Design and output spectral peak power optimization of E-band fiber-amplified spontaneous emission spectra

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Abstract. Fiber optic amplifiers will improve the power of signals propagating in optical fibers, usually using doped ions as amplifiers. The bismuth-doped fiber amplifier can amplify the current E-band signal light, which is less used, and provide a solution to enhance the communication transmission capacity.In this essay, Matlab is used as a research tool, and the bismuth-doped fiber amplifier is selected, and the energy level system is a three-energy levelThe 830 nm-wavelength pumping source amplifies the signal light at 1390 nm. The bismuth-ion velocity and power amplification propagation equations are established, and the amplified spontaneous radiated optical power is calculated. Amplified spontaneous radiation optical power, and through the calculation and simulated annealing algorithm to derive the amplified spontaneous radiation optical power amplification with the doping concentration and fiber length spectrum, in the fiber length of 3.3m and the number of doped particles of 9.1 * 10^25 to obtain the maximum optical power of 7.95*10^-9W.

Keywords: Fiber optic amplifiers, E-band, bismuth-doped.

1. Introduction

With the maturity of Dense Wave Multiplexing (DWDM) and the use of optical amplifiers, the limitations of transmission distance attenuation have been solved and the communication efficiency is also greatStill, the demand for fiber optic communication transmission capacity with the geometrical growth of the amount of information is also. At present, bait-doped fiber amplifiers work in the 1550nm operating window, covering only the C and L bandsSo far, there is still no optical amplifier that can directly amplify the entire optical fiber low-loss transmission window. To solve this problem, the bismuth-doped fiber amplifier with ultra-broadband near-infrared optical radiation characteristics with its excellent performance is believed to be the key to the future of high-speed communication, bismuth ion luminescence range can cover the entire fiber optic communication window, and through the light-wave multiplexing technology can be achieved through the communication effect of a substantial increase.

In 1999, K. Murata et al. discovered the near-infrared luminescence of bismuth ions for the first time [1]. 2003, Japanese scientists Y. Fujimoto et al. achieved optical amplification near 1.3 μm by using an 800 nm laser to pump a glass doped with Bi ions, proving the feasibility of bismuth-doped optical fiber optical amplification [2]. 2005, Dvoyrin et al. from Russia adopted an improved chemical vapor deposition technique (CVD) to achieve optical amplification[3]. In 2005, Dvoyrin et al. in Russia successfully prepared the first Bi doped aluminosilicate fiber by using the modified chemical vapor deposition technique (MCDV)[3], with a half-height and full width of the emission spectrum of 200 nm and an emission cross section as high as 6*10^-21 (cm)^2 [3], which opens up a new direction of the use of bismuth-doped fibers as optical amplifiers.In 2007, Dvoyrin et al. in Russia prepared a single-mode quartz optical fiber that is simultaneously bismuth-doped and aluminium-doped and used this doped fiber as a gain amplifier [4]. This doped fiber as a gain medium to build a laser, and finally used 1070 nm as the pump light, successfully achieving the laser output at 1160 nm, the following year, Dianov et al. also doped P, Ge in the core quartz components to produce phosphorus germanium silicate quartz fiber, change the fiber medium to create a P_2 O_5-SiO_2, GeO_2-SiO_2 based bismuth-doped fiber and in the 1300nm~1470nm, 1430nm~1495nm for laser

output and optical amplification [5]. Firstov realized bismuth-doped fiber lasers with multiple wavelengths, up to 2W, and conversion efficiencies in the range of 14-25% [6], and several scholars next investigated the bismuth-doped fiber lasers with even higher conversion efficiencies [7][8]. Young- Seok Seo et al. utilized the 850 nm and 850 nm fibers to create bismuth-doped fibers with. Seok Seo et al. excited a bismuth-doped quartz fiber using 810 nm pump lightThey achieved a gain coefficient of 0.038 dB/mW at 1308 nm [9], and in 2012, Y. Luo et al. used 830 nm pump light to excite a bismuth-doped fiber and achieved optical amplification in the range of 1350 nm-1470 nm [10]. in 2015, Firstov et al. obtained bismuth-doped and chromium fibers with bismuth content between 100 ppm-300 ppm, and achieved a laser output of 1700 nm using 1565 nm as the pump light [11]. Currently, domestic and foreign research is focused onto achieve different wavelengths of light amplification and thus expand the scope of application of bismuth-doped fiber. Although the prospect of bismuth-doped fiber is very broad, the nature of the near-infrared radiation center of bismuth element, how to improve the performance of bismuth-doped fiber, and how to efficiently achieve the amplification of the whole communication window and many other issues still need further research.

In this essay, mainly design the E-band bismuth-doped fiber amplifier, calculate the spontaneous radiated optical power in the whole band and use the simulated annealing algorithm to simplify the calculation to derive the maximum output spectral peak power of the spontaneous emitted optical power with the length of the fiber and the concentration of doping, which will provide a reference for the practical application of bismuth-doped fibers in the future.

2. Organization of the Text

2.1. Introduction to fiber optic amplifiers

Fiber amplifiers are mainly divided into nonlinear fiber amplifiers and doped fiber amplifiers, nonlinear fiber amplifiers are mainly divided into Raman fiber amplifiers and Brillouin fiber amplifiers, doped fiber amplifiers are mainly doped with rare earth particles, but also with metal ions.

2.1.1 Composition and workflow of pump light

The doped fiber amplifier is mainly divided into the following parts: pump light source, optical coupler, optical isolator, doped fiber, optical filter. At work, the pump light coupled into the doped light through the optical coupler, and the ion pumped to the excited state, the ion in the excited state will rapidly produce spontaneous radiation jump to the substable state, the substable state of the longer life and the formation of the number of particles with the base state inversion. At this time, coupled into the signal light at the same time in the role of the excited radiation will produce with their own frequency and direction of the photons are identical, so that the optical power amplification. The role of the optical isolator is to prevent the generation of echo reflection, ensure unidirectional transmission of light, and prevent light into the optical transmitter from affecting the work. The role of the optical filter is to prevent the introduction of spontaneous radiation caused by the system noise.

2.1.2 Pump structure of dopant fiber amplifier

(1) Co-directional pumping structure

Pump light and signal light are coupled into the doped fiber at the same end, the two light transmission direction is the same, the initial pump light power is higher, a large number of particles reversed, resulting in a high gain of the signal light. However, as the transmission distance becomes larger and the pump light attenuation, the signal light power at the end of the fiber gain saturation phenomenon.

(2) Bidirectional pumping structure

Two pumping light sources in the doped fiber at both ends of the pump, so as to solve the problem of uneven pumping optical power at both ends of the fiber, is the whole fiber ends of the number of substable particles at a high level, so that the signal optical gain is maintained at a very high level.

2.2. Models and methods

2.2.1 Three energy systems

When select 830nm pump light, the energy level structure of bismuth ion can be summarized as a three-level structure[4], Figure 1 represents a three-level system, E1, E2, E3 represent the ground state energy level, excited state energy level, substable state energy level, respectively. bismuth ion electrons will be absorbed and excited from E1 to E3 under the action of pump light, and at the same time the electrons in E3 will spontaneously jump to the top of E2, and then arrive at the bottom of E2 by a certain amount of time. At the same time, the electrons of E3 will spontaneously jump to the top of E2 and reach the bottom of E2 after a certain period, and then the electrons at the bottom of E2 will jump to E1 through spontaneous radiation.The signal light will be absorbed and jumped to the bottom of E2 from E1 under the action of pump lightThe electrons at the bottom of E2 will fall to E1 after generating the excited radiation or spontaneous radiation.

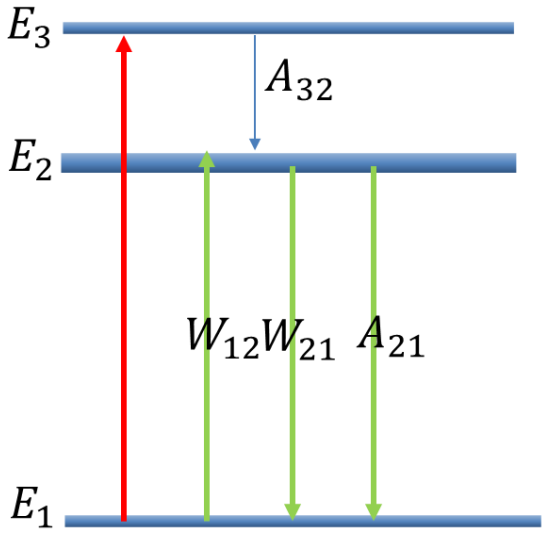


Fig. 1 Three energy system

2.2.2 Rate equations

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

$$\frac{\partial N_2(z)}{\partial t} = W_{12}(z)N_1(z) - W_{21}(z)N_2(z) - A_{21}N_2(z) + A_{32}N_3(z) \quad (2)$$

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

$$N = N_1(z) + N_2(z) + N_3(z) \quad (4)$$

$$W_p(z) = \frac{\sigma_{13}P_P(z)}{h\nu_{13}A_{eff}}\ W_{12}(z) = \frac{\sigma_{12}(\nu_{12})P_S(z)}{h\nu_{12}A_{eff}}\ W_{21}(z) = \frac{\sigma_{21}(\nu_{21})P_S(z)}{h\nu_{12}A_{eff}}\ A_{eff} = \pi r^2 \quad (5)$$

The equation describes the derivative of the number of particles at each energy level concerning time, which gradually tends to a steady state with time and eventually to 0. The number of particles at each energy level can be obtained by calculating the above system of equations. Table 1 describes the energy level system parameters

Table 1. Energy level system parameters

parameters	account
W_P	pump optical absorption rate
W_{12}	signal light absorption rate
W_{21}	signal light stimulated emission rate
A_{32}	radiation-free jump rate

2.2.3 Power propagation equation

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

$$\frac{dP_s(z)}{dz} = \Gamma_s(\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - a_s)P_s(z) \tag{7}$$

$$\pm\frac{dP_{ase}(z)}{dz} = \pm\Gamma_{ase}[\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - a_s]P_s(z) \pm 2\sigma_{21}N_2(z)h\upsilon\Delta\upsilon \tag{8}$$

$$G\left(P_p(z), P_s(z), N_2, N_1, z\right) = \frac{P_s(z)}{P_S(0)}(100\%) \tag{9}$$

$$G\left(P_p(z), P_s(z), N_2, N_1, z\right) = 10 * log10(\frac{P_s(z)}{P_s(0)})(db) \tag{10}$$

The power propagation equation is the variation of pump power, signal power, ASE, (P_p, P_S, P_ase) power with propagation length. Table 2 describes the energy level system parameters

Table 2. Energy level system parameters

parameters	account
P_p	pump power
P_S	signal power
P_{ase}	ASE
α	Loss factor of fiber optic material
$\Delta\upsilon$	Frequency half-height full width
Γ_p	pump optical overlap integral factor
Γ_s	Signal light overlap integration factor
Γ_{ase}	overlap integration factor for spontaneously radiating light
σ_p	pump optical absorption cross section
σ_{21}	Signal light emission cross section
σ_{12}	Signal light absorption cross section
h	Planck's constant

2.2.4 Simulated annealing algorithm

Simulated annealing algorithm is a stochastic optimization method proposed by Metrospolis et al. in 1953 to simulate the annealing process in a thermodynamic system [12], annealing refers to the process of heating a material above its melting point and cooling it to form a crystalline structure [13], in the algorithm, the atoms have several different states, and each state corresponds to different energies, and the algorithm treats the objective function as a system in which the state energies, after cooling thermal equilibrium to obtain the solid state and the global optimal solution corresponding to the problem. In each iteration, the current solution has the probability to be replaced by the new solution, so the algorithm effectively avoids falling into the local optimal solution.
The general flow of the SA algorithm is as follows.

Step 1: Initial temperature T0, termination temperature Tmin. Maximum number of iterations L, temperature reduction rate α.

Step 2: Randomly generate a random connection s, and calculate the objective function L(s) corresponding to s.

Step 3: Perturb s to generate a domain solution s', select a new solution s* in the domain and judge it, the criterion is Metrospolis criterion

Step 4: Calculate the fitness function C(s*) and C(s) for both the previous solution and the new solution and make a difference, if the difference is negative, the objective function becomes smaller and the solution is accepted. If the difference is positive, it means that the function value increases, then P=e^((C(s*)-C(s))/T) is used as the basis for judging whether to accept s*, and T is the current temperature.

Step 5: Judge whether the termination temperature Tmin or the maximum number of iterations L is reached, if not satisfied, then repeat steps 3, 4 and 5.

Step 6: Output the optimal solution.

2.2.5 Use of tools and solving methods

In this essay, the simulation process is carried out using Matlab, which first yields the number of particles in each energy level using the associative rate equations, which are brought into the power propagation equation and the differential equations about the power propagation equation are solved to derive the individual gains.

Overlapping Integral Factor Equation:

$$\Gamma_p = 1 - e^{-2\frac{r^2}{w^2}} \tag{11}$$

$$w = r(0.65 + \frac{1.619}{V^{\frac{3}{2}}} + \frac{2.879}{V^6}) \tag{12}$$

V is the normalized frequency, which is given by:

$$V = \frac{2\pi r}{\lambda}(n_1{}^2 + n_2{}^2)^{1/2} \tag{13}$$

The data Γp=0.856 and Γs=0.514 calculated by Chen M et al [14].

Based on the absorption spectrum [14], the absorption and emission cross sections can be calculated. The process of selecting 830 nm as the pump light wavelength is as follows:

$$ab(x) = t(/m) \tag{14}$$

$$\sigma_{ab} = \frac{ab(x)}{N_{Bi}} \tag{15}$$

Also calculated by Chen M et al [14], N(Bi) = 2.84 * 10^25.

$$\sigma_{em} = \sigma_{ab}(v) \times e^{\frac{\varepsilon_0 - hv}{\kappa T}} \tag{16}$$

Where ε0 represents the photon energy corresponding to the peak of the absorption spectrum, i.e., the photon energy at 1390 nm. The absorption and emission cross section spectra were finally obtained.

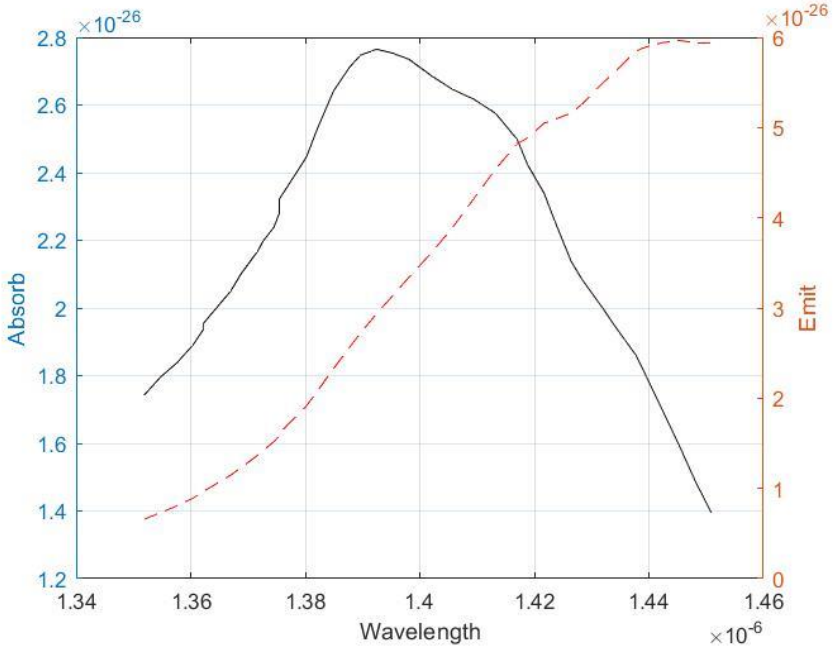


Fig. 2 Absorption and Emission cross-section frequency

2.3. Results and discussion

In this essay, we use 830nm pump light pumping, bismuth-doped fiber amplification of the E-band (1350nm ~ 1450nm) from Fig.2, take the central wavelength of 1390nm as the signal light, after the emission and absorption cross-section spectra can be obtained as the emission cross-section is 1.91*10^-26/m^2, absorption cross-section is 2.44*10^-26/m^2. The parameters used in the research process are shown in the Table3 [14].

Table 3. Parameter value used in the research process

parameters/unit	value
P_p/mW	200
P_S/dbm	-30
α/m	6.514417229*10-4
$\Delta v_{ASE}/nm$	2
Γ_p	0.856
Γ_s	0.514
σ_p	1.21*10-25
σ_{21}/m^2	2.44*10-26
σ_{12}/m^2	1.91*10-26

After solving the power propagation equation the following spontaneous radiant optical power gain spectrum with doping concentration and ray length is obtained

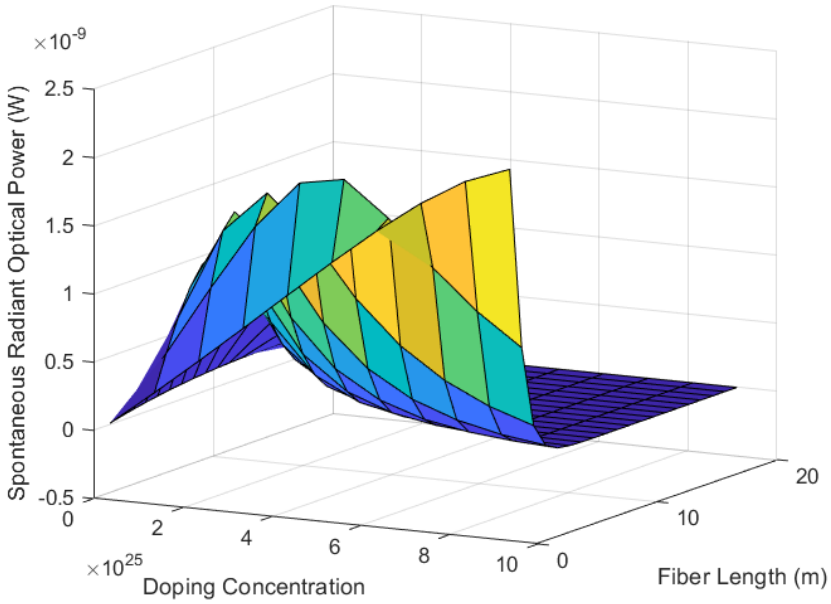


Fig. 3 Spontaneous radiant optical power vs. Doping concentration vs. Fiber length

The bismuth doped fiber amplified spontaneous radiation optical power with doping concentration and fiber concentration spectrum is obtained from Fig.3 The number of doped particles is set from 0 to 10^26, and the fibre length is set from 0 to 20 m. The maximum optical power is 2.18*10^-9 W when the fiber length is 1 m and the number of doped particles is 9.1*10^25, and the spontaneous radiated optical power tends to be 0 when the fiber length is larger than 10 m. From the figure, we can also derive that when the length of the light ray is fixed, the higher the doping concentration the higher the amplified spontaneous radiated optical power. The higher the peak value of the amplified spontaneous radiation optical power.

Simulation algorithm optimization:

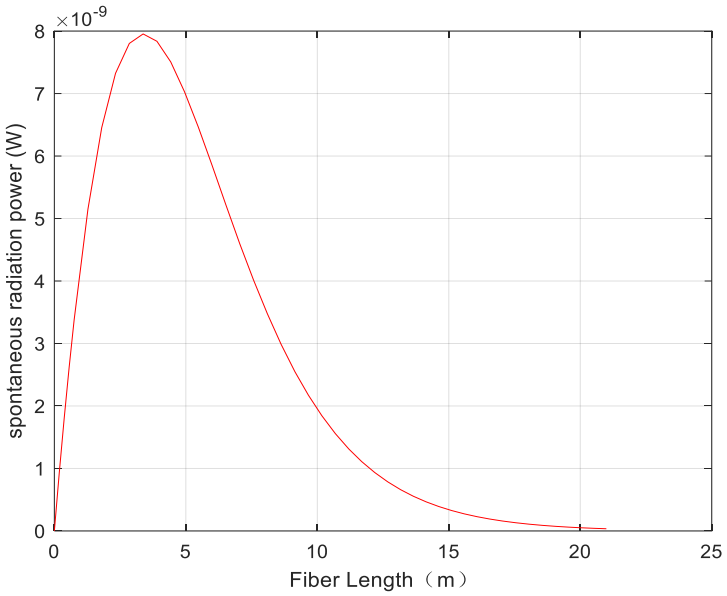


Fig. 4 Variation of spontaneous radiation intensity with fiber length

According to the simulated annealing algorithm from Fig.4 it is derived that the amplified spontaneous radiated optical power is 7.95*10^-9W at the fiber length of 3.3m when the dopant particle number interval is set from 1*10^25 to 3*10^25.

3. Summary

In this essay, designed an E-band bismuth-doped silicate fiber amplifier with a pump light of 830nm and a power of 200mW obtained the amplified spontaneous radiation optical power spectrum of bismuth-doped fibers with the change of the doping concentration and the length of the light. It is observed that the maximum gain of 2.18*10^-9W was observed in the light's length when the light was 1m. The number of doped particles was 9.1*10^25, and the maximum gain of 2.18*10^-9W was observed in the light's length when the fiber's length was 3.3m and the number of doped particles was 9.1*10^25. When the number of doped particles is 1*10^25~3*10^25, the amplified spontaneous radiation optical power is 7.95*10^-9W when the length of the fiber is 3.3 m. In this paper, the simulated annealing algorithm has a small number of iterationsand a numerical error, so there is an error in the maximum amplified spontaneous radiation optical power obtained from the exhaustive, and the parameter value is only the value of the Chen M experimentsThe calculation is also subject to an error. In this study, only the simulated annealing algorithm is used, and other algorithms can be used to compare the gain effect. There is still room for improvement in the construction of the physical model, and a double-pumped light source can be used to enhance the gain effect. Doped fiber optic amplifiers have a wide range of applications in the future, and one needs fiber optic amplifiers to reduce the loss of signals during transmission. There are many optical bands for transmitting signals, and each band has a corresponding doped fiber amplifier. However, there is less research on E-band doped fiber amplifiers, and there is not much exploration and demand for E-band, so the research and application of E-band doped fiber amplifiers should have a larger development space and market in the future.

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