Design and Optimization of Bismuth-Doped Fiber Amplifiers in the L+ Band (1600-1650nm)

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Abstract. This study investigates the design and optimization of bismuth-doped fiber amplifiers in the L+ band (1600-1650nm). The L+ band, as a promising optical communication frequency range, demands high-performance fiber amplifiers. However, existing amplifier technologies exhibit limitations in the L+ band, leading researchers to explore bismuth-doped fiber amplifiers to overcome these constraints. This paper first introduces the working principles and relevant background knowledge of L+ band fiber amplifiers. Subsequently, a comprehensive investigation of the gain characteristics of bismuth-doped fiber amplifiers in the L+ band is conducted. Based on theoretical models, a series of optimization designs, including adjustments of bismuth doping concentration, fiber length, and pump power, are carried out to achieve optimal performance. The proposed optimization scheme demonstrates significant performance improvements through MATLAB simulations and a genetic optimization algorithm, achieving high gain and excellent characteristics in the L+ band.

Keywords: bismuth-doped fiber amplifier, L+ band, MATLAB simulations, design and optimization, genetic algorithm.

1. Introduction

1.1. Introduction to fiber optic amplifiers

Fiber-optic amplifiers are used in fiber-optic communication lines to achieve an all-optical amplifier that amplifies signals, and are optical amplifiers that use doped optical fibers as the gain medium. The fiber optic amplifier compensates for the attenuation of the optical signals transmitted in the fiber optic so that the optical signals can be transmitted over long distances. In addition to this, the fiber optic amplifier simultaneously greatly improves the performance of the fiber optic transmission system and makes the system easy to integrate, enabling all-optical network communications. The EDFA Erbium-doped fiber amplifier the traditional optical-electronic-optical relay, which can amplify the multi-channel optical signal in a fiber at the same time and reduce the cost of optical relay It has the advantages of high gain and low noise, so it is successfully used in dry-dense, wavelength-division multiplexing. Optical communication system. However, with the rapid development of computer networks and other new data transmission services, long-distance optical fiber transmission, the system demand for communication capacity is growing rapidly [1].

1.2. Classification of fiber optic amplifiers

Erbium-Doped Fiber Amplifier (EDFA): EDFA is one of the most common and widely used fiber optic amplifiers. It uses erbium-doped fiber as the amplification medium and pumps light to excite the erbium-doped ions for signal enhancement. EDFA is mainly used to enhance signals in fiber-optic communication systems, and generally operates at wavelengths near 1550 nm.

Ytterbium-Doped Fiber Amplifier (YDFA): YDFA uses ytterbium-doped fiber as the amplification medium. Ytterbium ion-doped fiber amplifiers enable broadband amplification and are suitable for optical communication systems and lasers applications.

Erbium-Ytterbium-Doped Fiber Amplifier (EYDFA): EYDFA combines the advantages of erbium and ytterbium ions to provide high gain and broadband characteristics. It is widely used in long distance fiber optic communication systems.

Bismuth-Doped Fiber Amplifier (BDFA): The BDFA uses bismuth-doped fiber as the amplification medium and provides large gain in the near-infrared band. It has high gain, low noise and broadband characteristics for optical communication and sensor applications.

Thulium-Doped Fiber Amplifier (TDFA): TDFA uses thulium-doped fiber as the amplification medium. It provides gain in the near-infrared region in the wavelength range of 1900-2100 nm and is suitable for high-speed optical communications and lasers, among other applications.

The used fiber optic amplifiers are shown in Fig.1 [2].

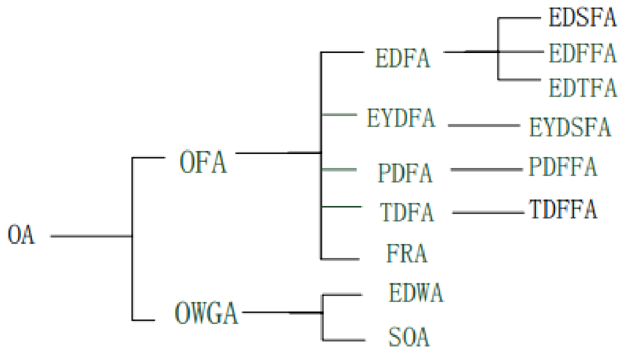

Fig.1 Commonly used fiber optic amplifiers[2].

1.3. Selection of fiber optic amplifiers

The signal is attenuated when it moves along a standard single mode fibre (SSMF). The signal will be distorted at a data rate above 10GB/s because of the influence of color dispersion and polarization pattern dispersion. In order to compensate for decay, an OFA is used. Introducing OFAs into a system results in problems like amplification, self-emission, and ASE noise. The ASE noise is progressively accumulated as the signal crosses a plurality of OFAs.

In order to make full use of the broad bandwidth of S (short: 1460-1530nm), C (center: 1530-1565nm) and L (length: 1565-1625nm), the bandwidth of the fibre is extremely broad. So it's very important to design an optical fiber amplifier for amplification of a signal on a fibre.

To make use of such a huge bandwidth, DWDM is adopted. Amplifiers are designed according to their particular applications, for example long distance underwater or land communications, multi-connection short distance networks, or metro facilities.

1.4. Selection of materials

The luminescence performance of Bi 3 + doped mercury ion materials with NS2 electron configuration has been investigated in recent years. Bi3+ has a ground state of 1s 0, and its excited states are 3p, 3p, 1, 3, 2 and 1 p 1. Due to the fact that the transition from the ground-state energy level 1s 0 to 3p 0 and 3p 2 is prohibited, it is possible to see only the transition from the ground state energy level 1 to the excited state (3p 1) and 1p-1 [3].

Bismuth ions have many properties.

1. Bismuth, with an atomic number of 83, belongs to the fifth main group of elements. Due to its low electronegativity, the lack of effective electron shielding results in the outer 6s and 6p orbitals being prone to electron loss, forming positively charged ions. As a result, bismuth ions are highly sensitive to their surrounding environment, the matrix of materials, and network structures. Moreover, its d-d transitions contribute to the existence of various oxidation states for bismuth ions.[4] Bismuth ions can form many different valence states, such as - 3, - 2, -1, 0, +1, +2, +3 and +5, etc., +3 is the stable state.

2. Bismuth ions can exist as cluster ions in some acid molten salts and molecular crystals

3. The outer electrons of bismuth ions have spin-orbit coupling characteristics, enabling bismuth ions to emit light in different substrates.

4. The energy level structure of bismuth ions is relatively stable. Unlike other ions, the level structure undergoes minimal changes with variations in the crystal field. As a result, the fluorescence spectral lines of these ions are comparatively stable. [5]

Since bismuth ions have the above properties, they are promising in the field of ultra-wideband optical fiber amplifiers and can meet our wavelength range in the L+ band, so we choose bismuth ions as the reference object. [6]

1.5. Energy level jumps

Our experiments mainly involve Bi3+, so I will focus on Bi3+. The ground state of Bi3+ is 1S0, and the excited states are 3P0, 3P1, 3P2, and 1P11S0→3P0. The 1S0→3P1 electron jump is forbidden. When the spin orbitals between 3P1 and 1P1 are coupled, the 1S0→3P1 electron jump is capable of occurring.1S0→3P2 electron jump is spin-forbidden. However, after coupling of asymmetric lattice vibrational modes, this electron jump is also allowed to occur.1S0→1P1 electron jump is allowed to occur. The emission spectral band of Bi3+ originates from the 3P1→1S0 electron jump. In this case, the 3P0→1S0 electron transition usually occurs at low temperatures. The positions of the emission peaks of Bi3+ are different due to the influence of different matrix crystal fields.
Bi3+ contains exactly the band we studied, which is the reason why we chose Bi3+ for our experimental sampling.[6]

1.6. Rate equations

$$\begin{gathered}\frac{\partial N_1(z)}{\partial t} = -\left[W_p(z) + W_{12}(z)\right]N_1(z) + A_{21}N_2(z) + W_{21}(z)N_2(z)\\ \frac{\partial N_2(z)}{\partial t} = W_{12}(z)N_1(z) - W_{21}(z)N_2(z) - A_{21}N_2(z) + A_{32}N_3(z)\\ \frac{\partial N_3(z)}{\partial t} = W_p(z)N_1(z) - A_{32}N_3(z)\\ N = N_1(z) + N_2(z) + N_3(z)\end{gathered} \tag{1}$$

Where. $\mathrm{W_p, W_{12}, W_{21}, A_{32}, A_{21}}$ are pump light absorption rate, spontaneous emission light absorption rate, spontaneous emission light excited radiation rate, no radiative excursion rate, and radiative excursion chance, respectively. (In units of s)-1

1.7. Power propagation equation

$$\begin{gathered}\frac{dP_p(z)}{dz} = (-\sigma_p N_1(z) - \alpha_a)P_p(z)\\ \frac{dP_s(z)}{dz} = [\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_s]P_s(z)\\ \frac{dP_{ase}(z)}{dz} = [\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_s]P_{ase}(z) + \sigma_{21}N_2(z)h\upsilon\Delta\nu\\ P_s(z) = f(P_p(0), P_s(0), N, z)\end{gathered} \tag{2}$$

Where α, Δv are the loss coefficient of the fiber material (/m) and the frequency half-height full width (Hz), respectively.

2. Literature review

Ref. [7] A summary of the different types of fibre amplifiers applied to the optical fibre communication. This paper deals with their operating principles, building methods and major features. It is emphasized that the selection of amplifiers depends on the application's particular needs. A cost effective multiplex and laser transmitter is adopted for metro/access networks that usually have a high loss. For EDFA, the distance and velocity of the repeater is currently 80-100 kilometers and 40gb/s. Meanwhile, they are 100 – 160 km and 160 – 320 Gb/s respectively for RA. [7].

Ref. [8] The key role of optical amplifiers in modem fibre communication systems and their importance in expanding the capacity of WDM designs is emphasized.

One of the main features of the paper is the possibility of extending the broadcasting spectrum to meet this increasing demand. Because of an Erbium Doped Fibre Amplifier (EDFA) amplifying band, a limited spectrum region is presently used for transmission by high-bit-rate communication systems in the range from 1530 to 1610 nm.

There is, however, a spectrum in the region from 1300 to 1500 nm in which silicon based fibres have an optical loss below 0.4 dB/km. Unfortunately, this range currently lacks efficient optical amplifiers. This paper proposes that developing a Bi - doped (Bi - doped) fibre can provide a basis for a highly effective Bismuth-doped Fiber Amplifier (BDFA) suited to this spectrum area and can significantly improve the transfer rate of optical fibre communication systems. [8].

Ref. [9] proposes a way to respond to the rapidly growing worldwide demand for information. Developing BDFAs has the potential to re-define spectrum areas that can be utilized effectively and thus improve total capacity.

It is possible to access the second communication window and generate a visible light source through a dual-doped fibre laser and an amplifier. At last, the paper deals with Bi - doped fibre used in pulsed laser, and presents a mode locked Bi - doped fibre laser working at 1440 nm, which shows the broad range of applications and possible progress in optics and other areas.

This work seems to contribute significantly to the current research on the application of bidoped fibres in a wide range of optical techniques, especially in lasers and amplifiers [9, 10].

3. Results and discussion

At 2000 nanometers, the absorption coefficient of bismuth trioxide is 1.0 per m. Its molecular weight is 465.96 grams per mole. Its density is 1.5 grams per cubic centimeter. The mass percentage of bismuth trioxide is 1 per cent. Afterwards the number of moles of bismuth trioxide is obtained by multiplying the density by the mass percentage divided by the number of molecules of bismuth trioxide. Afterwards, the molecular number of bismuth trioxide is obtained by multiplying by Avogadro's constant. We calculated the absorption cross section of bismuth ions to be 2.58*10^-25, and the emission cross section value and absorption cross section value are approximated to be about 2.58*10^-25. According to the topic setting and literature review, we set the pump power to be 200mW, the pump wavelength to be 2000nm, and the signal light wavelength to be 1620nm. The parameters are shown in Table 1.

Table 1. Calculate the date

Pump power (W)	Pump wavelength (m)	Signal light wavelength (m)	Emission cross-section (m2)	Absorption cross-section (m2)
0.2	2000e-9	1620e-9	2.58e-25	2.58e-25

Next, we use MATLAB simulation to get the following two figures. The 3D image of the gain spectrum with the fiber length and doping concentration is shown in Fig.2. We can get the maximum gain of 46dB at the doping concentration of 1.95*10^25 and the fiber length of 4.9 m. The optimization result of the Genetic Algorithm is shown in Fig.3. We can get the maximum gain of 41dB at the fiber length of 4.23 m.

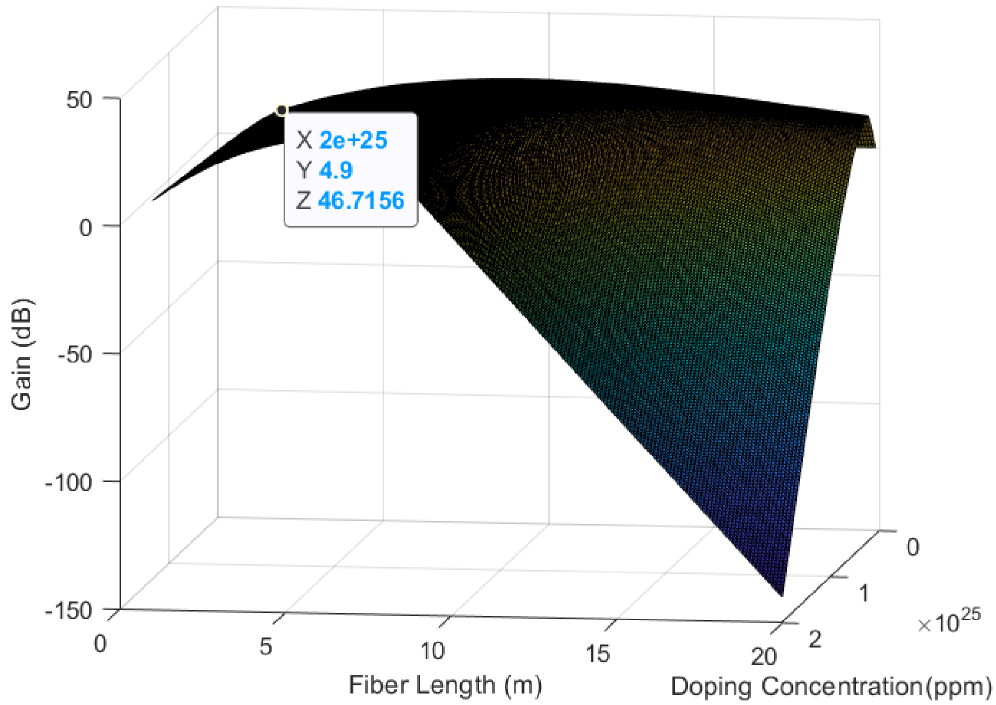

Fig.2 The 3D image of the gain spectrum with the fiber length and doping concentration

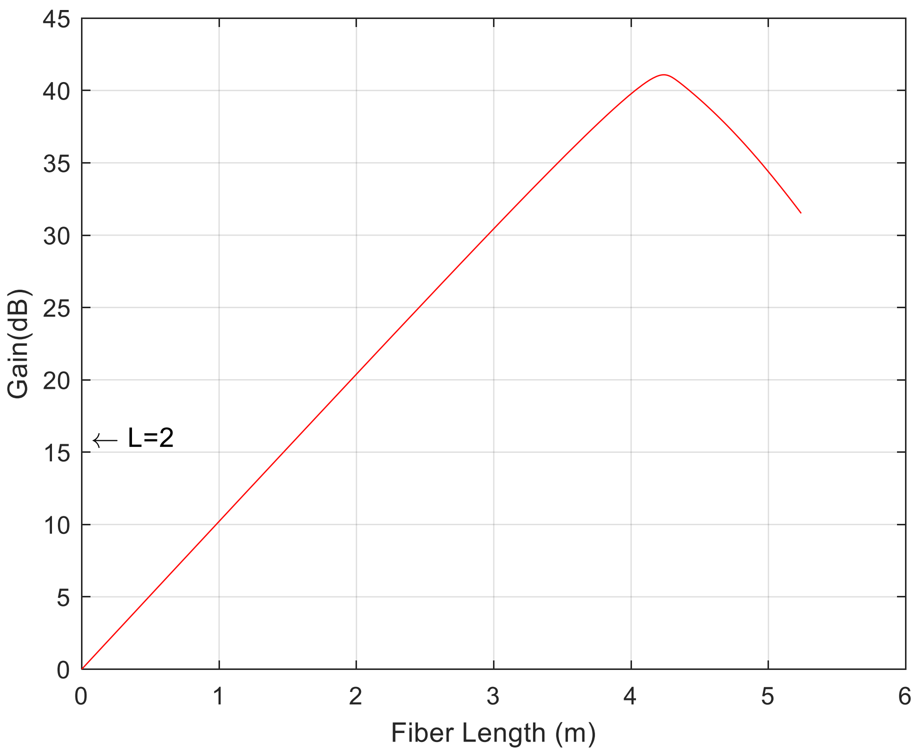

Fig.3 The optimization result of the Genetic Algorithm

4. Conclusion

A genetic algorithm (GA) is applied to optimize the optical fibre length and the dopant density in an L + Band Optical Amplifier in order to achieve maximum maximum gain. Based on the analysis of GA experiments, we conclude that:

Firstly, an L + - band optical amplifier is designed, and the GA is used to optimize it. Experiments indicate that GA is able to obtain the optimum solution. Through optimization of fibre length and dopant density, the maximal peak gain is obtained.

Next, it is discovered that the optical fibre length and the dopant concentration affect the maximum gain of the FBG. The maximum gain is higher with the increase of fibre length, but it begins to decline when the fibre is longer than some extent. When the dopant concentration is higher, the gain will be reduced as well. Thus, it is necessary to take into account both fibre length and dopant density in the design and optimization of L + band optical amplifier.

In the end, it is proved that the optimization of the fibre length and the dopant density in the L-band optical amplifier can greatly increase the peak gain. This research will be helpful to optimize the L + - band optical amplifier.

Finally, it is concluded that optimizing the optical fibre length and the dopant density of L-band optical amplifier by means of GA can achieve maximum peak gain. The results will be helpful to the design and optimizing of L + - band AF, and will be helpful to further study and apply in the area of optical communication.

Authors Contribution

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

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