Modeling and numerical simulation of the gain spectrum of Thulium-doped broadband fiber amplifiers

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Abstract. Nowadays, due to the complex signal medium conversion process of semiconductor laser amplifiers, the optical fiber amplifier, which is a new type of all-optical amplifier, is increasingly used in optical fiber communication lines for signal amplification because it can directly perform all-optical amplification of signals and are especially suitable for relay amplification of long-distance optical communications. Our research project is the gain spectrum of the Thulium-doped broadband fiber amplifier. The signal wavelength range is from 1450nm to 1520nm. The goal is to obtain the gain spectrum with fiber length variation, doping concentration, and pump power. This paper follows a logical order that presents the introduction, the formulas used in the experiment, and the result and analysis. According to the output wavelength range, energy level structure, and electronic transition process, we designed the pump wavelength and established the rate and power propagation equations. Eventually, gain spectrum with a variation of fiber length, doping concentration, and pump power is available using MATLAB for programming and calculating. With our research achievement, a more efficient optical fiber amplifier is possible to be made in the future.

Keywords: Thulium-Doped Fiber Amplifier; S-Band; Gain Spectrum; Fiber Length; Doping Concentration; Pump Power.

1. Introduction

In the history of telecommunications, the invention and growth of fiber optic transmission represent a significant revolution [1]. With the development of social informatization, the demand for data from the Internet and related industries is increasing dramatically, while the users' requirements for communication capacity are also gradually increasing. Driven by such high requirements, optical fiber communication is developing toward high capacity, long distance, and low loss. General optical amplifiers have gain medium, energy source, input and output, and coupling structure. The different gain media are divided into two types of optical amplifiers. One is using active media such as semiconductor laser amplifiers and doped fiber amplifiers. The other category is based on the nonlinear effect of optical fiber, using the exciting scattering mechanism to achieve direct light amplification such as fiber Raman amplifier and Brillouin amplifier [2]. Optical communication technology can be traced back to the late 19th century. In1880, Bell invented the optical telephone using light waves as carriers. In1962, Geusic and Scovil, physicists at Bell Laboratories, first introduced the concept of the traveling wave optical amplifier [3]. E. Snitzer of American Optical Company invented fiber-optic amplifiers and demonstrated a Neodymium-doped fiber-optic amplifier with an output wavelength of 1. 06 um, wrapped around a flash lamp excitation of neodymium atoms [4]. He also proposed using amplifiers in communications, the emergence of spontaneous radiation noise, and made the first solid-state erbium-doped fiber laser [5]. In1963, experiments were conducted with lasers for atmospheric optical communications, which were unsuccessful. In1970, Corning developed a quartz glass fiber with a loss of 20 decibels per kilometer, which made fiber optic communication practical. Later, Poole and colleagues at the University of Southampton used MCVD to fabricate rare-earth ion-doped single-mode fibers [6, 7] to obtain doped fibers with low background loss. Payne et al. from the University of Southampton successfully overcame the issue of thermal quenching of erbium-doped fibers between 1985 and 1986 and developed the first core-doped erbium fibers by MCVD.

Erbium-doped fiber amplifiers (EDFAs) have been used in fiber optic communications since 1987 when the University of Southampton discovered that erbium-doped fibers provide optical gain at1.55 μm, and have caused a profound change in the field of fiber optic communications. This was followed by extensive research in C-band ($1520-1560$ nm), L-band ($1570-1605$ nm), high gain, wide bandwidth, low noise, and high power to achieve the ideal amplifier for optical communications with low loss windows [8]. Tm^{3+} is a useful ion because it exhibits excellent quantum efficiency, a wide gain bandwidth, and a potent absorption band at wavelengths accessible from industrial high-power diode lasers, which are around 800 nm, with slope efficiencies over 70% in 790 nm pumped Tm^{3+}-doped fiber lasers[9]. Furthermore, Tm^{3+}-doped fibers are an appropriate gain medium for producing femtosecond pulses due to the wide gain bandwidth from 1.8μm to 2.1μm, which allows for a wide wavelength tuning range. The output power of Tm^{3+}-doped fiber lasers and amplifiers have increased to levels considerably above kilowatts in recent years [10]. With the continuous improvement of the double-clad optical red process, the output power of optical fiber amplifiers is getting higher and higher, gradually developing to various fields with the advantages of high efficiency and high brightness. In particular, main oscillation power amplification (MOPA) structures for light sources are an efficient way to obtain high pulse energy, high output power, and excellent beam quality [11]. Thulium-doped fiber amplifiers have a wide gain spectrum and can be realized for laser output in the $1.7\sim2.1$μm band, increasing the transmission capacity of wavelength division multiplexing (WDM). However, current research on fiber amplifier amplification in the S-band (1460nm~1530nm) is more limited, and effective optical amplification cannot be performed in the S-band. However, there exists an energy level of Tm^{3+} to achieve an amplification jump in the S-band, so the Thulium-doped fiber amplifier has now become the most promising research object to achieve S-band amplification.

This paper uses the energy level diagram of Tm^{3+} ions as the basis. After determining the signal light wavelength as S-band (1460 nm~1530 nm), the pump light wavelength of 790 nm is selected as the input. The three-energy-level system establishes the amplifier's rate equation and power propagation equation to determine parameters such as absorption and cross-sectional emission areas. In this study, these parameters are analyzed, and numerical models are established by program simulation. The results of this study are presented in the form of a three-level system, and the effects of pump power, fiber length, and doping concentration are explored in terms of the variation of the gain spectrum of thulium-doped fiber amplifiers. The effect of optical amplification and related parameters of the Thulium-doped fiber amplifier in the S-band is verified. The Thulium-doped fiber amplifier can expand the communication wavelength of high-speed fiber optic communication systems towards S and S+ bands, thus further widening the communication bandwidth and increasing the capacity of fiber optic communication systems [12].

2. Experiment

Tm^{3+}-doped tellurite glasses were used as starting materials. To facilitate the experiment, we approximate the energy level system of Tm^{3+} in tellurite glass to a three-level system (Figure 1). Under the action of the pump with a wavelength of790nm, the electron at $^3H_6$ level transits to $^3H_4$ level, and then emits signal light with a central wavelength of 1470nm when it spontaneously radiates to $^3F_4$ level.

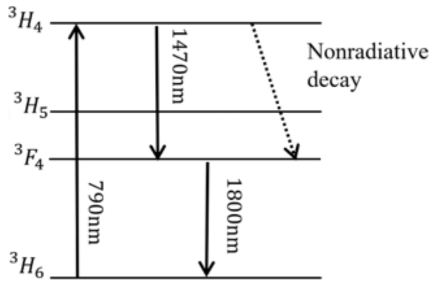

Fig 1. Energy-level diagram of Tm^{3+}.

The number of electrons in each level can be obtained by listing the differential equation of the change of the number of electrons in each level with time. The factors that affect the number of electrons in each level include sparse transition rate, pump absorption rate, signal light absorption rate, stimulate emission rate, and radial transition rate. If $^3F_4$ level and $^3H_6$ are only filled by $^3H_4$ level, the radiative transition rate can be obtained by the following formula [13]:

$$A_{32} = \frac{\beta_{32}}{\tau_3} \tag{1}$$

$$A_{21} = \frac{1}{\tau_2} \tag{2}$$

The electron at $^3H_4$ level transits to $^3F_4$ level and $^3H_6$ level. The ratio of electrons transiting to the $^3F_4$ level is $^3H_4 \rightarrow {}^3F_4$ Branching ratioβ. The pump power, signal power and ASE power (P_p, P_s, P_{ase} change with the propagation length) can be obtained from the power propagation equation. The absorption cross-section, stimulated-emission cross-section, the loss coefficient, the overlap factor and the number of electrons in each level will affect the power propagation. In this paper, we set the loss coefficient of Tellurite glass (/m) to0. 1. The absorption cross-section and the stimulated-emission cross-section at 1470nm are approximately equal [14], which are recorded asσ_{21},σ_{12}

Table 1. Spectroscopic Parameters of Tm^{3+}-Doped Tellurite Glasses.

Parameter	Value
$^3H_4$ State Lifetime(ms)	0. 29[13]
$^3F_4$ State Lifetime(ms)	1. 7[13]
$^3H_4 \rightarrow {}^3F_4$ Branching ratio β	0. 09[13]
Stimulated-emission cross-section of $^3H_4 \rightarrow {}^3F_4$ at 1470nm σ_{21}(pm^2)	0. 36[15]
Absorption cross-section for pump $^3H_6 \rightarrow {}^3H_4$ at 790nm σ_p(pm^2)	0. 89[15]
Spontaneous transition rate $^3F_4 \rightarrow {}^3H_6$ A_{21}(s^{-1})	588. 24
Spontaneous transition rate $^3H_4 \rightarrow {}^3F_4$ A_{32}(s^{-1})	310. 35

The pump power, signal light power, ASE power can be obtained by solving the differential equation of power. The ratio of the signal light power to the initial signal light power is defined as gain. The gain of the Tm^{3+}-doped fiber amplifier can be obtained from the signal light power.

Under the given initial conditions, change the fiber length, pump power, and Tm^{3+} doping concentration, respectively, and use MATLAB to draw the gain change with the fiber length, pump power, and thulium ion doping concentration.

3. Experimental results and analysis

3.1. Variation of the gain spectrum with fiber length

The incident signal light in 1450 to $1520nm$ wavelength is amplified by pumping with a pump wave at $790nm$[15]. Fig. s (a), (b), (c) are the gain coefficients of TDFA versus fiber length with input signal power $P_{s0} = 0.001mW$, pump power $P_{p0} = 1mW$, and Tm^{3+} concentration of $N = 0.5 \times 10^{25}(pcs/m3)$.

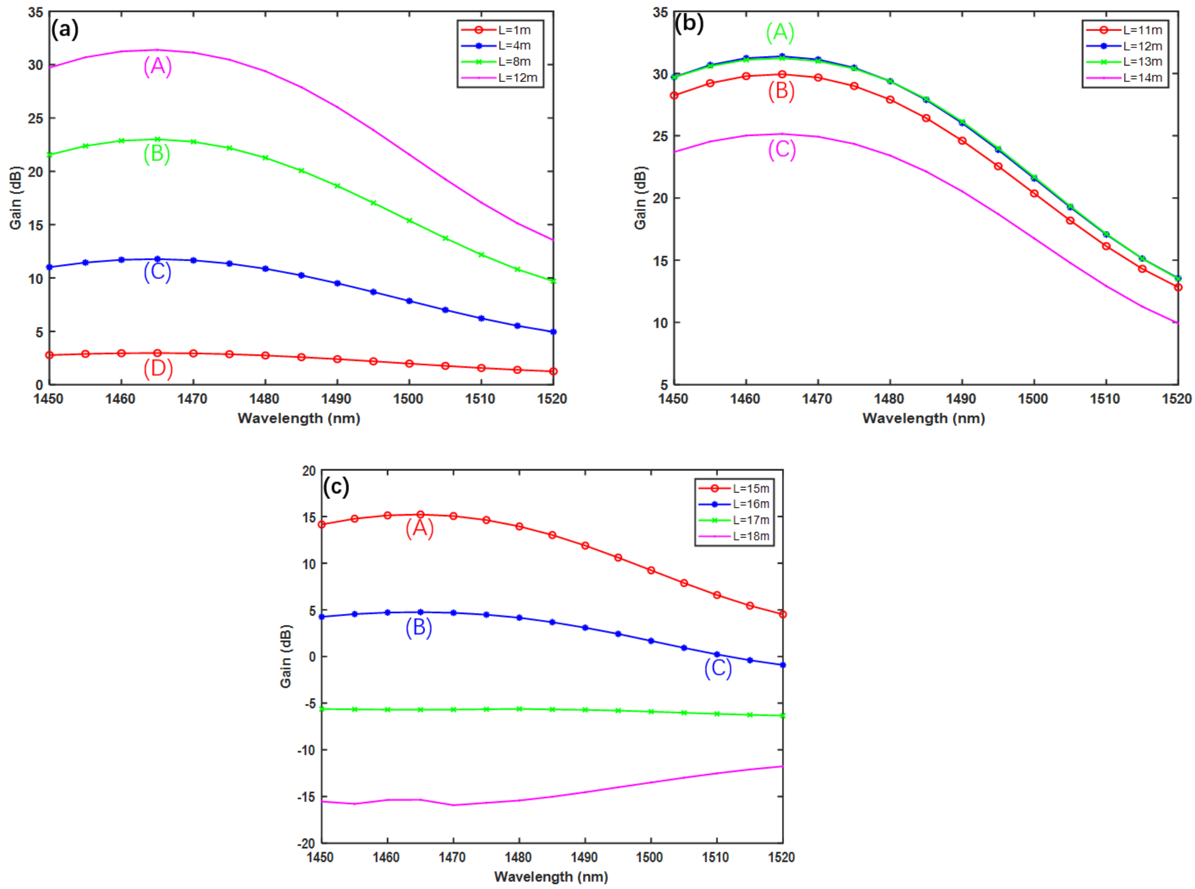

Fig. 2 (a) The gain is plotted for fiber lengths of $1m, 4m, 8m, and\ 12m$ respectively.
(b)The gain is plotted for fiber lengths of $11m, 12m, 13m, and\ 14m$ respectively.
(c)The gain is plotted for fiber lengths of $15m, 16m, 17m, and\ 18m$ respectively.

Fig.2 (a) shows the gain of the signal increases gradually over the fiber length range of $1\ to\ 12m$ The gain at different fiber lengths varies in the same trend in the signal light wavelength range of $1450nm - 1520nm$ reaching a peak at the signal light wavelength of $1465nm$, They are points A, B, C, and D in Fig. 2. (a). The gain curve is flatter because the pump light is not fully utilized at 1m fiber length, and the pumping rate decreases so that only a few particles are inverted[16], peaks at point D of Fig. (a) At about $2.96dB$. At $4m$ the gain reaches $11.78dB$ at point C; at $8m$ and at $12m$ the gain peaks at $23.00dB\ and\ 31.39dB$ show in point B and C.$12m$ Is a tenfold increase compared to the gain at? $1m$

Fig.2 (b) shows that the gain gradually decreases when the fiber length is greater than $12m$. The gain curve for $13\ m$ fiber length is comparable to that at a $12\ m$ fiber length, with a gain of roughly $31.24d$B at point A in Fig. 2 (b). The gain is about $29.95dB$ Given that the fiber length exceeds the recommended length of $12\ m$. As the fiber length is greater than the optimal length of $12m$, the Tm^{3+}reabsorption of signal light causes the gain to decrease, decreasing to $25.15dB$ at the fiber length of $14m$ at point C.

As in Fig.2 (c), the gain decreases sharply as the fiber length increases. When the fiber length is $16m$ and the signal light wavelength is $1510nm$ the gain reaches a minimum of approximately $0.221dB$ at point C Fig. 2 (c). If the fiber length is greater than $17m$ the gain of the signal will be negative. The reason the gain spectrum becomes flattered as the fiber length increases above $14m$ is that when the fiber length is greater than the optimum length of the optical front, the particle number is not fully inverted, and therefore the odds of each energy level having a carrier number do not match the odds determined by the excited scattering cross-section [17].

It can be concluded that the fiber length is the key factor affecting the gain, and the optimal gain is achieved at a fiber length of $12m$ and a signal wavelength of$1465nm$.

3.2. Variation of gain with Tm^{3+} doping concentration

A pump wavelength of $790nm$ was used to generate the signal light at wavelengths between $1450nm$ and$1520nm$. Fig. s 3 all show the results from numerical modeling and varying doping concentration parameters.

High doping concentrations can achieve the gain of Thulium-doped fiber amplifiers, but too high a doping concentration in fibers where Tm^{3+} tends to form ionic clusters, making the doping concentration non-uniformly distributed in the fiber and seriously affecting the performance. Hence, a suitable ionic doping concentration exists to achieve the best performance of the amplifier.

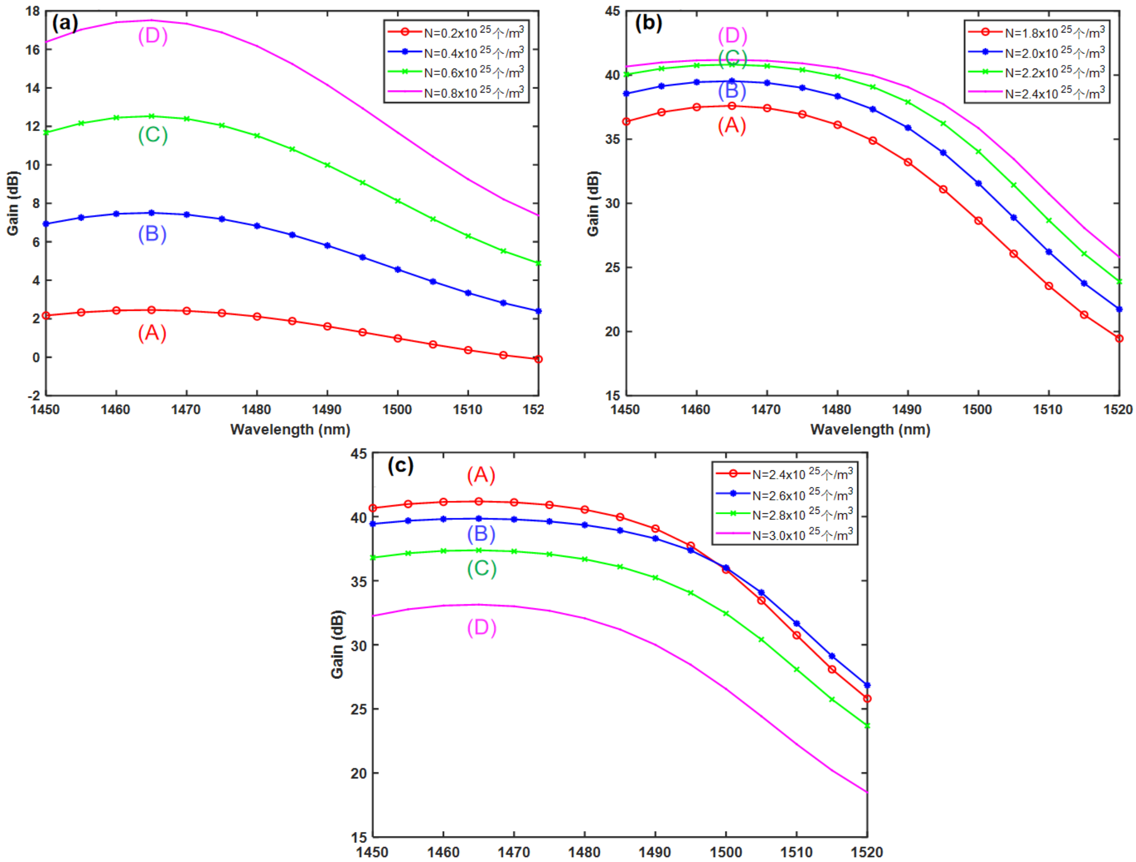

Fig 3. (a)Gain spectrum curves with doping concentrations of 0.2×10^{25},0.4×10^{25}, 0.6×10^{25},$0.8 \times 10^{25}$$(/m^3)$. (b)Gain spectrum curves with doping concentrations of 1.8×10^{25},2.0×10^{25},2.2×10^{25},$2.4 \times 10^{25}$$(/m^3)$. (c)Gain spectrum curves with doping concentrations of 2.4×10^{25},2.6×10^{25},2.8×10^{25},$3.0 \times 10^{25}$$(/m^3)$.

As shown in Fig. 3 (a), we can obtain the preliminary conclusion that the gain of the fiber amplifier increases with the increase of doping concentration; the gain rises and then decreases with the increase of wavelength. When N is 0.2×10^{25},0.4×10^{25},0.6×10^{25},0.8×10^{25} the optical amplifier gain obtains the maximum value at the wavelength of 1465nm, which is $2.45dB$, $7.50dB$, $12.53dB$, $17.51dB$ respectively. They are points A, B, C, and D in Fig. 3 (a), and the growth rate of gain decrease gradually, from 206% to 40%, from which we can initially conclude that the doped rare earth ion concentration is the crucial factor affecting the gain of the optical amplifier, with the maximum gain value at the wavelength of $1465nm$.

According to the conclusion in Fig. 3 (a), we appropriately increase the doping concentration and build a numerical model to investigate whether it is consistent with the preliminary conclusion. As shown in Fig. 3. (b), when N is 1.8×10^{25}, 2.0×10^{25}, 2.2×10^{25}, 2.4×10^{25}, the optical amplification gain obtains the maximum value at the wavelength of $1465nm$, $37.60dB$, $39.53dB$, $40.81dB$, $41.18dB$, respectively. They are points A, B, C, and D in Fig. 3(b), and the separation between the four curves becomes smaller and smaller, and the growth rate of the gain decreases from 5% to0.9%. It can be concluded that the higher the doping concentration, the lower the gain growth rate, but the overall trend is up. Therefore, we propose the hypothesis that the gain curve of the optical amplifier reaches its maximum at a certain value of doping concentration and decreases beyond this certain value.

According to the hypothesis, we proceeded to increase the value of doping concentration and build a numerical model to investigate whether the hypothesis holds. As shown in Fig. 3(c), when N is 2.4×10^{25}, 2.6×10^{25}, 2.8×10^{25}, 3.0×10^{25} the optical amplification gain obtains the maximum value at the $1465nm$ wavelength $41.18dB$, $39.84\,dB$, $37.37dB$, and $33.13dB$, respectively. They are points A, B, C, and D in Fig. 3. (c). When the doping concentration exceeds2.4×10^{25}, the gain curve shifts down as a whole, from which it can be seen that the doping ion concentration of 2.4×10^{25} is the threshold value, beyond which the gain curve decreases. The above assumptions and preliminary conclusions are valid, the concentration of doped rare earth ions is the key factor affecting the gain of the optical amplifier, and the gain is maximum at the wavelength of $1465nm$.

3.3. Gain spectrum with a variation of pump power

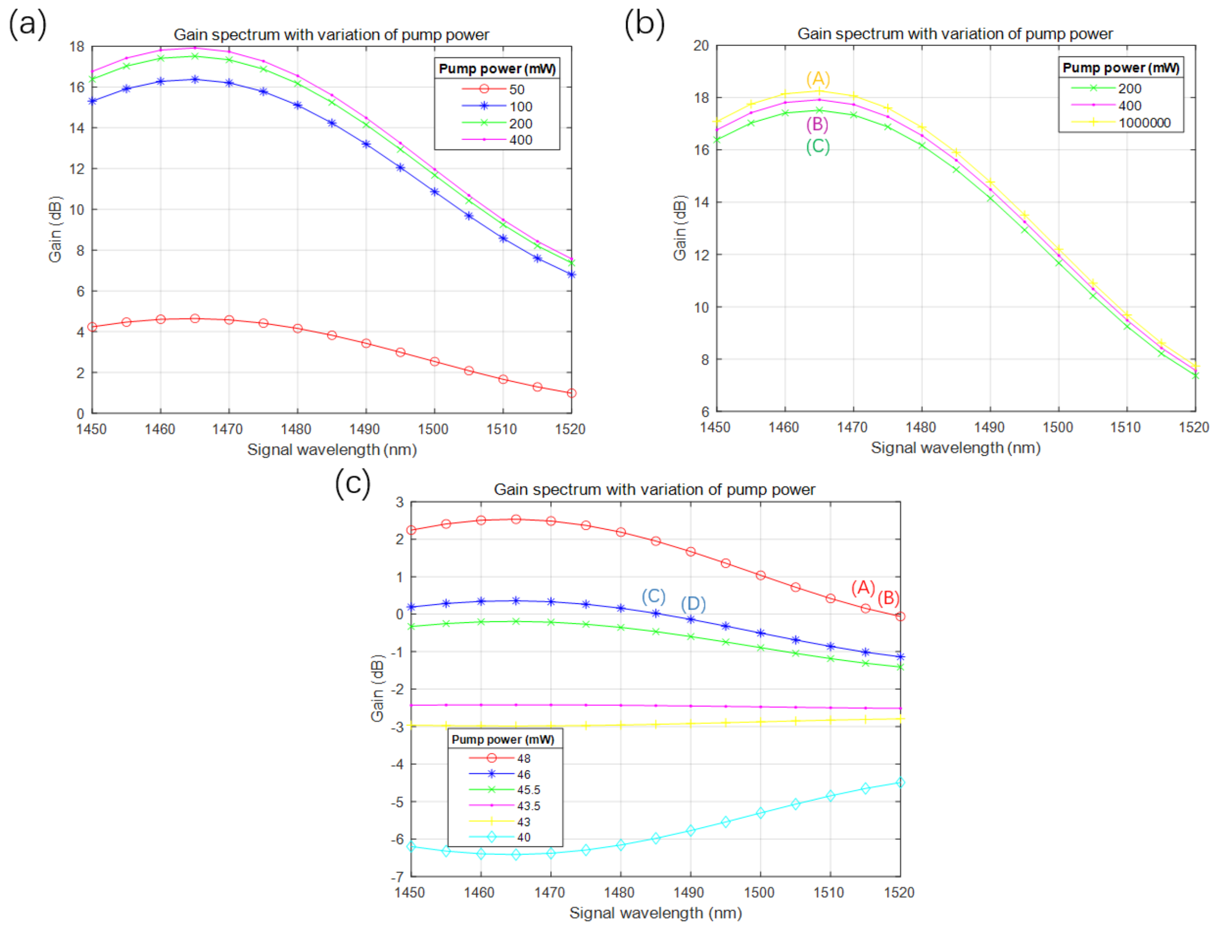

Fig 4. (a) Gain spectrum with pump power at $50mW$, $100mW$, $200mW$ and $400mW$. (b) Gain spectrum with pump power at $200mW$, $400mW$ and $1000W$. (c) Negative gain with pump power at $48mW$, $46mW$, $45.5mW$, $43.5mW$, $43mW$ and $40mW$.

First, four different pump power values were used in Fig. 4 (a), which are 50mW , 100mW,200mW,400mW. Each value is twice as big as its previous one. We can see that the gain values of the four curves first increase and then decrease. It peaks as the signal wavelength is1465nm. The curvature of the red curve with a lower power is the least obvious, indicating that when the pump wavelength is50mW, the gain variation of different signal light wavelengths is small. Secondly, it can be seen from Fig.4 that as the pump power increases by the same multiple, the gain increase becomes smaller, so I simulated increasing the pump power to1000W. As shown in Fig. 4 (b), it is a graph that includes the pump power values of200mW,400mW, and 1000W. And point (C), (B) and (A) shown in Fig. 4 (b) are the values of gain at the signal light wavelength of 1465nm which are about 17.5, 17.9, and 18.2, respectively. Through comparison, it can be found that the gain difference between 400mW and 1000W is even smaller than the gain difference between 200mW and 400mW. Therefore, the gain value does not increase infinitely with the increase of the pump power, but reaches the gain saturation.

Next is the case where the gain is negative, as shown in Fig. 4 (c). When the pump power is48mW, it can be found that at point (A), the gain is about 0.15 when the wavelength of the signal light is1515nm, and at point (B) the gain is about -0.06 when the wavelength of the signal light is1515nm. Similarly, when the pump power is further reduced to46mW, the gain changes from positive to negative when the signal light wavelengths are between 1485 and 1490nm (The gain at point (C) is about 0.02 and the gain at point (D) is about-0.14). It can also be found that as the pump power decreases, the curve’s curvature decreases. When the pump power is43mW, the curve changes from increasing first and then decreasing to decreasing first and then increasing. When the pump power continues to decrease to40mW, the curvature increases.

4. Conclusion

This paper studies the gain effect of Tm^{3+}-doped fiber amplifier pumped by 790nm laser. The amplification gain of Tm^{3+}-doped fiber amplifier in the 1450nm~1520nm band is simulated. The digital model is established, and the change in gain spectrum is observed by changing the pump powerP_p, fiber length L and doping concentration N. It is found that under the action of 790nm pump, the length of the fiber is12m, and the doping concentration of Tm^{3+} is2.4×10^{25} /m^3, and the greater the pump power within the safe range, the greater the gain. The amplification performance is the best when the signal wavelength is1465nm.

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