Optimal Design of Fiber Amplifier based on Thulium, YttErbium and Bismuth.

Peiyuan Wang*

Hebei University of Science and Technology University, Shijiazhuang, 050091, Hebei Province, China

* Corresponding Author Email: peiyuanwang@students.federation.edu.au

Abstract. Although Erbium-doped fiber amplifier is still the mainstream of optical fiber communication nowadays, it has some limitations. The operation of EDFA is limited to 1530-1610nm, so it is an important research direction to explore different elements. This paper introduces three kinds of fiber amplifiers doped with different rare earth elements: Thulium-doped, YttErbium-doped, and Bismuth-doped fiber amplifiers. The optimal optimization performance is obtained through comparison logic by adjusting various parameters. The maximum gains of three rare-earth-doped fiber amplifiers in different wavelength ranges are obtained: The maximum gain of a Thulium-doped fiber amplifier is 51dB in the wavelength range of 1900nm to 2050nm. The maximum gain of a YttErbium-doped fiber amplifier is 62. 5dB in the wavelength range of 1020nm to 1080nm. The maximum gain of a Bismuth-doped fiber amplifier is 23dB in the wavelength range of 1640nm to 1770nm. These works pave the way for future research.

Keywords: Thulium-doped fiber amplifier; YttErbium-doped fiber amplifier; Bismuth-doped fiber amplifier.

1. Introduction

In 1960, the first advent of the laser solved the problem of light sources [1]. In 1970, Corning pulled out the first low-loss quartz fiber with an attenuation of 20dB/km. Since that, people have entered the field of optical communication. In the initial optical communication, it is converted by optical and electrical signals, that is, optical signals - electrical signals. In the eighties of the last century, with the rapid development of fiber amplifiers doped with rare earth elements, a variety of optical fiber materials, dopants and pump sources were widely used [2]. After 1987, the advent of Erbium-doped fiber amplifiers (EDFA) revolutionized optical communications. Its advantage is that it abandons not only the original high-speed electronic circuit but also the data rate and format can be more intuitively understood [3], reducing costs. At the same time, single-mode rare-earth-doped fiber also received great attention. A specific type of optical fiber devices is created by applying rare-earth dopants to the single-mode fiber's core. Still, more importantly, these light source devices are the basis of all-fiber fiber optic circuits, stimulating people's strong interest in single-mode fiber lasers [4]. Since broad bandwidth is the future of fiber optic communication systems, creating new band fiber amplifiers has become an essential priority [5]. And a fiber amplifier doped with rare-earth elements is critical in realizing this technology.

In recent years, there has been more research on fiber amplifiers, and people have made many breakthroughs in this field. Firstly, using Erbium-doped fluorotellurite glass fiber as the gain medium, an optical broadband fiber amplifier with a gain value of more than 18dB and a wavelength range of 1560~1618nm has been developed. The research shows that the Erbium-doped fluorotellurite glass fiber can be used to develop broadband fiber amplifiers [6]. The demand for increased communication capacity is now greater than the gain bandwidth of standard fiber amplifiers, which poses significant obstacles to the advancement of optical communication [7]. In addition, the scalable amplification characteristics of fiber amplifier networks provide solutions for many new applications, such as laser-based particle accelerators, laser-driven nuclear waste treatment, Earth orbit debris cleaning, and laser-driven fusion energy [8]. Besides, to improve the amplification bandwidth of the Raman Fiber Amplifier (RFA) and the transmission capacity of the optical fiber communication system, a

broadband RFA with a bandwidth of 100 nm is designed using four pumps with different wavelengths [9]. At present, the working bandwidth of a mainstream Erbium-Doped Fiber Amplifier (EDFA) is concentrated in the C+L band (1530-1610nm) [10]. There are many ways to realize fiber amplifiers, most doped with rare earth elements.

Three representative works are featured in this study. These are Thulium, Ytterbium, and Bismuth-doped fiber amplifiers. As the need for network bandwidth grows, EDFAs in the 1530-1610 nm spectral area have constraints. Simulating different parameter values yields the ideal approach for optimizing performance. Rare-earth-doped fiber amplifiers with high output power, wide gain bandwidth, and high pump conversion efficiency are widely employed in industrial manufacturing, military, pulse amplification, and space optical communication.

2. Theoretical analysis

The basic principle of the doped rare-earth element fiber amplifier is: In the optical fiber production process, a special process is used to incorporate a very small concentration of rare-earth element ions into the fiber core layer deposition. The optical fiber communication system has two low-loss working windows of 1. 55μm band and 1. 31μm band. When people doped different rare-earth element ions, they can make the fiber amplifier work in different working windows. The fiber-doped ions in it are stimulated by pump light and transition from the ground state to the excited state. Then the ions are induced by the signal light to produce stimulated radiation, thereby forming a coherent signal amplification, causing gain to achieve optical amplification. This makes optical fiber communication systems simpler and more flexible. Fiber amplifiers doped with different rare-earth elements have a wide range of application prospects in the future, and people's exploration in this field is continuing. Next, the theoretical basis used in the design of three different rare earth element fiber amplifiers is introduced. Then the diversity and breadth of rare earth element fiber amplifiers are demonstrated.

The principle that rare-earth elements can excite optical fiber amplifiers is that under the stimulation of signal light, electrons transition from the ground state to the excited state, and stimulated emission occurs when appropriate photons are incident. In this process, atomic electrons can also transition from high to low energy levels, emitting a photon simultaneously, thus amplifying the optical signal. The energy level structures of different rare earth elements are different, but all of them are stimulated emissions to realize optical signal amplification. For the working principle of 3. 1, simulate how the length of the active fiber, the pump coupling ratio, the slope efficiency, and the wavelength of the signal affect the amplifier's performance by using the variable coupling of a single-stage TDFA between a common pump and reverse pump. The gain and output power are studied as the changes in active fiber length and input signal power, and the final optimized performance is obtained by changing these parameters. For the working principle of 3. 2, the Yb-doped fiber amplifier with a two-stage in-band asymmetric pumping scheme is used. By adjusting the pumping power and wavelength, the optimized length of Yb-doped silicon fiber and the optimized doping concentration of Yb3+ are obtained. Finally, the peak gain and output power of the signal wavelength of 1033nm are obtained. For the working principle of 3. 3, the BDFA pumped by commercial laser diode with bidirectional configuration is adopted, and the best performance can be obtained by adjusting the total Bi concentration.

3. Outcome discussion

3.1. Needed improvement and design of an able to share pump single-clad 2 μm TDFA[11]

The parameter optimization design of the TDFA architecture will be discussed here, and the data reported in the Fig. will demonstrate a number of important aspects of how the shared pump TDFA functions.

When selecting the ideal fiber length for gain amplifiers, the strength of the input signal comes first. The fiber gain is greatest at -30 dBm input with a 14-meter fiber length at a 50% coupling ratio. The optimal fiber gain occurs at a fiber length of 7-8m for a -15dBm input. The NF values are still rather close to the quantum limit of 3 dB for these low signal input levels. The power amplifier's maximum analog output power will be achieved with an optimal fiber length of around 3. 5 m and a signal wavelength of 1952 nm. The numbers obtained in the Fig. fit well with the optimum fiber length. The ideal length for maximizing output power at this point is between 3 and 4 meters when the pump coupling ratio is 50%. Based on the calculations, Fig. 1(a-b) demonstrates that a coupling ratio of 50-95% may be employed when the highest output power is at a wavelength of 1952 nm.

The output power changes linearly with pump power, as seen in Fig. 1.b. The respective simulated powers are 0.83 W, 1.7 W, and 2.55 W. No other nonlinear effects are observed in this investigator's experiment, meaning that the pump power can be increased to increase the amplifier's output power, reaching the limit at which nonlinear effects are initially observed. For the parameters in the current experiment, using a single stage shared pump design to produce a power amplifier with simple construction and high signal output power, but they do not have a threshold for the nonlinear effects in the pump amplifier now. And this high-power amplifier will be extremely attractive.

For multi-purpose amplifiers, Fig. 1 (c-d) illustrates that the fiber amplifier's working bandwidth and center wavelength (λc) strongly depend on the active fiber's length. Different fiber lengths correspond to different maximum wavelength response lengths. Fig. 1. c simulates the wavelength region from 1900nm to 2050nm and the length of the fiber from 1. 5m to 9m and concludes that when the fiber length L is 9m and longer, the maximum wavelength response should be above 2000 nm, and the bandwidth of the amplifier tends to shift towards longer signal wavelengths. The amplifier's bandwidth tends to shift towards shorter signal wavelengths for shorter fibers such as 1. 5 m and 2m. As shown by the horizontal arrow in Fig. 1. d, for the short fiber (3m) and the longest fiber (9m), the working bandwidth at 50% slope efficiency is 198 nm, 160 nm, and λc is 1896 nm and 1940 nm, respectively. A shorter fiber length provides a larger working bandwidth and a lower center wavelength. Next, when the coupling ratio k=50%, the change of NF with the wavelength λs is not obvious, indicating that the noise performance of this amplifier is not dependent on the wavelength change. Therefore, it will be very attractive to those who want to use many applications of such TDFA.

Finally, the result proves that it is possible to achieve progress for the first-stage shared pump TDFA with a larger range of parameters when the active fiber length L is 7m and the coupling ratio k=50%.

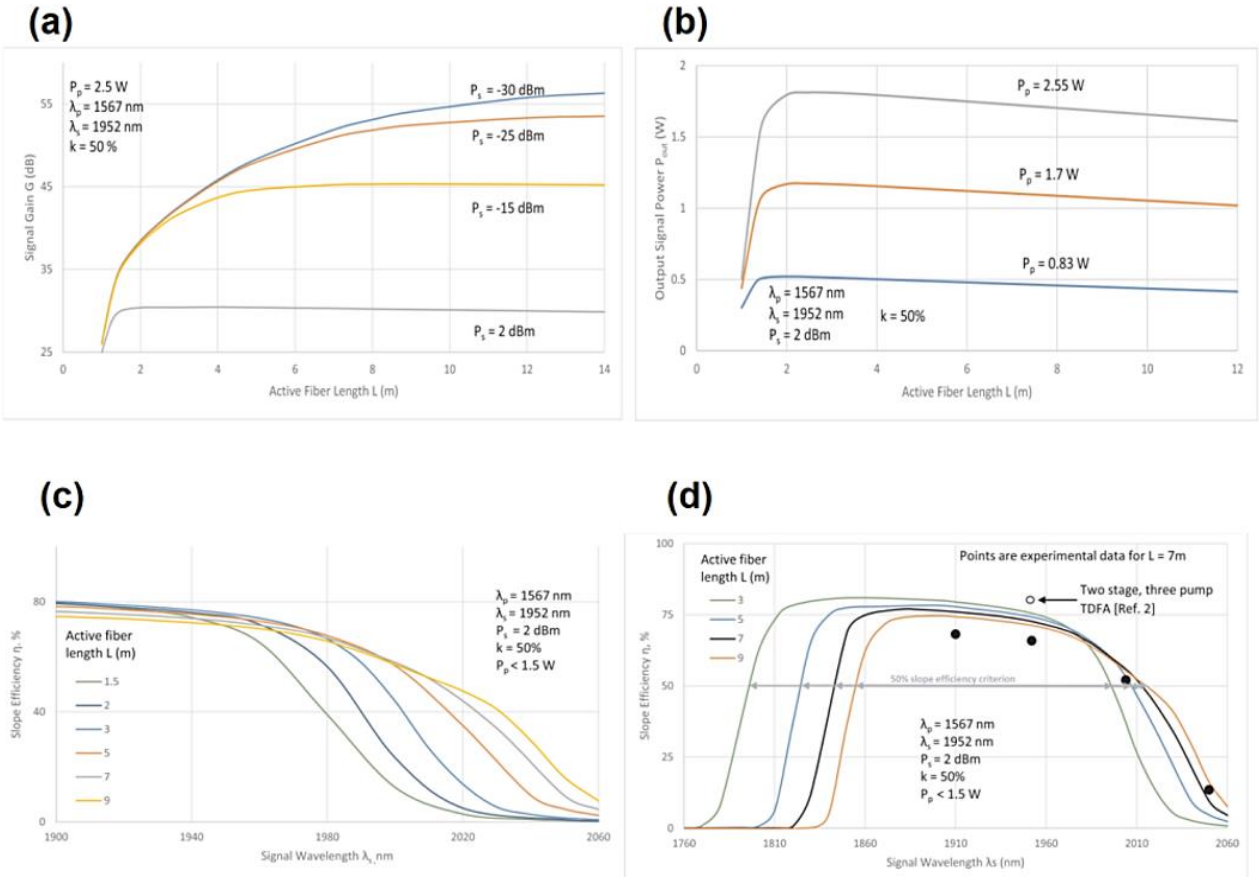

Fig 1. (a) Four variable Levels of Ps's Signal Gain (G). (b) Simulated Output Power for k = 50%. (c) Simulated slope efficiencies. (d) Slope Efficiency.

3.2. YttErbium-Doped Fiber Amplifier Performance Improvement [12]

Firstly, three factors affect the performance of fiber amplifiers: the length of YDF, the doping concentration of Yb3+, and the pump configuration. By adjusting these factors, the best performance of YDFA can be achieved. In the end, the performances of their proposed designs are compared by bidirectional pumping, YDF length of 2. 5 meters, Yb3+ doping concentration of $75\times10^{24}m^{-3}$, signal wavelength of 1033nm and peak gain of 51dB.

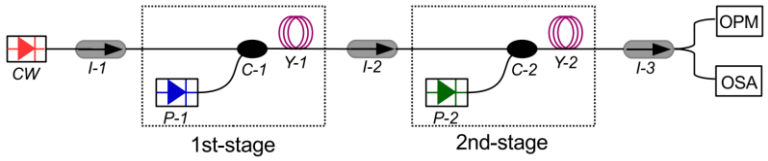

Fig 2. Schematic of the proposed YDFA.

Next, optimize the performance of their design based on the above values. Firstly, the length of Y-1 and the doping concentration of Yb3+ are 1m, $50\times10^{24}m^{-3}$, and the power of p-1 is 1W. In this case, the length and doping concentration of Yb3+ in Y-2 are optimized, and the peak gain of the signal wavelength range from 1020nm to 1080nm is obtained. Fig. 3. a shows when the signal wavelength is 1033nm, the approximate peak gains of different lengths 3m, 6m, and 9m of Y-2 are 62dB, 62. 5 dB and 60. 8 dB, respectively. And Fig. 3. b shows the approximate peak gains of different Yb3+ doping concentrations of Y-2 are 62 dB, 62. 6 dB, and 61 dB. By comparison, the maximum peak gain is obtained when the length is 6m and the doping concentration is $50\times10^{24}m^{-3}$. When the gain peak is about 62. 5dB, the pump power and signal power are 4W and -35dBm, respectively.

Next, investigate how the amplifier's output power and gain are affected by the pump's wavelength, and adjust the pump power to 2W, 4W and 6W, respectively. Fig. 3. c shows the stable output power

of the amplifier with pump wavelengths ranging from 940nm to 960nm are about 1. 75 W, 3. 5 W and 4. 5 W, and Fig. 3. d shows the peak gains of the amplifier are 59 dB, 62. 5 dB and 63. 5db. From the Fig. below, at the pump wavelength of about 965nm, the amplifier's output power and the gain curve will decrease sharply. Then, with the increase of the pump wavelength, the curve will keep the same law as the previous curve because the pump photon absorption is the highest at the pump wavelength of 965nm, which will lead to the saturation of the amplifier and the temporary decrease of stimulated emission. When the pump wavelength increases, the pump photon absorption decreases, and both the output power and the amplifier gain will recover. The signal power determines the saturation of the gain, but the smaller the signal input power is, the closer the gain is to saturation. In this study, when the signal power decreases to -40dBm, the saturation will stop, but will not increase further. And when the pump power is higher, the gain to saturation is higher.

The change of NF when the pump power is swapped. Fig. 3. e shows that P-1 and P-2 are 1W and 4W. The NF of -5dBm signal power is lower than that of -35dBm signal power. Excess ASE is produced at the output when the powers of P-1 and P-2 are switched, as shown in Fig. 3.f. Compared to the prior condition, the NF value rises when the lengths of Y-1 and Y-2 and the doping concentration of Yb3+ were held constant.

Finally, the result proves that YDFA performance can be improved by optimizing the design in the wavelength range from 1020nm to 1080nm based on the two-stage in-band asymmetric pumping scheme. When the signal wavelength is 1033nm, the highest peak gain is about 62. 5dB, the output power is 3. 5W, and the minimum NF of the amplifier is 4. 01dB when the wavelength is 1070nm, and the NF of the amplifier changes when the power of P-1 and P-2 are interchanged.

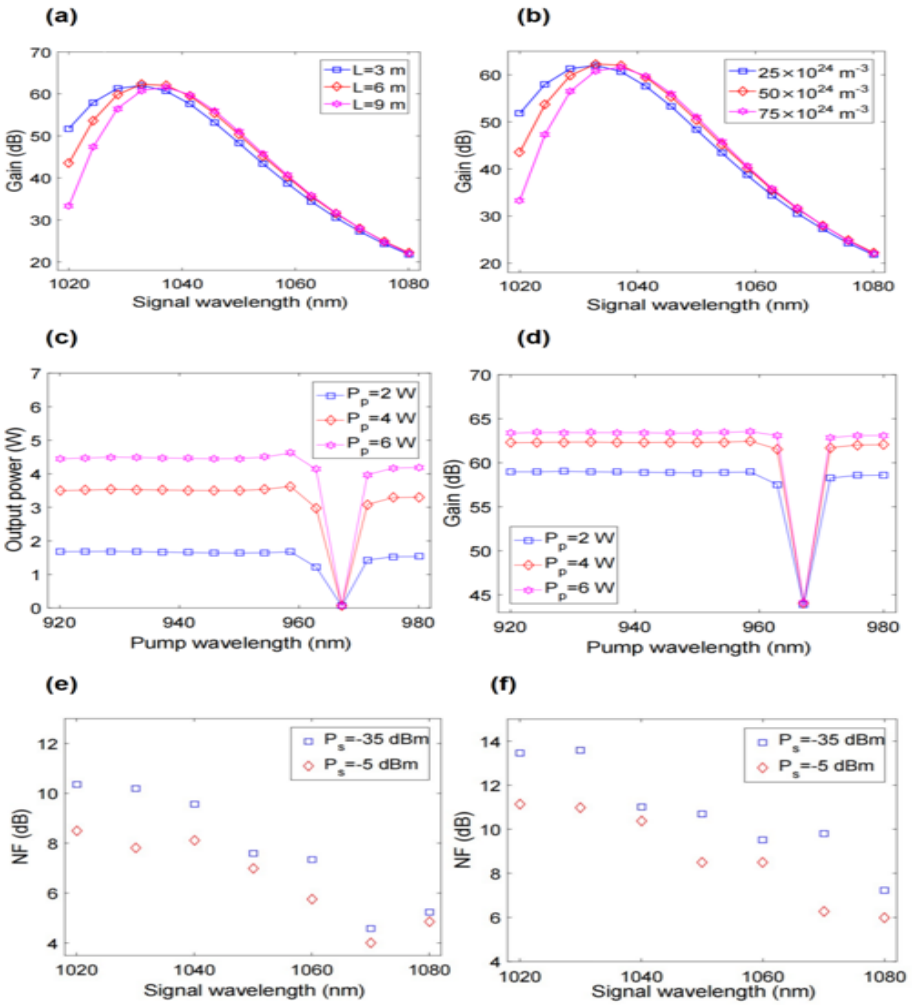

Fig 3. (a) Various Y-2 lengths; (b) Yb3+ doping levels with versus pump wavelength. (c) Output power plots; (d) gain plots.

3.3. A 1700-nm band 23-dB bismuth-doped optical fiber amplifier [13]

The prepared fiber preforms containing Bi: 50Geo2-50SiO2 by the MCVD process. By increasing the sheath fiber with a standard 125μm cladding diameter, the corresponding core diameter, cutoff wavelength, and numerical aperture are drawn, which are 2-μm, 1. 2-μm and 0. 45, respectively. Under this condition, the preform can be formed.

Here, an optical fiber is mainly studied, with a total Bi concentration of 4. 5×10^{-3}wt, total absorption of 0. 92 dB/m at 1650nm, and unbleachable loss at 1650nm of 0. 11 dB/m. Two distinctive bands at 1400 and 1650 nm make up the absorption spectra at this time. Because people pay more attention to the second band of BAC-Ge at 1650nm, it can achieve the gain at 1700nm. At the same time, because the primary factor causing Bismuth-doped fiber's laser efficiency to decline is unbleached loss, the fiber with lower unbleached loss can have good efficiency in optical amplification of fiber amplifier. The unbleached loss level has no strong dependence on the signal wavelength in the spectrum range of 1300-1700nm. The concentration of BACs connected to Ge can be estimated using a wavelength of 1650 nm without unbleachable loss, so the unbleached loss value of optical fiber in the wavelength region of 1650nm can be a good estimate of its loss level. Fig. 4. a

In order to measure the gain of the amplifier and the spectral dependence of the noise figure, a super luminescent source doped with bismuth is used to create a multi-line signal source. The wavelength of this signal source is from 1600nm to 1800nm, and the spectrum of the input signal is comb shaped. This signal source's wavelength range consists of 13 narrow lines (about 1nm), evenly distributed in the step of 15nm. In the studies for measuring the saturation characteristic of the amplifier, a double-doped fiber laser operating at 1680 nm was employed as the signal source. Increasing the bismuth concentration can enhance gain efficiency when the overall absorbance remains less than 1.5 dB/m. When the concentration continues to rise, the gain efficiency falls precipitously. The optimal bismuth doping concentration is 0.01%-0.02%.

The spectrum dependency of the gain and noise Fig. of the BDFA under 300mW bidirectional pumping is shown in Fig. 4.b. Such signal power will not have an evident gain of the measured wavelength when the input power signal is less than -20dBm. Research shows that the greatest gain is 23 dB at 1710 nm, and the gain spectrum's 3 dB width equals 40 nm. The spectral region between 1670 and 1730 nm has a minimum noise value of about 7 dB. The saturation characteristics of the BDFA under pumping settings of 300 mW are depicted in Fig. 4 when the BDFA's maximum gain factor is 0. 1 dB/mW. (c - d). Under a 3 dB gain compression, the input and output signal powers are 13 dBm and +5 dBm, respectively.

According to the above experimental results, the BDFA with 50m active fiber length is constructed by the new optical fiber with a total Bi concentration of 18×10-3wt. Total absorption of 2. 4 dB/m at 1650nm and unbreakable loss at 1650 nm of 0. 2 dB/m. The spectrum dependency of the gain and noise of BDFA under 300mW bidirectional pumping is shown in Fig. 4.b. Such signal power will not have an evident gain of the measured wavelength when the input power signal is less than -20dBm. Research shows that the greatest gain is 23 dB at 1710 nm, and the gain spectrum's 3 dB width equals 40 nm. The spectral region between 1670 and 1730 nm has a minimum noise value of about 7 dB. The BDFA's saturation characteristics under-pumping settings of 300 mW are depicted in Fig. 4. (c-d) when the BDFA's maximum gain factor is 0.1 dB/mW. Under a 3 dB gain compression, the input and output signal powers are 13 dBm and +5 dBm, respectively. The corresponding pump-to-signal conversion efficiency is 1%.

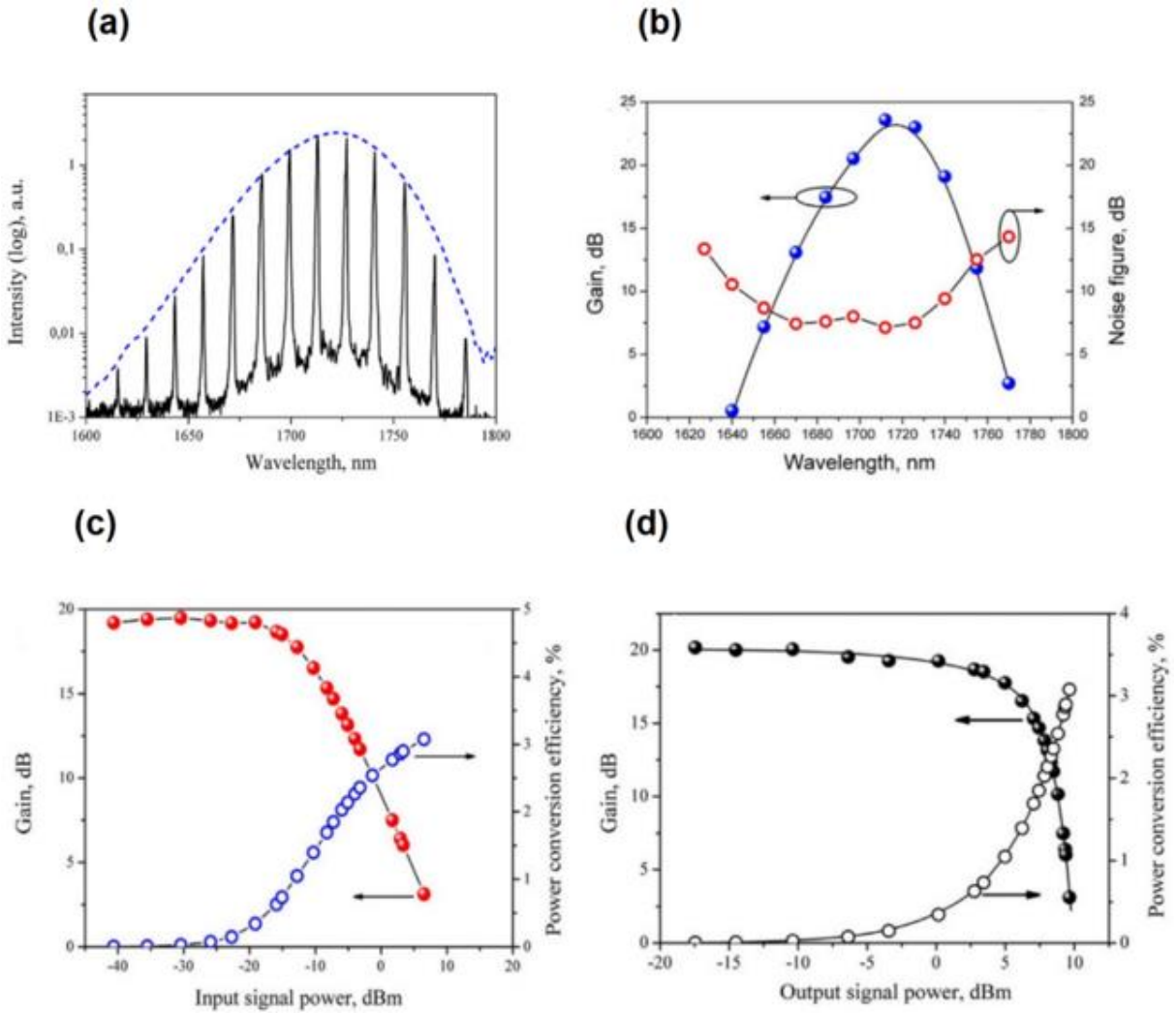

Fig 4. (a) Spectra of an input signal and a super luminescent bismuth-doped fiber source (b) Gain and noise ratio; (c, d) Gain at 1680 nm and power conversion effectiveness.

4. Comparative analysis

Table 1. The comparison between Rare-earth doped fiber amplifiers.

Rare-Earth Doped Fiber Amplifier	Wavelength Range	Maximum Gain	NF
Thulium-doped fiber amplifier	1900nm to 2050nm	51dB	3. 5dB
YttErbium-doped fiber amplifier	1020nm to 1080nm	62. 5dB	4. 01dB
Bismuth-doped fiber amplifier	1640nm to 1770nm	23dB	7dB

From the table, rare-earth-doped fiber can be applied in multiple wavebands. The Yb-doped fiber amplifier has a maximum gain of 62. 5 dB, whereas the Bi-doped fiber amplifier has a minimum gain of 23 dB. The NF of the Thulium-doped fiber amplifier is 3. 5dB, while that of the Bismuth-doped fiber amplifier is 7dB.

5. Conclusion

The three kinds of rare-earth-doped fiber amplifiers introduced in this paper will be widely used in the future. They provide new and efficient possibilities for optical transmission systems and are the current main research areas. For example, the optimized performance of TDFA discussed in this paper shows that shared pump TDFA can compete with multi-stage and multi-pump TDFA, which is more complicated. With the YDFA mentioned in this paper, people can achieve high gain and high

output power in the 1000nm band, because of the unique emission characteristics of YttErbium. In the future, people's research on Yb-doped fiber amplifiers will focus on the 1000nm band. Of course, people's research on fiber amplifiers doped with rare earth elements will continue. In the future, more and more band fiber amplifiers will be developed and put into commercial fields, thus bringing convenience to people's lives.

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