Simulation and Algorithm Optimization of a Bismuth-doped Optical Fiber Amplifier for the U-band (1650-1700 nm)

Xinyu Li*

School of Astronautics, Harbin Institute of Technology University, Harbin, China

*Corresponding author: 1910631238@mail.sit.edu.cn

Abstract. Based on the current situation of tightening capacity of fiber optic communication systems, it has become a necessity to find new technologies to expand the range of bands for commercial fiber optic amplifiers. With the research on ytterbium, neodymium, erbium, and thulium ion-doped optical fibers in recent years, the short wavelength region (1100-1550 nm) band of optical communication has been developed, but doped optical fiber amplifiers in the long wavelength region (1650-1700 nm) are still immature. The paper reports the simulation and algorithmic optimization of a bismuth-doped optical fiber amplifier. Referring to the realistic experimental parameters, the theoretical optimal gain of 54.2697 dB was obtained by setting the center wavelength of 1550 nm pump source, 200 mW pump energy, and the center wavelength of 1650 nm signal source. Further, an adapted fiber length of 1 m and a doping concentration of 4.0248×10^{24} m^{-3} for the approximate optimal gain were obtained by the optimization algorithm. Moreover, the differences between the two optimization algorithms are compared and the reasons for the differences in the results are briefly analyzed.

Keywords: bismuth-doped optical fiber amplifier, genetic algorithm, simulated annealing algorithm.

1. Introduction

Driven by the rapid development of new technologies such as edge computing, blockchain, augmented reality, and robotic process automation computing, various sectors of society have begun the transition from networked to intelligent. The network traffic, resulting exponential growth, has increased the demand for optical fiber data transmission capacity in the communication network [1,2], in order to avoid system overload and maintain stable data processing. This quest has inspired the exploration of fiber-optic communication technologies, for example, wavelength division multiplexing, higher-order modulation [3].

In 1985, a team from the University of Southampton, solved the problem of thermal quenching, which in turn led to the first invention of erbium-doped fiber optical amplifiers (EDFA). The EDFA, which has matured considerably over the past 30 years, is widely used as the dominant commercial optical fiber amplifier for 1530-1610 nm band [4]. However, compared to the entire low-loss spectral range of the fiber-optic communication band (1100-1700 nm), the bandwidth is severely limited by EDFA covered only 80nm, which is unable to meet the requirements of the era of high-speed and large-capacity communication transmission. As a result, there is great potential for finding new commercial transmission windows of fiber-optic communication [5], given the technological bottleneck of reducing fiber loss or increasing the response speed of electronic components.

Over decades, with the innovation of ion-doped optical fiber preparation technology, optical fiber amplifiers doped with lead, praseodymium, ytterbium, neodymium, erbium, thulium ions [6–9] have been able to achieve good signal gain in 1100-1650 nm band. However, each specific ion-doped amplifier can only achieve coverage in a small wavelength interval (no more than 200 nm), accompanied by the presence of defects such as low ion efficiency and poor mechanical strength, and there are even fewer solutions [10,11] for U-band (1650-1700 nm). It will be necessary to search for suitable doping materials to create optical fiber amplifiers that operate in longer wavelength (1650-1700 nm) regions.

Targeting the less explored U-band (1650-1700 nm), this paper reports the development of a bismuth-doped fiber amplifier simulation model. Using the conventional algorithm, a theoretical

maximum gain of 54.2697 dB was obtained. Without changing the pump source and signal source, the output characteristics were simulated and analyzed with respect to the structural parameters. In addition, to optimize the conventional computations, a genetic algorithm and a simulated annealing algorithm were used. It determined the appropriate doping concentration and the fiber length that were required to achieve a near-optimal solution gain. Moreover, the results obtained for the two different algorithms were compared and the reasons for the differences are briefly analyzed in terms of the algorithmic principles.

2. Simulation of the Bismuth-doped Optical Fiber Amplifier

2.1. Current Situation

Currently, there are two main types of doped optical fiber amplifiers for the U-band. One, the bismuth-doped germanium silicate-based fiber amplifier (BDFA) [10] can achieve a maximum gain of 23 dB and a minimum noise figure of ~7 dB at 1710 nm, with a center wavelength of 1550 nm and a pump power of 150 mW, under bi-directional pumping conditions. Another, the thulium-doped silica fiber amplifier (TDFA) [11] can achieve a small-signal gain of 29 dB and a minimum noise figure of 6.5 dB at a center wavelength of 1560 nm and a pump power of 200 mW, under bi-directional pumping conditions.

In comparison, the emission spectrum of thulium ions in silica fiber is from 1550 nm to 2200 nm with a center wavelength of 1850 nm, which makes it more suitable for fiber lasers in 2000 nm band rather than optical fiber amplifiers in 1650-1700nm. In addition, thulium-doped optical fiber amplifiers have a strong amplified spontaneous emission (ASE) signature in 1800-1900 nm wavelength region due to the high residence number inversion of Tm ions. As a result, for better gain results, it requires additional special equipment, such as erbium-thulium co-doped optical fiber, home-built ASE filter, which makes it difficult to achieve commercial penetration.

Another type, bismuth-doped optical fibers have become a top priority for the breakthrough of fiber amplification technology due to their unique optical properties. Previous studies showed that the spectral properties of bismuth-doped fibers, such as luminescence and absorption, can be altered by changing the chemical composition of the glass [12]. It lead that choosing the different glass composition for the fiber core [12-14] can make the bismuth-doped optical fibers to achieve signal coverage across the all fiber-optic communication band: refence emission spectral range: Bi: Al_2O_3-SiO_2 (900-1400 nm), Bi: P_2O_5-SiO_2 (1000-1500 nm), Bi: GeO_2-SiO_2 (1500-1850 nm). Therefore, in-depth research around the related technologies of bismuth-doped fiber amplifiers, such as bismuth-doped preparation technology, is highly commercially promising and valuable in the field.

Considering the continuity of future scientific work, researcher selected more promising bismuth-doped fiber amplifiers to accomplish all of the research tasks.

2.2. Parameters Setting

For the simulation experiments, researcher used the characteristic parameters of optical Fiber #232 fabricated by Modified Chemical Vapor Deposition (MCVD) technique. The core glass composition of optical Fiber #232 [10] is Bi: $50GeO_2$-$50SiO_2$, with the ~2 μm core diameter, a cutoff wavelength of 1.2 μm and numerical aperture (NA) ~0.45.

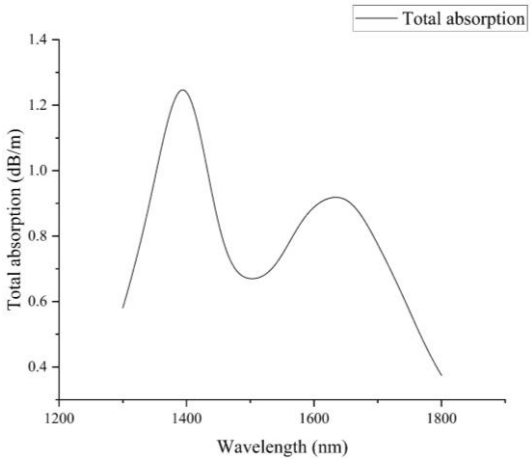
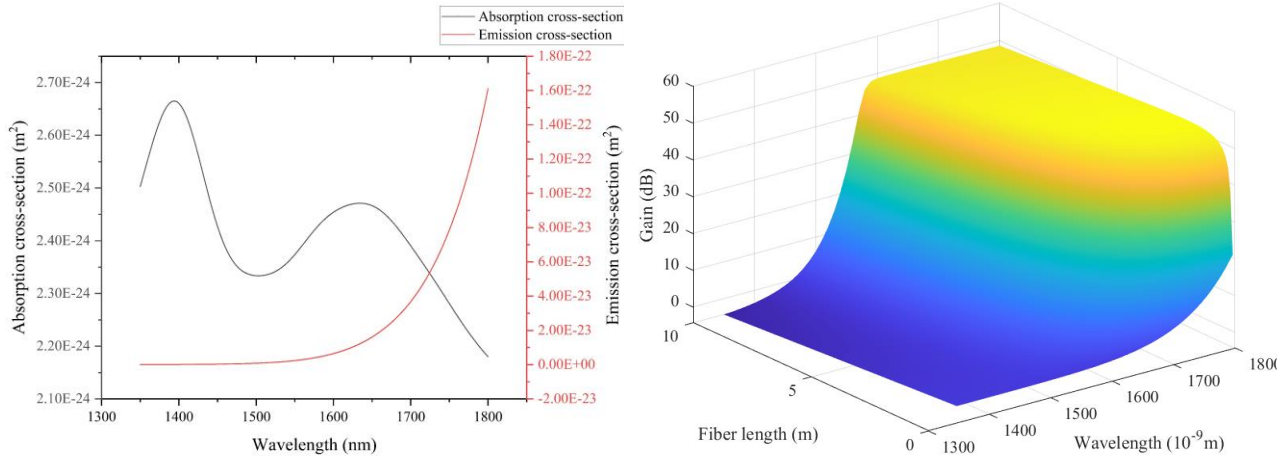


Fig. 1 Total absorption spectrum of Fiber #232 [10]

The absorption spectrum of optical Fiber #232 is shown in Fig. 1. Since the core glass composition of optical Fiber #232 is made by co-doping two ions, silicon and germanium, there are two absorption peaks, one at ~1400 nm and another at ~1650 nm. The peak at 1400 nm is the center of the bismuth activity associated with silicon. The peak at 1650 nm is the center of the bismuth activity associated with germanium.



A **b**

Fig. 2 Process calculation volume of Fiber #232

Fig. 2 (a) shows the cross section of the pump optical absorption and the signal optical emission versus signal wavelength curve. This was calculated from the absorption coefficients while the pump source was kept constant at 1550 nm. Through Fig. 2 (b), because it is for U-band optical communication, researcher set the signal light wavelength to 1650nm so that the fiber could work under the regional absorption peak to obtain a better quality signal output.

The pump light absorption cross section can be calculated from the bismuth doping concentration and the obtained absorption coefficient of Fiber #235 at 1650 nm of 0.92 dB/m. In turn, the signal light emission cross section can be calculated, in the pump light center wavelength of 1550 nm and the signal light center wavelength of 1650 nm. Doping concentration and fiber length were set as variables to explore their effects on gain. In the simulation, the previously mentioned emission cross section was kept constant. In fact, by changing the doping concentration, the fiber absorption coefficient also changes, and the cross-sectional area calculated by both are also affected. However, the material characteristic curve of bismuth ion absorption coefficient changing with doping concentration is difficult to obtain in the current research process, and the cross section has a small influence on the results. So this simulation, setting the cross-sectional area constant, used semi-quantitative parameters method.

2.3. Programing and Simulation Results

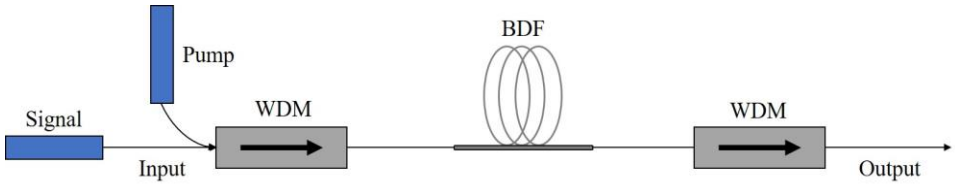


Fig. 3 Theoretical experimental setup of BDFA

Fig. 3 shows the theoretical experimental setup of the bismuth-doped fiber amplifier. For the study of 1650-1750 nm optical communication band, the bismuth-doped optical fiber amplifier can be regarded as a two-energy level system, which requires pump light around 1550 nm to excite the lower energy level particles to excited states. Therefore, for the pump source parameters, researcher refered to commercial laser diodes and set the wavelength maximum output power to 200 mW. Table 1 shows other relevant parameters used in the simulation process of this paper.

Table 1. Relevant parameters of simulation

Symbolic	Physical Parameter	Numeric	Units
λ_p	Pump optical center wavelength	1550	nm
σ_a	Pump optical absorption cross section	2.4689×10^{-24}	m^2
Γ_p	Pump optical power fill factor	0.4	-
λ_s	Signal light center wavelength	1650	nm
σ_e	Signal light emission cross section	1.6138×10^{-23}	m^2
Γ_s	Signal optical power fill factor	0.6	-
h	Planck constant	6.626×10^{-34}	J·s
C	Speed of light in vacuum	3×10^{8}	ms^{-1}

First, researcher wrote the rate equation and power equation to program the function. This was done to facilitate quick and direct calls of the algorithmic program later. Then, the main program used a double nested "for" loop structure to set the doping concentration in increments of 1×10^{22} m^{-3} from 1×10^{23} m^{-3} to 1×10^{25} m^{-3} and the fiber length in increments of 0.01 m from 0.1 m to 10 m.

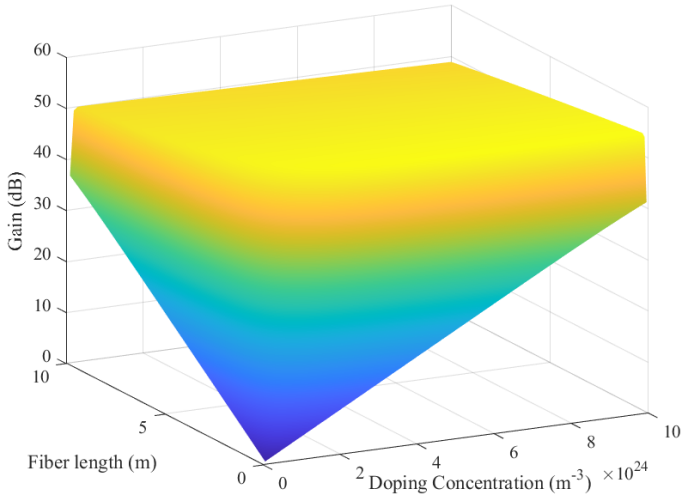


Fig. 4 Three-dimensional plot of gain versus doping concentration and fiber length

Fig. 4 shows the gain versus doping concentration and fiber length. It can be seen in the figure that each doping concentration corresponds to an optimal fiber length that maximizes the gain to ~50 dB. And among all the groups, there is one set of fiber length and doping concentration that enables the gain to reach the theoretical maximum value of 54.2697 dB. However, with the traditional algorithm, the time for Matlab to solve the simulation results using the ode45 function under the previous setup conditions was 1529.3711 s. (There is a difference in the computation time for different CPUs). It

seriously reduced the efficiency of scientific research and practical applications. Thus, it is necessary to carry out an optimization of the algorithm.

3. Algorithm Optimization

The exhaustive algorithm is the traditional algorithm that is used to find an optimal solution. In this process, based on the conditions of the question, the general range of the answer is determined, and all possible cases are checked one by one until all of them are verified. In general, using the exhaustive algorithm, the computation of simple equations does not take much time. However, when equations become complex and a greater accuracy is required, such as nonlinear equations, complex functions, and multi-loop nested calculations, the time of the traditional computational methods will increase significantly. In this way, the use of optimization algorithms can facilitate faster and higher quality practical applications of scientific theories.

In this paper, researcher used genetic algorithm [15,16] and simulated annealing algorithm [17] to optimize the model respectively. In the genetic algorithm, the 50 population size, the 200 max generations, the 0.8 crossover fraction, the 1×10^{-6} constraint tolerance were set. In the simulated annealing algorithm, the 100 initial temperature, the 600 max function evaluations, the 1000 max stall iterations, the 1×10^{-6} function tolerance were set.

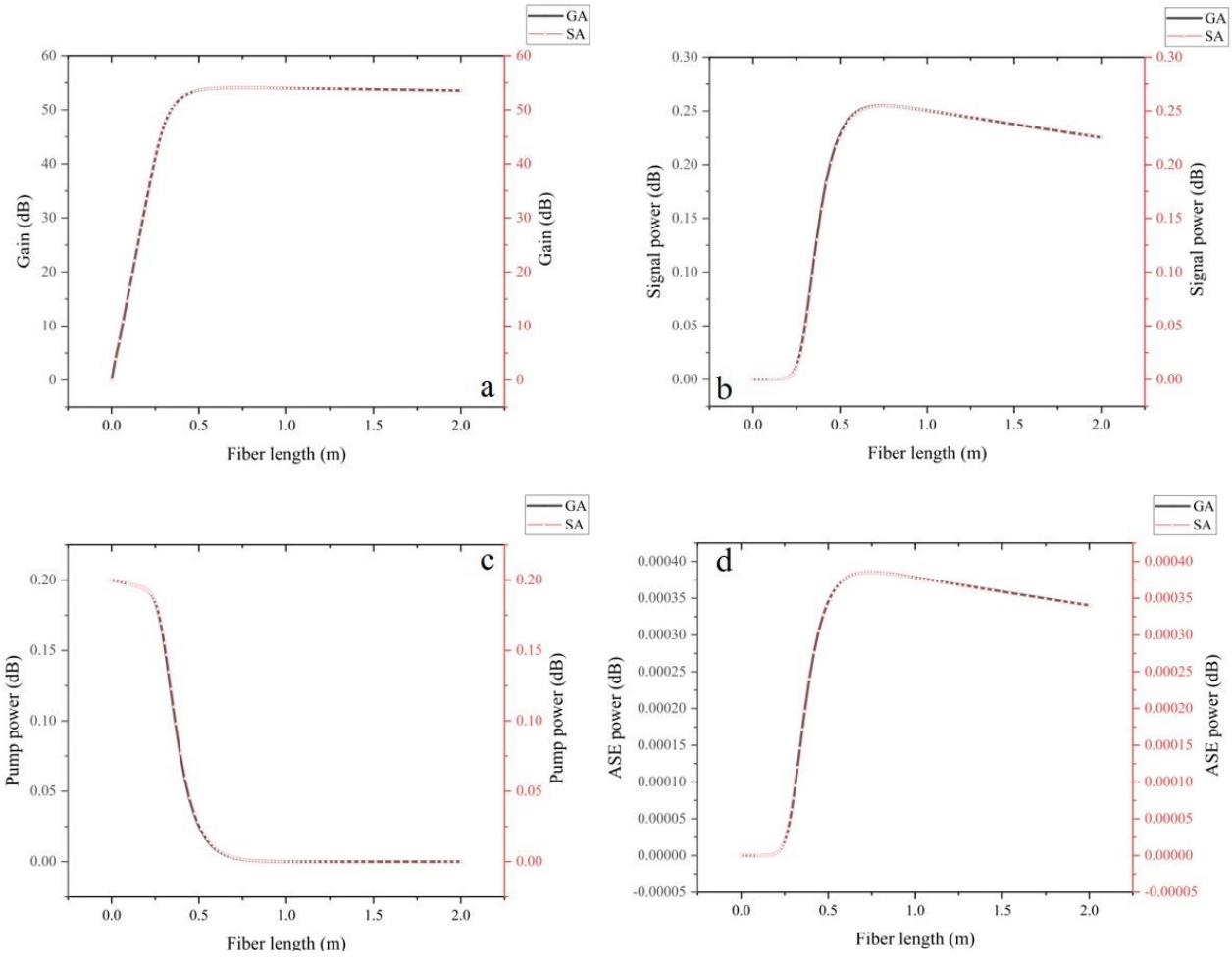


Fig. 5 Characteristics of the BDFA

Fig.5 shows the characteristics of the BDFA under the optimization algorithm. In this case, bismuth ion doping concentration is fixed. The results of the genetic algorithm are slightly different from those of the simulated annealing algorithm in terms of accuracy values. At large scales, the two curves go in the same direction, almost overlapping. The data from each can confirm the accuracy of the other.

Fig. 5 (a) shows the curve of gain with fiber length. It can be seen that the maximum gain is achieved at fiber length 0.7 m, which is smaller than the adapted fiber length 1 m obtained earlier. This is due to the fact that the optimum gain is also affected by the doping concentration. Under the combined work of the two variables, the image peak point and the optimal fetch point are shifted. From Fig. 5 (b, c), the signal power increases with the fiber length, and decreases slowly after the peak until it levels off, while the pump power intensity decreases significantly with the increase of the fiber length until the energy is completely exhausted. Therefore, the higher pump power can meet the longer distance optical signal transmission, and choose the appropriate fiber length can achieve gain maximization and optical signal energy transmission maximization, to meet the needs of high-quality signal transmission.

The ASE power increases with increasing fiber length as shown in Fig. 5 (d). It indicates that at higher gains, there is more ASE noise that cannot be ignored. In high gain amplifiers, spontaneous radiation amplification is an effect that must be eliminated, limiting the gain of a single stage fiber amplifier to 40-50 dB. Therefore, to achieve higher gain, the length and doping concentration can be optimized or means such as multi-stage amplification can be used.

Table 2. Results of running the optimization algorithm

Symbolic	Genetic algorithm	Simulated annealing algorithm
Optimal Gain (dB)	53.9876	53.9871
Doping concentration (%)	4.0248×10^{24}	4.2970×10^{24}
Fiber length (m)	1.0004	1.0000
Run-time (s)	7.661982	5.352701

The optimization results of genetic algorithm and simulated annealing algorithm are shown in Table 2. It is easy to see that the gains obtained by the optimization algorithms are all lower than those calculated by the traditional method, and the error between the optimization algorithms and the traditional method is no more than 0.5%. This is because the optimization algorithms find the near-optimal solution [16]. The use of optimization algorithms to find approximate optimal solutions is acceptable in real production processes, as compared to traditional algorithms that are almost impossible to find optimal solutions in complex problems.

It can also be seen that both algorithms run in close time and both are more than ten times faster than the traditional algorithm. Specifically, the genetic algorithm provides more accurate optimal gains and the simulated annealing algorithm provides faster optimization results. As the nature of the simulated annealing algorithm is exhaustive and comparative, and the genetic algorithm is based on exhaustive and comparative with the addition of population crossover and mutation, which makes the results more accurate but also increases the computation time.

4. Conclusion

Through the theoretical analysis and simulation experiments, a bismuth-doped fiber amplifier with Bi:$50GeO_2$-$50SiO_2$ as core material prepared by MCVD process, by 1550 nm pumping wavelength, was achieved with the optimal gain of 54.2697 dB signal output in the U-band (1650-1700 nm), under the state of 200 mW pumping energy. The near-optimal solution has an adapted fiber length of 1.0004 m and a doping concentration of 4.0248×10^{24}.

The relationship graphs between gain, signal power, pump power and fiber length obtained by the algorithm are analyzed and summarized to provide theoretical guidance for the field application of bismuth-doped optical fiber amplifiers according to the different mission requirements-distance to the target site, signal strength requirements, etc.

By comparing two optimization algorithms, it can be found that both of them can do model optimization and improve the efficiency of the best gain calculation. However, to achieve the same level of accuracy, the Simulated Annealing algorithm will take more time to complete. This is because that the simulated annealing algorithm needs to be set to a reasonable enough annealing time length

to ensure that the algorithm is able to process all solutions, i.e. cover all peaks. In fact, the genetic algorithm also has the hidden problem that it can only find the local optimal solution. However, in this study, there was no need to worry about the defects of the genetic algorithm because the 3D images of gain, doping concentration, and fiber length were obtained first, and it was clear that there was no presence of multiple wave peaks.

For the U-band (1650-1700 nm), a longer wavelength band in fiber optic communications, bismuth-doped germanium silicate fiber optic amplifiers using the optimization algorithm can be efficiently used to obtain good signal gain, and can be expected to be commercially mass-produced as the concentration of bismuth doping is further increased through technological process optimization.

References

[1] Shevchenko N A, Nallaperuma S, Savory S J. Maximizing the information throughput of ultra-wideband fiber-optic communication systems[J]. Optics Express, Optica Publishing Group, 2022, 30(11): 19320–19331.

[2] Fei Y. Characteristics of fiber optic communication technology and its applications [J]. Integrated Circuit Applications, 2023:240-241.

[3] Eid M M, Seliem A S, Rashed A Z, et al. High speed pulse generators with electro-optic modulators based on different bit sequence for the digital fiber optic communication links[J]. Indones J Electr Eng Comput Sci, 2021, 21: 957–67.

[4] Puttnam B J, Rademacher G, Luís R S. Space-division multiplexing for optical fiber communications[J]. Optica, Optica Publishing Group, 2021, 8(9): 1186–1203.

[5] Kaushik P, Singh D P, Rajpoot S. Fibre optic communication in 21 st century[A]. IEEE, 2020: 125–129.

[6] Meirui F, Yuyang Y, Shuang Z, Xiaolan S. Fiber optic amplifier based on the combination of mesoporous silica and lead sulfide quantum dots [J]. Optical Communication Technology, 2021, 45(11): 59–62.

[7] Li J, Rui S, Jiuru H, Jing H, et al. Realization of 714 W visible to near-infrared supercontinuum spectrum laser output in a fiber amplifier [J]. China Laser,2022, 49(9): 205–206.

[8] Feng W. Doped fiber amplifier development and its applications [J]. China New Communications, 2018: 80.

[9] Kangyu R, Wei S, Yating Z, Janquan Y. High-temperature aging output power of Erbium-Ytterbium co-doped fiber amplifiers [J]. Journal of Optics, 2022: 23–30.

[10] Firstov S V, Alyshev S V, Riumkin K E, et al. A 23-dB bismuth-doped optical fiber amplifier for a 1700-nm band[J]. Scientific Reports, 2016, 6(1): 28939.

[11] Li Z, Jung Y, Daniel J M O, et al. Exploiting the short wavelength gain of silica-based thulium-doped fiber amplifiers[J]. Optics Letters, 2016, 41(10): 2197.

[12] Bufetov I, Dianov E. Bi-doped fiber lasers[J]. Laser physics letters, IOP Publishing, 2009, 6(7): 487.

[13] Khegai A, Afanasiev F, Ososkov Y, et al. The influence of the MCVD process parameters on the optical properties of bismuth-doped phosphosilicate fibers[J]. Journal of lightwave technology, IEEE, 2020, 38(21): 6114–6120.

[14] Xiaoke Y, Le H, Shaoke L, et al. Bismuth-doped phosphate fiber enables O+E band amplification [J]. China Laser, 2023: 1–12.

[15] Mirjalili S, Mirjalili S. Genetic algorithm[J]. Evolutionary Algorithms and Neural Networks: Theory and Applications, Springer, 2019: 43–55.

[16] Katoch S, Chauhan S S, Kumar V. A review on genetic algorithm: past, present, and future[J]. Multimedia tools and applications, Springer, 2021, 80: 8091–8126.

[17] Delahaye D, Chaimatanan S, Mongeau M. Simulated annealing: From basics to applications[J]. Handbook of metaheuristics, Springer, 2019: 1–35.