly defining these parameters ensures that the algorithm operates effectively and efficiently. Following the parameter setup, the algorithm proceeds by initializing the population. This involves creating a group of potential solutions, referred to as individuals, which will undergo evolutionary changes to improve the controller's performance. Once the population is established, the binary encoding of each individual is converted

into the actual parameters of the controller. This step bridges the gap between the genetic algorithm's encoding scheme and the real-world parameters that define the controller's behavior. With the parameters defined, the next step is to calculate the fitness function for each individual. The fitness function quantifies how well each controller performs in addressing the given optimization problem. This assessment serves as the basis for selecting individuals for the next generation. Genetic manipulation is a pivotal stage in this process. It involves a series of operations, such as selection, crossover, and mutation, aimed at generating a new population of individuals with potentially improved controller parameters. These operations mimic the principles of natural selection and genetic recombination to enhance the population's overall quality. At this juncture, a crucial decision point arises whether the algorithm has reached the desired evolutionary algebra, meaning the convergence or optimization goal has been achieved. If the algorithm has not yet met the specified criteria, the cycle continues with genetic manipulation and fitness evaluation until the desired result is obtained.

4.2. Result and analysis

Figure 5 optimization concluded due to surpassing the predefined maximum number of generations.

```
>> GLN
Optimization terminated: maximum number of generations exceeded.

x =

    1.0056   53.0133
```

Fig.5 Maximum number of generations (Photo/Picture credit: Original)

Figure 6 is drawn by MATLAB to show the relation between fiber length and gain.

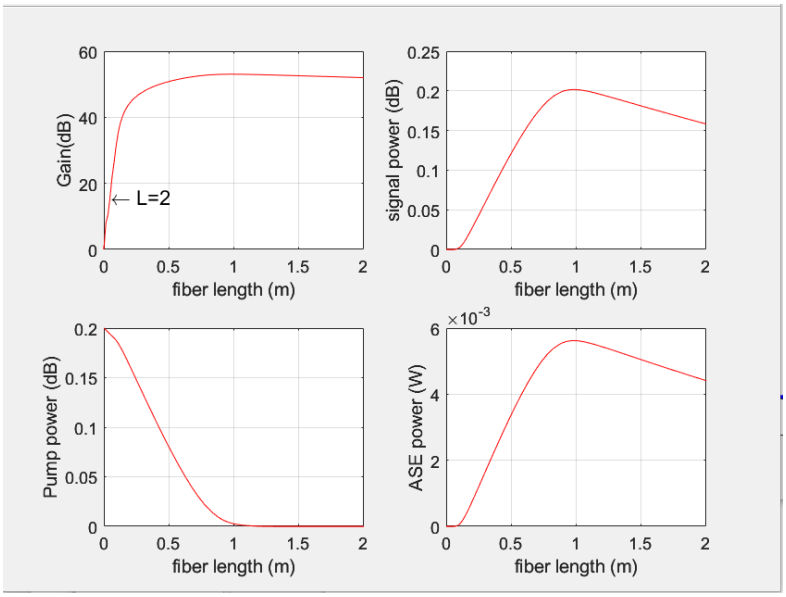


Fig. 6 Relation between fiber length and gain (Photo/Picture credit: Original)

ASE power peak and corresponding fiber length are obtained by genetic algorithm. It can be seen from the figure that the error between the result obtained by genetic algorithm and the result obtained by exhaustive method is within a reasonable range. By establishing the mathematical model of the image, we get the output spectral power of the spontaneous emission spectrum amplified by the fiber in the fiber length at 1.0m, the doping concentration is 6.18*10^25, the peak value is 5.85mw. The algorithm was optimized by genetic algorithm, and the output spectral power of the optical fiber

amplified spontaneous emission spectrum reached the peak value when the fiber length was 1.0056m and the doping concentration was 5.3*10^25, and the peak value was 5.6mw.

5. Conclsuion

The striking similarity between the two results serves to reinforce their mutual validity. This comprehensive study has yielded not only an optimal set of variable values but also the corresponding gains and output power levels. These findings hold profound significance for the advancement of optical fiber communication and the evolution of U-band optical fiber amplifiers. Our experimental evidence unequivocally demonstrates the efficacy of bismuth-doped fibers in amplifying signals within the U-band range. Furthermore, the optimization process has paved the way for achieving higher spectral peak power output. Consequently, these results establish a solid theoretical and experimental foundation for the design and production of U-band fiber amplifiers.

Nevertheless, it's essential to acknowledge that certain parameters in the experimental process may necessitate further optimization. The use of genetic algorithms, while powerful, can introduce some degree of error and may potentially lead to instances of local optimization. Additionally, variations may arise in three-dimensional point plotting, contributing to disparities in results. Hence, ongoing research and refinement are warranted to address these intricacies and enhance the overall robustness of the findings.

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