

# Design of O-Band Bismuth-doped Fiber Amplifier (BDFA) and Optimization of Genetic Algorithm

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**Abstract.** In this study, the o-band (1260nm-1360nm) fiber amplifier is designed and optimized based on the characteristics of bismuth-doped materials and the theoretical study of its spectrum. Taking the use of full-band fiber amplifiers as an example, considering that there is still some bandwidth unused in current fiber optic communications, this paper aims to design o-band fiber amplifiers with better gain and higher efficiency. By comparing the spectral properties of different materials, we chose bismuth-doped materials as the gain medium and three-level systems as the model. Based on this model, we established the rate equation and the power propagation equation in the steady state to analyze the effects of fiber length, doping concentration and pump power on the gain of the fiber amplifier. We used a genetic algorithm to optimize the fiber length and doping concentration. Then we designed a center wavelength of 1310nm and a gain factor greater than 26.1Db under the condition of pump light with a wavelength of 830nm and a power of 200mW.

**Keywords:** O-Band, Bismuth-doped Fiber Amplifier, Genetic Algorithm.

## 1. Introduction

Due to the increasing demand for bandwidth in recent years, the use of new frequency bandwidth is a research direction on improving data transmission efficiency in recent years. It is particularly important to study o-band fiber amplifiers [1]. Based on the application of wavelength division multiplexing (WDM) technology, including data-center interconnection and intracity internet traffic, the o-band fiber amplifier is studied to make data transmission on channels with different bandwidths more efficient [1]. Moreover, various factors, including the manufacturing techniques for active fibre and their complex applications, the cost and dimensions of the finished devices, all impact fiber amplifiers [1]. WDM and complex modulation modalities reduce the receiver's power per channel and sensitivity, so optical amplification is required [2]. In addition, the o-band has more research potential because its emission wavelength is near the optical fibre's zero-dispersion wavelength ( $\lambda_0$ ) and does not require optical or electronic dispersion compensation [2]. Semiconductor optical amplifiers (SOAs) can enhance o-band signals, but self-gain and cross-gain modulation introduce significant distortion [3]. SOAs have also been shown to magnify multiple dispersion and expand the channels [4]. Still, SOAs are not suitable for transmitting strength modulation formats such as PAM-4, which work close to zero scattering ( $\lambda_0$ ) [2]. Among the many doped materials, non-silicon body glass is often needed for a Praseodymium Doped Fibre Amplifier (PDFA) having a bandwidth of 1280nm to 1320nm, which increases their cost [5]. Ultradry silica fiber has been able to cover signal light with a central wavelength of 1250-1700 nm, and has a significant low loss window in this range [6]. The signal light passing through the o-band of bismuth-doped glass tends to be strong and broad [6]. Double-doped fibers containing bismuth ions have made good progress such as Bi-doped aluminosilicate fiber laser action at 1150-1300nm [7] and 1443-1459nm [8]. As a new metal ion gain medium, bismuth-doped material can enable the applied fiber amplifier to have an extremely wide bandwidth from 1000nm to 1700nm [9]. In its effective bandwidth of o-band, we will design the pump wavelength based on the energy level structure of the bismuth ion and our target amplification wavelength. Use MATLAB to build the velocity and the power transmission equations. Thus, the

relation of the BDFA's gain spectrum to the fibre length and the dopant concentration of the BDFA in a given O band is derived, and the parameters are optimized by genetic algorithm to maximize the peak gain.

## 2. Experimental and theoretical analysis

### 2.1. Variation of fiber gain under different conditions

#### 2.1.1. Energy levels

Since this research focuses on the O-band (1260nm-1360nm), The signal optical wavelength is set at 1310nm, which is the center wavelength, for evaluation of a bismuth-doped fibre amplifier (BDFA). Based on the energy band schematic diagram of  $Bi^{+}$  as shown in Fig. 1., the pump light wavelength is set to 830nm, corresponding to the three-level system. This research will analyze the correlation between gain magnitude, fiber length, and doping concentration using MATLAB.

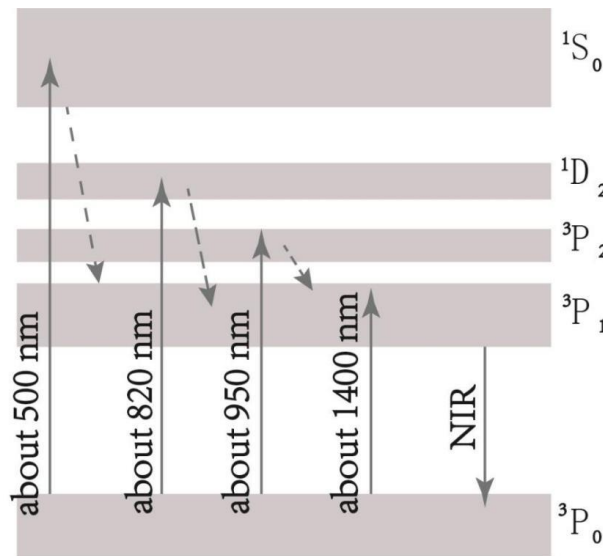


Figure 1. Schematic diagram of  $Bi^{+}$  energy level band

#### 2.1.2. Model-gain

To get the gain magnitude, the expressions for the number of  $Bi^{+}$  on each energy level ( $N_1, N_2, N_3$ ) in steady state should be represented first. The following rate equations are the bulk density of ions ( $N/m^3$ ) on each energy level changing with time. Then using the symbolic computation to derive from the rate equation set in MATLAB. The steady state means there is no  $Bi^{+}$  transfer between different energy levels which can be represented by defining equations (1), (2), (3) equals to zero. The relevant parameters are illustrated on Table 1. The generated numbers of  $Bi^{+}$  are shown in equation (9), (10), (11).

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

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

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

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

$$W_P(z) = \frac{\sigma_{13}P_P(z)}{h\nu_{13}A_{eff}} \quad (5)$$

$$W_{12}(z) = \frac{\sigma_{12}(v)s(z)}{hv_{12}A_{eff}} \quad (6)$$

$$W_{21}(z) = \frac{\sigma_{21}P_s(z)}{hv_{21}A_{eff}} \quad (7)$$

$$A_{eff} = \pi r^2 \quad (8)$$

$$N_1 = \frac{A_{21} \cdot A_{32} \cdot N + A_{32} \cdot N \cdot W_{21}}{W_{13} \cdot W_{21} + A_{21} \cdot A_{32} + A_{21} \cdot W_{13} + A_{32} \cdot W_{21} + A_{32} \cdot W_{13} + A_{32} \cdot W_{21}} \quad (9)$$

$$N_2 = \frac{N \cdot (A_{32} \cdot W_{12} + A_{32} \cdot W_{13})}{W_{13} \cdot W_{21} + A_{21} \cdot A_{32} + A_{21} \cdot W_{13} + A_{32} \cdot W_{21} + A_{32} \cdot W_{13} + A_{32} \cdot W_{21}} \quad (10)$$

$$N_3 = \frac{N \cdot W_{13} \cdot (A_{21} + W_{21})}{W_{13} \cdot W_{21} + A_{21} \cdot A_{32} + A_{21} \cdot W_{13} + A_{32} \cdot W_{12} + A_{32} \cdot W_{13} + A_{32} \cdot W_{21}} \quad (11)$$

**Table 1.** Symbols used in rate equations

Parameter	Symbol
Planck constant ( $j \cdot s$ )	$h$
Ion number of ground state level	$N_1$
Ion number of metastable state level	$N_2$
Ion number of excited state level	$N_3$
Pump light absorption rate ( $s^{-1}$ )	$W_p$
Signal light stimulated emission rate ( $s^{-1}$ )	$W_{12}$
Signal light absorption rate ( $s^{-1}$ )	$W_{21}$
Nonradiative transition rate ( $s^{-1}$ )	$A_{32}$
Radiative transition rate ( $s^{-1}$ )	$A_{21}$
Fiber core radius ( $m^2$ )	$r$
Cross-section area of fiber core ( $m^2$ )	$A_{eff}$
Pump light absorption cross-section ( $m^2$ )	$\sigma_{13}$
Signal light absorption cross-section ( $m^2$ )	$\sigma_{12}$
Signal light radiation cross-section ( $m^2$ )	$\sigma_{21}$
Pump light frequency (Hz)	$v_{13}$
Signal light frequency (Hz)	$v_{12}$
Signal light frequency (Hz)	$v_{21}$

The expressions for the number of  $Bi^+$  on each energy level in steady state ( $N_1, N_2, N_3$ ) will be used to construct the power propagation equations which define the pump power, signal power and ASE power changing with the propagation distance, shown in the equation (12), (13), (14). The relevant parameters are illustrated in Table 2.

$$\frac{dP_P(z)}{dz} = -\Gamma_P(\sigma_P N_1(z) + \alpha_a)P_P(z) \tag{12}$$

$$\frac{dP_S(z)}{dz} = \Gamma_S[\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_S]P_S(z) \tag{13}$$

$$\frac{dP_{ase}(z)}{dz} = \pm \Gamma_{ase}[\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_S]P_S(z) \pm 2\sigma_{21}N_2(z)h\nu\Delta\nu \tag{14}$$

$$\Delta\nu = \frac{c}{\lambda^2}\Delta\lambda \tag{15}$$

$$\Gamma = 1 - \exp\left(-2\frac{r^2}{w^2}\right) \tag{16}$$

$$w = r\left(0.65 + \frac{1.619}{V^{\frac{3}{2}}} + \frac{2.879}{V^6}\right) \tag{17}$$

$$V = \frac{2\pi r}{\lambda}(n_1^2 - n_2^2)^{\frac{1}{2}} \tag{18}$$

$$G(P_P(z), P_S(z), N_2, N_1, z) = 10 * \log_{10}\left(\frac{P_S(z)}{P_S(0)}\right) \text{ (dB)} \tag{19}$$

**Table 2.** Symbols used in power propagation equations

Parameter	Symbol
Light field simulation radius (m)	$w$
Fiber normalized frequency (Hz)	$V$
Pump power (W)	$P_P$
Signal power (W)	$P_S$
ASE power (W)	$P_{ase}$
Pump overlapping integration factor	$\Gamma_P$
Signal overlapping integration factor	$\Gamma_S$
ASE overlapping integration factor	$\Gamma_{ase}$
Fiber length loss factor ( $m^{-1}$ )	$\alpha$
Full width at half maximum (Hz)	$\Delta\nu$
Gain (dB)	$G$

Since the computation of gain magnitude (equation (16)) uses the power expression (P(z)), not its derivative, the ode.45 function is applied to get the differential equation for  $\frac{dP(z)}{dz}$  in MATLAB.

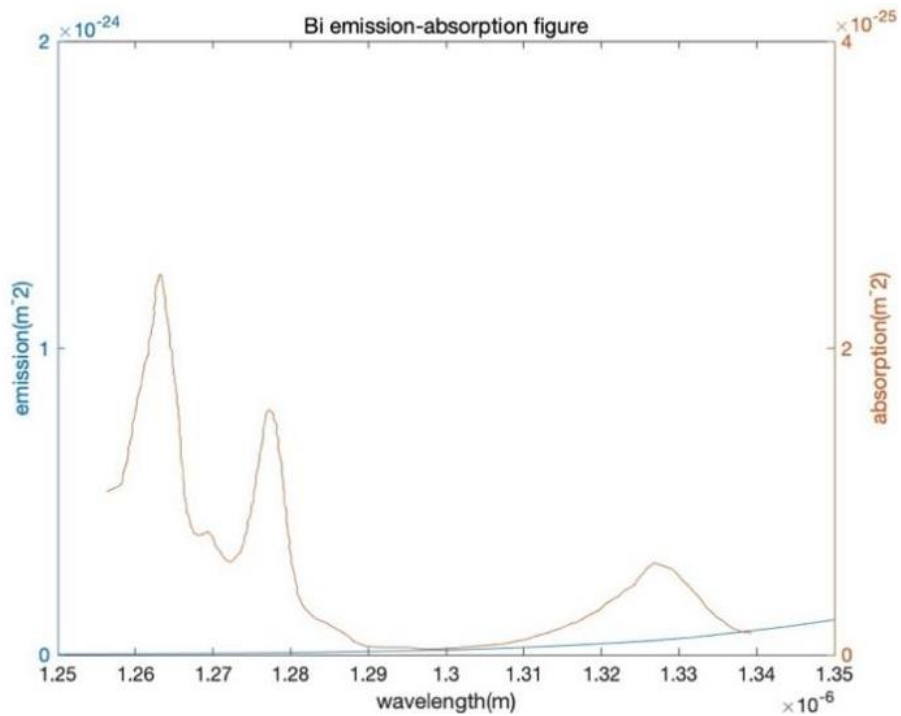
The absorption cross-section parameter ( $\sigma$ ) is measured by referring to the absorption spectrum of bismuth-doped optical fiber [10]. The coordinates on the curve are extracted by using the GetData software and then import into MATLAB which can be used for computing the absorption and emission cross section vector, see the example of the calculation. At last, the figure depicting the relationship between the wavelength and absorption/emission from 1250nm to 1350nm is plotted in MATLAB (Fig. 2).

Example:

$$absorption\ coeff. \left(\frac{dm}{m}\right) = \frac{absorption\ coeff.}{10\log_{10}^e} = absorption\ coefficient(m^{-1}) \tag{20}$$

$$\sigma_{12} = \frac{absorption\ coeff.(m^{-1})}{N_{Bi}(m^{-3})} \tag{21}$$

$$\sigma_{21} = \sigma_{12} \cdot e^{\left(\frac{\epsilon_0 - h\nu}{KT}\right)} \tag{22}$$

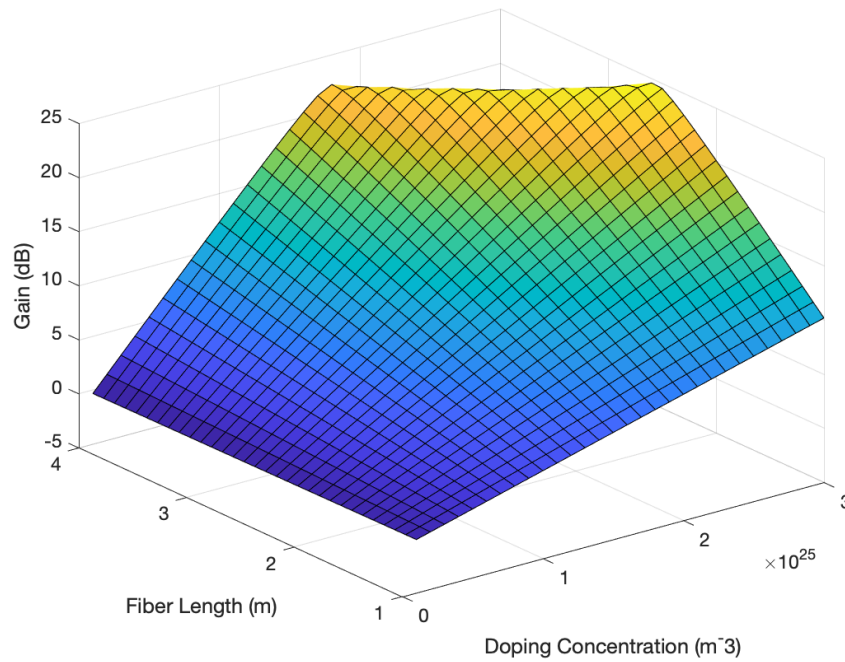


**Figure 2.** The relation of  $Bi^+$  ion emission and absorption cross section parameters with wavelength variation

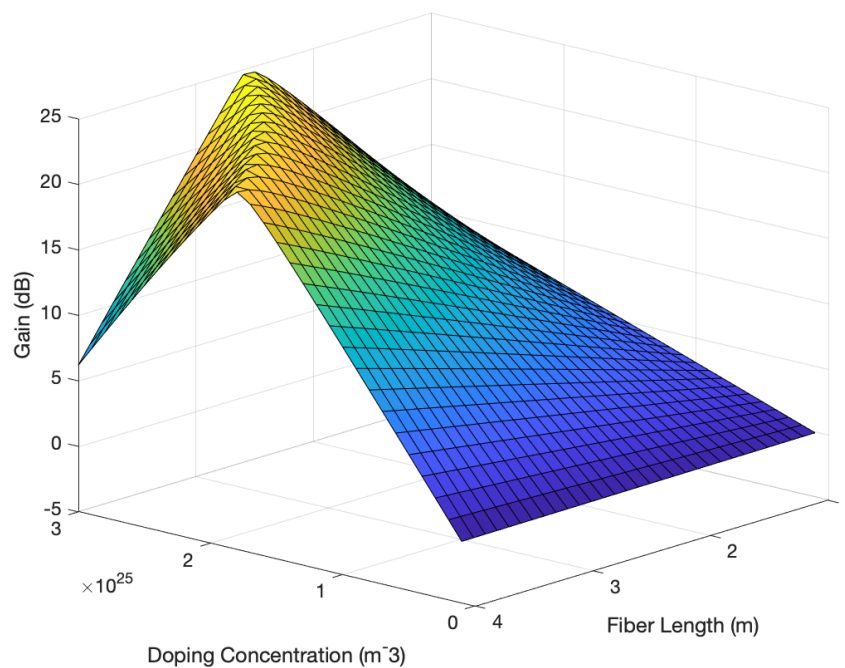
We define the range of fiber length is from 1m to 4m and the range of doping concentration is from  $1 \times 10^{25}m^{-3}$  to  $3 \times 10^{26}m^{-3}$ . Then we iterated the value of fiber length and doping concentration by using nested for loops in Matlab and then got the gain value. Finally, the correlation between the gain magnitude, fiber length, and doping concentration is demonstrated in 3D. All the values of the parameter are illustrated in Table 3.

**Table 3.** Parameters used for simulation

Parameter	Symbol	Value
Pump light wavelength (nm)	$\lambda_{swl}$	830
Signal light wavelength (nm)	$\lambda_{pwl}$	1310
Pump light power (mW)	$P_p$	200
Signal light power (mW)	$P_s$	$10^{-3}$
ASE power (mW)	$P_{ase}$	0
Fiber loss factor (dB/m)	$\alpha$	0.1
Nonradiative transition rate ( $s^{-1}$ )	$A_{32}$	10000
Radiative transition rate ( $s^{-1}$ )	$A_{21}$	2000
Pump light absorption cross-section ( $m^2$ )	$\sigma_{13}$	$2.4745 \times 10^{-24}$
Signal light absorption cross-section ( $m^2$ )	$\sigma_{12}$	$2.0283 \times 10^{-25}$
Signal light emission cross-section ( $m^2$ )	$\sigma_{21}$	$2.0283 \times 10^{-25}$
Fiber core radius (m)	$r$	$3 \times 10^{-6}$



**Figure 3.** The Relation of Gain, Dopant Concentration and Fibre Length in 3D Visualization (front view)



**Figure 4.** The Relation of Gain, Doping Concentration and Fibre Length in 3D Visualization (side view)

Figure 3 and Figure 4 illustrate the relation of gain, dopant concentration and fibre length, the doping concentration and fiber length. The maximum gain can be obtained by using the “max” function in Matlab, which is 26.1dB.

## 2.2. Genetic algorithm

Through MATLAB's 3D visualization, it is observed that there exists a certain relationship between the gain, fiber length, and doping concentration. This study uses a genetic algorithm based on the research data to optimize this process and obtain more precise values for the fiber length and doping concentration that yield maximum gain. A genetic algorithm is a powerful optimization and search technique inspired by natural selection and evolution in biology. It's used to search for optimum or near optimum solutions to difficult problems by imitating the principles of evolution.

In the study, two variables, namely fiber length and doping concentration, are defined. The respective ranges for these variables are given as constraints, where the fiber length ranges from 1m to 4m, and the doping concentration ranges from  $1 \times 10^{25}m^{-3}$  to  $3 \times 10^{26}m^{-3}$ . After running the optimization, the results show that the maximum gain of 26.3 dB is achieved. This result is in good agreement with the values obtained from the three-dimensional images which is 26.1 dB, further validating the accuracy of the experimental conclusion.

### 3. Conclusion

The purpose of this research is designing an O-band (1260nm-1360nm) bismuth-doped fiber amplifier (BDFA) and evaluate its performance by investigating the correlation between the gain magnitude and the fiber length and doping concentration using 3D demonstration and genetic algorithm in MATLAB. We applied the 3-level system for BDFA and set the wavelength to 1310nm, pump light wavelength to 830nm, to analyze their correlation and find the maximum gain. Combining the conclusions drawn from the three-dimensional visualization with those derived from the genetic algorithm leads to the following observations. Modification of fibre length and dopant concentration can improve the gain of fibre efficiently. Moreover, the gain of fiber amplifier increases as the fibre length and the concentration of dopants increases. Initially, the gain of BDAF is strengthened as the fiber length and dopant concentration are raised. After a certain point, it reaches its peak value and starts to decrease, and for excessive lengths, the gain becomes negative. For the range of the fiber length which is from 1m to 4m, and the range of doping concentration which is from  $1 \times 10^{25}m^{-3}$  to  $3 \times 10^{26}m^{-3}$ , the maximum gain obtained from the 3D demonstration is 26.1dB. The peak gain is further enhanced to 26.3dB by applying the genetic algorithm for gain optimization. We anticipate that the use of additional BDFA as fiber amplifiers will facilitate the expansion of transmission range.

### Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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