Matlab-based gain modeling and simulation of a 1300-1400 nm wavelength band neo-doped fiber amplifier

Yuxiang Liu [1,†], Zhirui Wang [2,†], Junjie Zhang [3,*,†]

[1]College of Optics and Electronic Information，Huazhong University of Science and Technology, Hubei, 430074, China

[2]School of Precision Instruments and Opto-electronics Engineering, Tianjin University, Tianjin, 300072, China

[3]College of Science, Donghua University, Shanghai, 201620, China

*Corresponding author:190120110@mail.dhu.edu.cn

†These authers contributed equally to the work

Abstract: A systematic investigation of gain-modulated neodymium-doped fiber laser is carried out. The numerical model of gain modulated thulium-doped neodymium fiber laser oscillator and amplifier is constructed based on the rate equation and transmission equation, and solved by the time domain finite difference method. The nano-second laser output in the 2 μm band with high conversion efficiency, narrow linewidth, and single polarization was obtained by numerical simulation. A 2 μm pulsed laser output with a maximum power of 340 mW and amplification of 42 dB was obtained using a master oscillator, and a 2 μm pulsed laser output with a maximum power of 9.13 W was obtained using a power amplifier. The model can be used as a reference for experimental research and engineering design of this type of laser.

Keywords: Laser, Nd-doped fiber laser, Numerical simulation, Doping concentration.

1. Introduction

Rare-earth-doped fiber-optic amplifiers can be integrated with full-band multi-wavelength autocorrelation sources, high-speed modulation arrays, and modulators to form very high-capacity long-range fiber-optic communication systems and networks to enhance channel transmission rates. As an important element in current optical fiber communication systems, rare earth element doped fiber amplifiers are also part of the most researched and applied today, such as niobium doped fiber amplifiers, praseodymium doped fiber amplifiers, and neodymium-doped fiber amplifiers and their gain effects. In recent years, the emission of the rare earth element neodymium ion at the near-infrared wavelengths of 1060nm and 1330nm has become a hot topic of research as it can be used to achieve optical amplification in lasers as well as in the second window of optical communication.

The pulsed amplified fiber laser consists of a pumped light source, a gain fiber, and a seed light source. The pulsed laser is injected into the LD-extracted double-clad fiber as a seed source, and the main oscillation power of the seed source is used to amplify the high-energy pulsed laser output. The fiber amplifier is a late development compared to the fiber laser, the first erbium-doped fiber amplifier was developed in 1986, because of its high gain, low noise, polarization-insensitive, and a series of outstanding advantages. Its wavelength is right in the optical communication window, so it can be used to extend the transmission distance of optical communication[4]. In 1988, Snitzer et al. introduced the concept of double-clad fiber and developed a double-clad fiber laser doped with neodymium ions. In 2003, vJeon et al. at the University of Southampton, UK, developed a 1kw fiber laser and obtained a laser output of 1.36kw in December. In 2003, Kong Yong et al. analyzed the change of cut-off wavelength with a gain of baited fibers under different bending radii and found that for neodymium-doped fiber amplifiers (NDFA) there is no serious excitation absorption phenomenon like baited and ytterbium-doped fiber amplifiers, which can reach the quantum noise factor The NDFA is not as severe as the bait-doped and bait-ytterbium-doped fiber amplifiers in terms of excitation absorption and can reach the limit of the quantum noise coefficient, which is of great

significance for the analysis of the gain of NDFA at different signal wavelengths and fiber bending radii;[13]; the influence of the nonlinear refractive index of the fiber amplifier on the variation of parameters such as doping concentration, pumping power and signal power on the nonlinearity, noise coefficient, dispersion, and other parameters brings important implications for the optimal design of the short-wave transmission, cascaded fiber, soliton transmission, etc. In 2004, Yong Kong et al. computationally simulated the influence of changes in parameters such as input signal power, pump power, and signal wavelength on the nonlinear refractive index of Nd-doped fiber amplifiers using the nonlinear refractive index equation for doped fibers developed by Kai Song et al. This study streamlined the numerical analysis procedure and increased efficiency [5]. This simplified the process of numerical analysis and improved the efficiency of the analysis[5]. In 2006, Yu Ling et al. investigated ultra-broadband erbium-doped amplifiers, extending from the traditional C-band (1525-1565 nm) to the C+L-band[14.] Then, in 2009, Ren Guangjun et al. conducted a high-gain, low-noise pulsed fiber amplifier using a self-made picosecond mode-locked laser with a neodymium-doped double-clad bias-preserving fiber as the gain medium as the seed source. In 2009, Ren Guangjun et al. obtained stable picosecond pulsed laser output using a neodymium-doped double-clad mode-locked laser as the seed source [4]. As a new type of solid-state laser with high efficiency, good beam quality, easy heat dissipation, and compact structure, the high-power double-clad fiber laser has obvious advantages over traditional gas and solid-state lasers and has very important applications in industrial, national defense, and space fields. A research team represented by Professor Lou developed a 1.75kW domestic Yb-doped double-clad fiber laser in 2009[12]. Subsequently, Liu Yi et al. designed a new signal ring structure in 2020, making the EDFA gain spectral part of the ring all flat[15].

This paper aims to address the gain characteristics of neodymium-doped fiber amplifiers in the 1300~1400 nm band. In this paper, a numerical model of the gain modulated Nd-doped fiber laser is constructed by combining the laser rate equation and the laser transmission equation in the fiber and solved by the finite difference in time domain (FDTD) method to obtain the output characteristics of the laser. The validity and accuracy of the numerical model are verified experimentally, and the effect of different pump light parameters and laser structure parameters on the output characteristics of the gain-modulated neodymium-doped (HoyaLHG-5) fiber laser is investigated theoretically. In this paper, the Nd-doped fiber oscillator and amplifier are modeled using numerical simulations and solved numerically using the PDTD method, which is an effective modeling method to realize the Nd-doped fiber amplifier.

2. Numerical model

In 1979, Gan's study of the energy transfer process of Nd ions in inorganic glasses showed that an activated Nd ion interacts with an unactivated neighboring Nd ion in a doped fiber. Suppose the two ions have the same energy intercept between their jump energy levels. In that case, one can jump from the sub-stable state to the other, resulting in a radiation-free resonance transfer [8]. With this study as a basis, it is possible to build a suitable numerical model using Matlab, and given only the appropriate parameters and the relational equations, it is possible to simulate results that are comparable to the experimental ones.

To investigate the effect of pump light and laser structure parameters on the output characteristics of a gain-modulated fiber laser and to obtain a high power, narrow pulse width 2μm laser output, a numerical model of a gain-modulated fiber oscillator amplifier is developed. The model is based on a system of laser rate equations and transmission equations in neodymium-doped fibers. The laser output characteristics are obtained by solving the equations using the FDTD method. The numerical model is described in detail as follows.

2.1 Numerical model of the oscillator

The typical structure of a laser oscillator is shown in Figure 1, where a 1300-1400 nm pulsed laser is used as the pump source, an FBG as the laser cavity mirror, and a neodymium-doped fiber as the gain medium, combined with a passive fiber to form a resonant cavity. Similar to the energy level jump of ND-YVO4 to 1064 nm in a four-energy level structure[1], the neodymium ions of the neodymium-doped (HoyaLHG-5) fiber in the inorganic glass are luminous at four levels. However, since the probability of an electron leap from four energy levels to one energy level is very small, it can be approximately neglected in the calculation. Similarly, only the electron leap at adjacent energy levels needs to be considered in the construction of the numerical model.

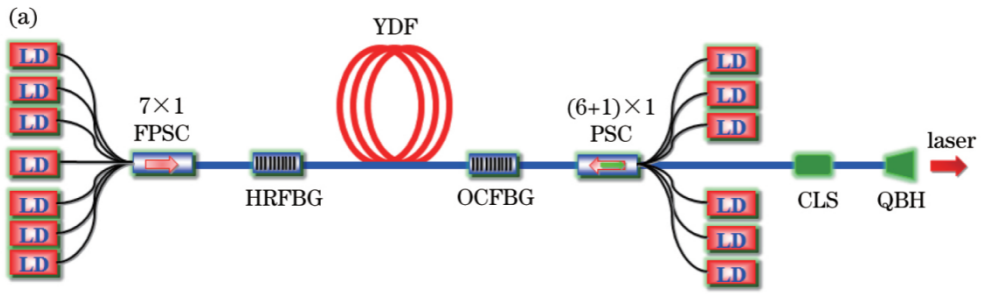


Fig 1 Structure of the laser oscillator

The energy level jumping process of the Nd ion is shown in Figure 2. The Nd ion absorbs the pump light energy, where 4f electrons produce inner shell layer jumping, first from the ground stateN_1 to the excited state N_4, then from the excited state N_4 to the semi-stable state N_3, after accumulating a certain amount of particles, in the process of jumping from $N_3$to $N_2$to produce laser or fluorescence, and finally, from N_2 back to N_1[2].

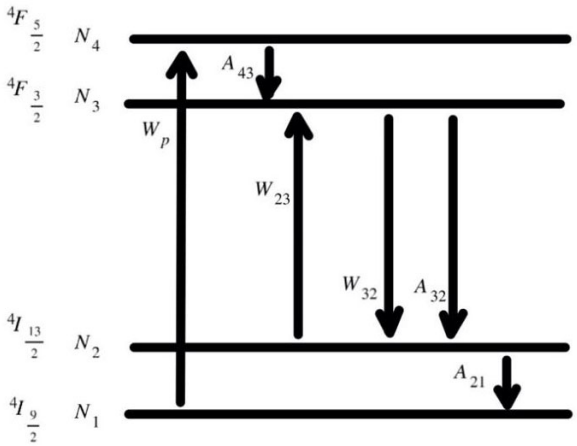


Fig 2 Neodymium ion energy level jumping diagram

2.2 Laser amplifier working model

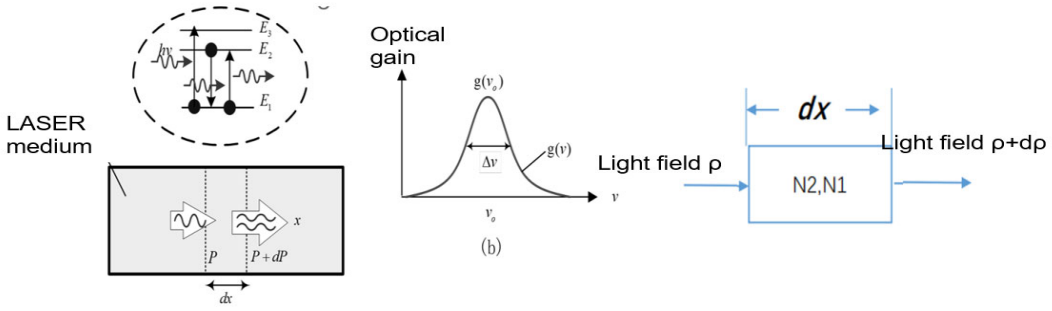


Fig 3 Laser amplifier operating gain principle

In the principle of laser amplification, as shown in the figure 3, the light propagates in the fiber in x direction. At a certain position, the power of the signal light is P. The laser medium is known to satisfy a four-energy level structure from P to P+dP. At position x, the power of the signal light is P. The laser medium is known to satisfy the four-energy level structure, and the change in power obtained in the medium per unit length dx is from P to P+dP. Defining the amplification multiplier (gain coefficient) as g, the magnitude of g affected by υ can be derived, satisfying the form of the Lorentz waveform

Define the gain coefficient g as a multiple of the amplification of the optical power P per unit gain of the length of the medium (/m or /cm).

$$g = \frac{\mathrm{dP}}{\mathrm{Pdx}} \tag{1}$$

The amplification g is usually converted into units of dB for easy calculation.

Conversion of magnification to dB.

$$\mathrm{G} = 10\log 10\left(\frac{\mathrm{I(L)}}{\mathrm{I(0)}}\right) \tag{2}$$

magnification

Where

$$\mathrm{A}=\frac{\mathrm{I(L)}}{\mathrm{I(0)}} \tag{3}$$

Units are percent %, G is gain in db (decibels)

2.3 Power propagation equation

Here, an 800 nm continuous laser is used as the pump source for unidirectional pumping, and the gain fiber length is the total length of the simulation. In this case, the process of generating a 2 μm laser at 800 nm pump light by neodymium ions from a neodymium-doped fiber is achieved by a four-energy system

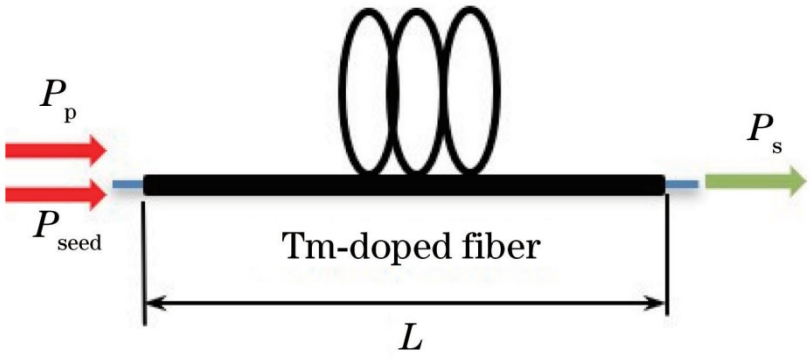


Fig 4 Fibre optic power transfer model

The variation of pump power, signal power with fiber length is called the power transfer equation

$$\frac{dPp(z)}{dz} = (-\sigma p\ N1(z) - \alpha a)Pp(z) \quad (4)$$

$$\frac{dPs(z)}{dz} = (\sigma 32\ N3(z) - \sigma 23\ N2(z) - \alpha s)Ps(z) \quad (5)$$

3. Experimental results

Based on the numerical and experimental models of the oscillator, this paper investigated the changes in the output laser characteristics (power) by changing the parameters in the 1323 nm pump laser (optical signal power, fiber length, doping concentration).

3.1 Model fitting of fiber amplifier parameters to fiber length

Firstly, to investigate the effect of univariate fiber length, the initial frequency of the pump light was set to 808 kHz, the length of the resonant cavity was 50 cm, the doping concentration of the fiber was 1.2×10^{25} g/m^3, the initial power of the signal light was 10^{-6} W

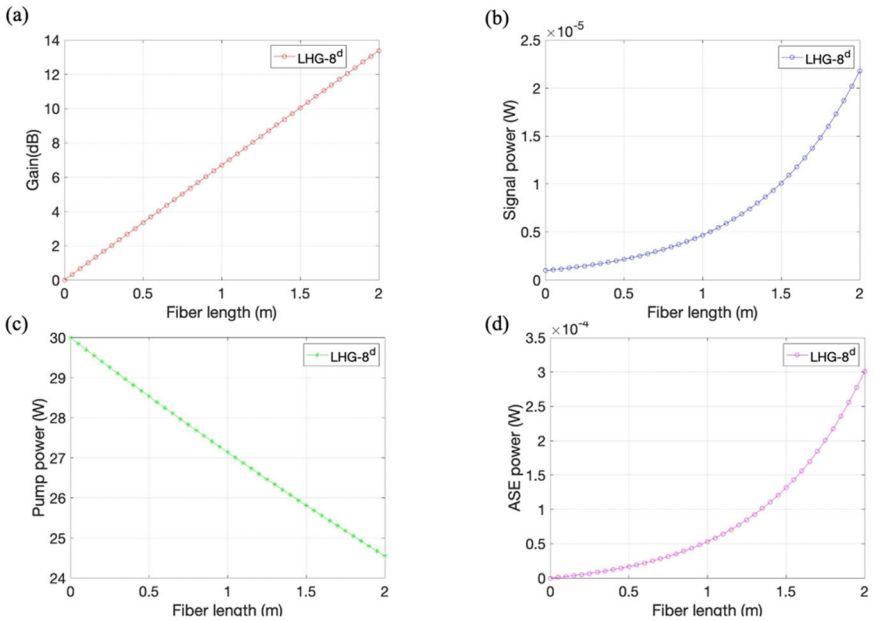


Fig 5 Fiber amplifier magnification, optical signal power, pump optical power and ASE optical power versus fiber length (small range)

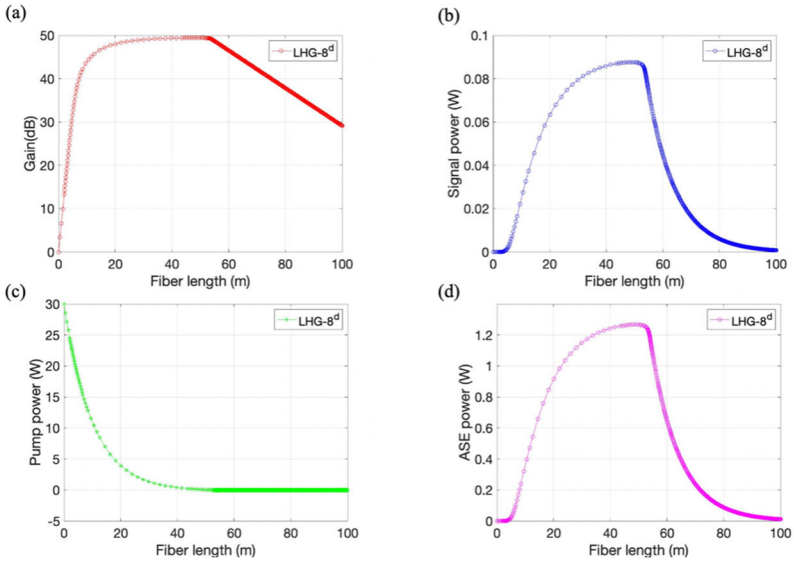


Fig 6 Fiber amplifier magnification, optical signal power, pump optical power and ASE optical power versus fiber length (large range)

As shown in Figure 5(a), the variation curve of fiber amplifier magnification with fiber length is linear in the small enough range (0-2m), and the fitting equation of the curve is G=6.692z+0.002603 by polynomial approximation. The goodness of fit of the regression equation is R^2=1. However, as the light length continues to increase, as shown in Figure 6(a), the magnification increases at the fiber length L=7m and reaches the maximum value of G_max=49.4263 dB at the fiber length L=48.4767m. The amplification slows down at the fiber length L=7m, and reaches the maximum amplification G_{max}=49.4263 dB at the fiber length L=48.4767m, after which the fiber amplification shows an approximately linear decrease. In this analysis, without changing the repetition frequency of the pump light, the optical signal power and the doping concentration of the fiber.The zone of action of the inversion distribution of the number of particles expands with fiber length, lengthening the period of particle motion in the fiber.And the probability of excitation increases, which triggers more signal light amplification, expressed as an increase in gain multiplicity. However, when the fiber length increases to a certain level, the loss in this phase also gradually increases until it exceeds the amplification power, resulting in a decrease in amplification.

Similar to the trend of amplification with light length, in a small range (0-2m), the trend of optical signal power is approximately exponential, and the fitting equation is P_s=1.0001×10^(-6) exp(1.541z), with the goodness of fit R^2=0.9973, as shown in Figure 5(b). The signal optical power maximum P_{smax}=0.0876 W is then reached at the fiber length L=49.5368 m and decreases sharply thereafter, as shown in Figure 6(b). Similarly, consider the curve of ASE optical power with fiber length, whose curve reaches the ASE optical power maximum P_{asemax}=1.2676 W at fiber length L=48.6747 m. Consider the reasonthat the loss of fiber material increases rapidly after the fiber length reaches a certain value, which causes its curve to show this state.

As the input signal in the fiber amplifier, the pump optical power tends to decrease linearly in a small range, with the fitted equation P_p=-2.721z+29.91, the goodness of fit R^2=0.9993and then approaches 0 when the light length reaches L=53.2272 m. Thus, it can be seen that during the amplifier operation, the loss of the fiber material becomes non-negligible after a certain length. negligible, which subsequently makes the final detected pump optical power tighten to 0.

3.2 Relationship between each parameter of fiber amplifier and fiber length at different fiber doping concentrations

The variation of signal power, pump power, ASE power, and gain coefficient with fiber length for the fiber amplifier system was simulated at 1323 nm with different fiber doping concentrations.

For the amplifier, the effect of its gain fiber length on the laser output power was investigated. Without loss of generality, the output power of the seed source is set to 683 mW, and the Nd-doped fiber with the length of 0-2 m is selected as the amplifier gain medium for the simulation experiment, as shown in Figure 7.

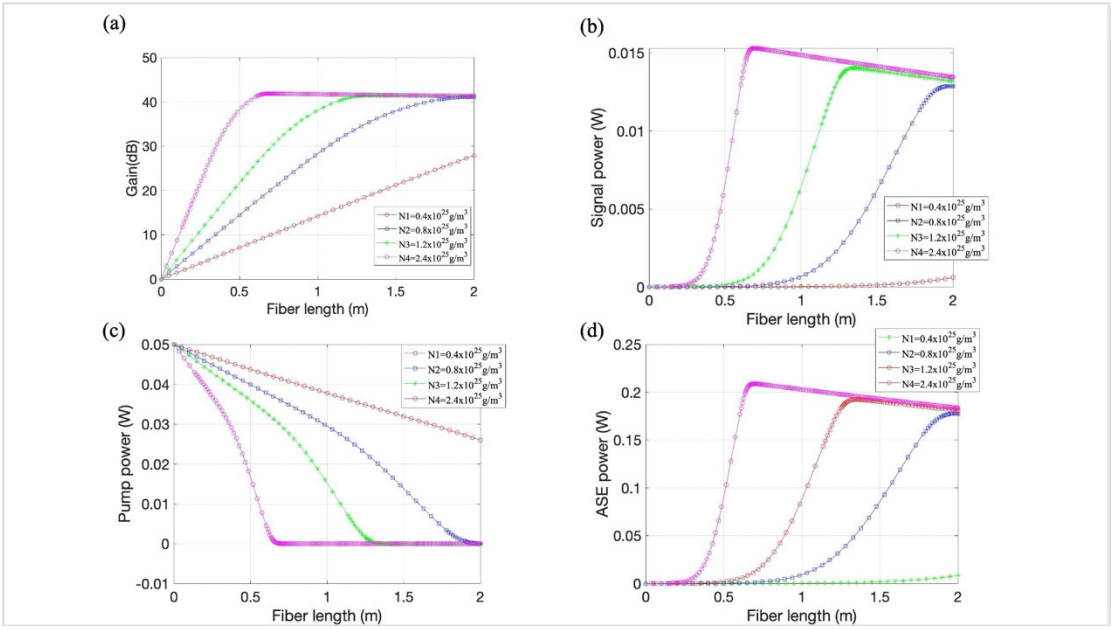


Fig 7 Fiber amplifier magnification, optical signal power, pump optical power and ASE optical power versus fiber doping concentrations

From Fig. 7(a), it can be found that the amplification of the fiber amplifier varies approximately proportionally with the fiber length for a small enough fiber length with the same initial pump power input, and then the amplification reaches a great value and then decreases slightly as the fiber length continues to increase. As shown in this figure, the fiber amplification reaches a maximum value of $G_{max} = 41.8463\,dB$ at the fiber length L=0.6940 m when the doping concentration is $N = 2.4 \times 10^{25}\,g/m^3$; when the doping concentration is $N = 1.2 \times 10^{25}\,g/m^3$, the fiber amplification reaches a maximum value of $G_{max} = 41.4695dB$ at the fiber length L=1.3523 m; when the doping concentration is $N = 0.8 \times 10^{25}\,g/m^3$, the fiber amplification reaches the maximum value of $G_{max} = 41.0963\,dB$ at the fiber length L=1.9796 m; and when the doping concentration is $N = 0.4 \times 10^{25}\,g/m^3$, the amplification of the fiber changes slowly with the fiber length until the amplification reaches the maximum value of $G_{max} = 39.9941\,dB$ at the fiber length of L=3.7525 m.. At the same time, the variation of fiber amplification with doping concentration at the same fiber length is analyzed. It can be seen that the fiber amplification increases with the increase of Nd doping concentration and the fiber length required to reach the fiber amplification decreases. It is speculated that the number of particles in the excited $^4F_{3/2}$energy level increases as the concentration of Nd particles increases, thus increasing the number of particles involved in the inversion, which eventually leads to the increase of the fiber magnification. Considering that the effect of both light length and doping concentration on fiber amplification is positively correlated, the light length required to reach the same peak amplification decreases as the doping concentration increases.

Figure 7(b) plots the variation of signal light with fiber length at different doping concentrations. When the fiber length is less than 0.2 m, the signal light power is close to the initial value of $P_{s0} = 1.0 \times 10^{-6}W$. As the fiber length continues to increase, the signal light power reaches its maximum value with an approximately linear growth trend and then decreases at a slower and approximately linear rate. From the analysis of the curves in the figure, it is known that when the doping concentration is $N = 2.4 \times 10^{25}\,g/m^3$, the signal optical power reaches a maximum value of $P_{smax} = 0.0153\,W$ at fiber length L=0.6937 m. When the doping concentration is $N = 1.2 \times 10^{25}\,g/m^3$, the signal optical power reaches a maximum value of $P_{smax} = 0.0140\,W$ at fiber length L=1.3441 m. when the doping concentration is $N = 0.8 \times 10^{25}\,g/m^3$, the signal optical power reaches the maximum value of $P_{smax} = 0.0100\,W$ at the fiber length of L=3.7524 m. Considering the effect of different concentrations on the signal optical power, when the doping concentration increases, the signal optical power increases faster in the nearly linear phase, which

shows a larger slope of the curve. The slope of the curve is larger, and the larger doping concentration also makes the signal optical power reach the maximum value at a smaller fiber length. The decreasing curve of ASE optical power is similar to the changing curve of signal optical power, and its image is shown in Figure 7(d).

The variation curves of pump optical power with fiber length for different doping concentrations are shown in Fig. 7(c). As the fiber length increases, the pump optical power decreases approximately linearly until it decreases to 0. However, it is worth noting that after the fiber length reaches a certain value, the pump optical power increases as the fiber length decreases, showing that there is a more obvious turning point in the curve. When the doping concentration is $N = 2.4 \times 10^{25}\ g/m^3$, the signal optical power reaches 0 at the fiber length of L=0.7057 m, and the curve shows a turning point of the decreasing rate at the fiber length of L=0.3915 m. When the doping concentration is $N = 2.4 \times 10^{25}\ g/m^3$, the signal optical power reaches 0 at the fiber length of L=1.3818 m, and the curve shows a turning point of the decreasing rate at the fiber length of L=0.75 m. When the doping concentration is $N = 0.8 \times 10^{25}\ g/m^3$, the signal optical power reaches 0 at the fiber length of L=2.0520 m, and the curve turns at a decreasing rate at the fiber length of L=1.3735 m. When the doping concentration is $N = 0.4 \times 10^{25}\ g/m^3$, the signal optical power reaches 0 at the fiber length of L=3.5 m. When the doping concentration is $N = 0.4 \times 10^{25}\ g/m^3$, the signal power reaches 0 at the fiber length of L=3.8606 m, and the curve turns at a decreasing rate at the fiber length of L=2.2085 m.

3.3 Relationship between each parameter of fiber amplifier and fiber length at different signal optical initial power

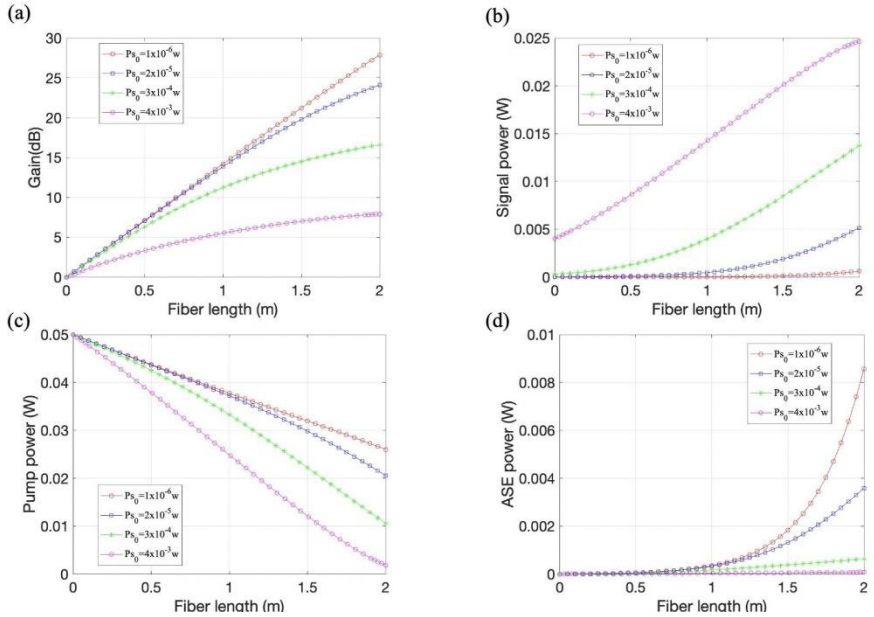


Fig 8 Variation of fiber amplifier magnification, signal optical power, pump optical power and ASE optical power with light length at different signal optical initial power

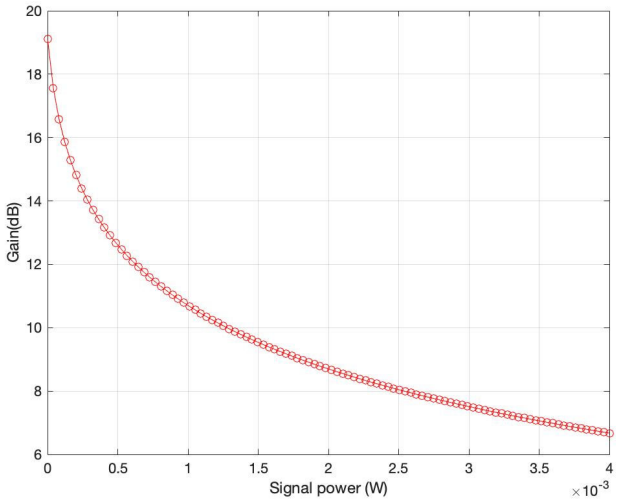


Fig 9 Fiber amplifier magnification versus signal optical power

First, according to Figure 8 to explore the effect of the initial power of the signal light, without loss of generality, set the pump laser repetition frequency of 808 kHz, resonant cavity length of 50 cm, and the fiber doping concentration is.

From Figure 8 (a), the signal light initial power of 4×10^{-3}W is the most significant increase in signal light power. Presumably,the number of signal photons per unit time and the fiber material is the best match at this power. At the same time, the initial power of 10^{-6}W the signal light photon number is too small, the power issued is too low, and not suitable for practical applications.With an initial signal light power (up to 0.025W), the fiber amplifier has a signal light power of 410-3W, equivalent to roughly 310-4W. It is three times as powerful as the fiber amplifier with an initial signal light power of 210-5W and twice as powerful as the fiber amplifier with an initial signal light power of 10-5W. It may infer that elements like doping concentration reduce the impact of the signal light's starting power on the signal light power.

From Figure 8(b), the larger the initial power of the signal light, the smaller the pump light power, and approximately constitutes a linear relationship. Specifically, the pump light power of 10^{-6}Wthe fiber amplifier with the initial power of the signal light, is the largest, 0.025W (2m fiber length). Presumably, because the signal photon energy per unit time increases, resulting in the energy difference with the jump energy decreases, only a smaller pump light power is required to jump.

According to Figure 8(c), the ASE of the fiber amplifier decreases as the initial power of the signal light increases, and it constitutes an approximately exponential relationship. In particular, the effect of the signal light initial power on the ASE power is not obvious when the fiber length is less than 1.2m. In comparison, the amplifier ASE power changes dramatically with fiber length (from 0.75mW to 8.75mW) for the signal light initial power of 10-6W when the fiber length is greater than 1.2m. The amplifier ASE power of 2×10^{-5}W increases relatively slowly for the signal light initial power (from 0.75mW to 3.5 mW), and none of the changes are significant at the smaller initial signal light power in the figure. The reason is that the smaller initial power of the signal light will lead to too few high-energy particles entering the reversal field per unit time, and it is difficult to produce the expected jump under the excitation of the pump light, and increasing the fiber length means extending the distance of particle reversal, which is not obvious before breaking the threshold.

As can be seen from Figure 8(d), the gain coefficient of the signal light of 10^{-6}Wdecreases as the signal light power increases. Specifically, the image of the initial power is approximately linear, while the enhancement of the fiber length gradually reduces the gain multiplicity as the initial power of the signal light increases. The reason for this phenomenon is presumed to be that the energy available from the pump light is certain, and the more signal photons per unit time, the less energy a single photon obtains on average, and the probability of leapfrogging decreases, manifesting as a decrease in gain multiplicity.

From Figure 9, the fiber amplifier gain multiplier decreases monotonically with increasing signal optical power. It is necessary to try to reduce the system's signal optical multiplier to reach the system's peak amplification, which also explains the correlation between Figures9 (a-b).

3.4 Experimental expansion: numerical relationship between fiber amplifier parameters and signal light wavelength at a certain fiber length

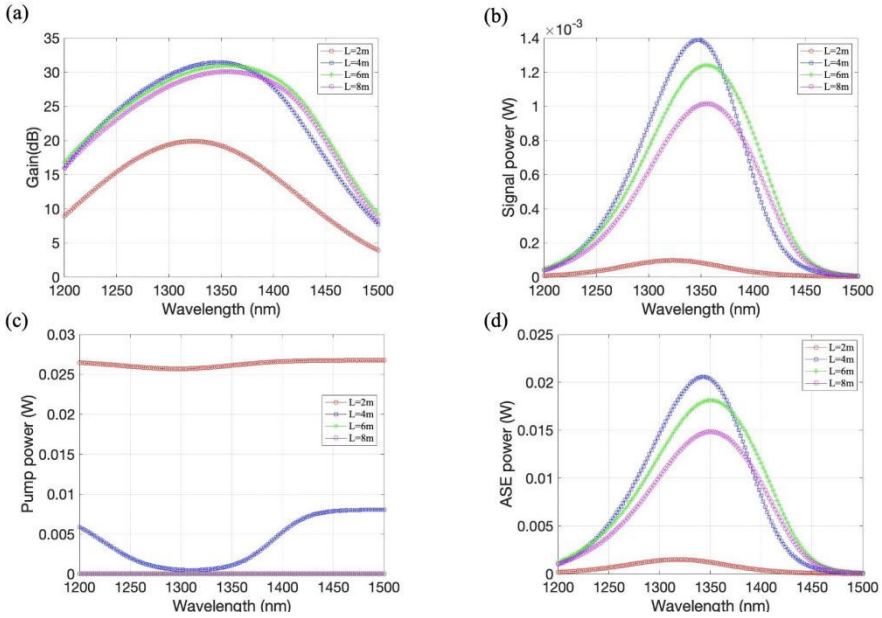


Fig 10. Relationship between the amplification

Fig 10. Relationship between the amplification, signal optical power, pump optical power and ASE optical power of the fiber amplifier with the wavelength of the signal light at different fiber lengths

In the above experiments, the relationship between fiber amplifier parameters and fiber length at 1323 nm signal wavelength is clear. However, whether there are better fiber amplification parameters at similar wavelengths is yet to be proven. Therefore, the next simulation reveals the effect of fiber length on fiber amplifier parameters in the 1200-1500 nm band, and many features can be analyzed from the data plots.

From Figure 10(a), it can be seen from the image trend that the ASE power is single-peaked with increasing signal light wavelength at different fiber lengths, presumably because the amplification and reabsorption of the fiber amplifier are wavelength dependent. The total reflection condition determines the capture rate of spontaneous radiation.So the ASE light power will reach a maximum at a specific wavelength.E.g., the signal light wavelength (ASE light wavelength) is about the ASE power of fiber amplifiers with fiber lengths of 4, 6, and 8 m. All reach their peak at 1340 nm. Specifically, in the 1340 nm band, the ASE power decreases as the fiber length becomes larger, 0.021 W (4m), 0.018 W (6m), and 0.015 W (8m), respectively; in the 1323 nm band, the ASE power is 0.02 W (4m), 0.017 W (6m), and 0.013 W (8m). Compared to the two bands ASE power value difference is not large, is within 0.002W, and the actual production impact is not significant, according to the actual needs of discretionary choice. Unlike the other three fiber lengths, for fiber amplifiers with a fiber length of 2m, 1323nm wavelength is more advantageous. Still, the ASE power is smaller (0.002W), the overall change in ASE power is smooth and the difference is no more than 5% from 1310nm to 1330nm. In addition, the purple curve (4m) intersects with the green curve (6m) and the pink curve (8m) in the 1375nm and 1385nm bands, respectively, presumably because the spatial coherence of ASE light is highly dependent on the environment. The smaller the fiber length the more sensitive it is to the perception of wavelength changes.A signal light with a wavelength of around 1340 nm should be used for fibers between 4 and 8 meters, while one with a wavelength of 1310 nm to 1330 nm should be chosen for fibers under 2 meters.

As can be seen from the image trend, the amplification of the fiber amplifier increases and then decreases with the increase of signal light wavelength at different fiber lengths, presumably because the ratio of signal light absorbed photons to exciting radiation photons is related to the wavelength. There is always an optimal wavelength for a specific fiber length to optimize the ratio of the two, that is, there will be a peak. For example, the signal light wavelength (ASE light wavelength) is about 1350nm (1375nm) at the fiber length of 4, 8m (6m) fiber amplifier ASE power is at peak. Specifically, the peak gain of EDFA in the 1350nm band is 32dB (4m) in order, 32dB (6m), 30dB (8m), which is better than the 1323nm of the previous experiment, but the difference is less than 5%. For the fiber amplifier with a 2m fiber length, although the 1323nm wavelength is more advantageous, the amplification is smaller, about 20dB. It is speculated that the power gain increases and then decreases with the increase of fiber length, which is similar to the previous study. The longer the length of Nd-doped fiber, the longer the action area of the number of particles that can be reversed, and the longer the action area, the larger the corresponding power gain will be. However, with the further enhancement of the fiber length, the loss will also increase, even more than the increased power, which is manifested as the reduction of power gain. It can be concluded that for a 4/8m fiber, 1350nm signal light should be used, for a 6m fiber, 1375nm signal light should be used, and for a 2m fiber, 1323nm signal light should be used.

As can be seen from Figure 10(c), for fiber amplifiers with a fiber length of 2, 6, and 8m, the pump light power has almost no relationship with the signal light wavelength (ASE light wavelength), while for amplifiers with a fiber length of 4m, the pump light power reaches a low peak at 1300nm wavelength, and then increases first and then remains unchanged. The presumed reason is that the signal light wavelength is relatively independent of the pump light power. The optical excitation of the pump light source at a specific fiber length is affected by the inversion of the signal light particle number, which is manifested as a power reduction. The pump light power is lower at the optimum wavelength of about 1350 nm for the 4m fiber. The signal light at 1375 nm can be used to maintain a certain pump light power while maintaining a high amplification efficiency.

As can be seen from Figure 10(d), the fiber amplifier with fiber length of 4-6m reaches the peak signal optical power at signal light wavelength (ASE light wavelength) of about 1350nm, specifically 0.0014W (4m), 0.00125W (6m), 0.001W (8m). The fiber amplifier with fiber length of 2m reaches the maximum signal optical power at a wavelength of about 1325nm (0.0001W). The overall trend is consistent with Figure b. There is a coherent relationship between ASE light and signal light, and the optimal parameters of the two are the same.

4. Conclusion

In this experiment, the output characteristics of gain modulated neodymium-doped (HoyaLHG-5) fiber oscillator and amplifier are investigated from numerical simulation. Based on the laser rate equation and the transmission equation, the numerical models of the oscillator and the amplifier were constructed and solved by the FDTD method to obtain the output of the laser. The gain-modulated neodymium-doped fiber laser with an all-fiber MOPA structure was constructed, and the effect of these parameters on the output characteristics of the laser was investigated by varying the doping concentration of the fiber and the resonant cavity structure. Finally, according to the simulation results, the laser was optimized in the fiber length range of 0-2m, with the parameters of 1.3m, doping concentration of 1.2×10^{25}W, and initial power of 3×10^{-4}signal light, to obtain a high conversion efficiency, narrow linewidth and single polarization laser output in the nanosecond 2μm band. The 2 μm pulsed laser output with a maximum power of 340 mW and amplification of 42 dB was obtained by using the main oscillator, and the 2 μm pulsed laser output with a maximum power of 9.13W was obtained by using a power amplifier. The numerical model based on the FDTD method can be effectively applied to the experimental and engineering design of gain modulated neodymium-doped fiber laser, so that the laser can be constructed to meet the requirements of relevant applications.

According to the extended experimental conclusions, although longer fiber lengths can provide better parameters, the signal light (ASE light) at 1323 nm can provide better amplification performance for fiber lengths below 2 m.

References

[1] Li Jian, He Jingliang, Hou Wei, Chen Yuchuan, Xu Zuyan. Study on the effect of Nd~(3+) doping concentration on the output characteristics of high-power all-solid-state Nd:YVO_4 laser [J]. China Laser, 2000(04): 298-302.

[2] Gan Fuxi. The energy transfer process of neodymium ion Nd~(3+) in inorganic glass—I. Radiation transition[J]. Science Bulletin, 1978(12):723-726.

[3] Yang Dianlai. Optical and Spectral Properties of Rare Earth Ions in Bismuth Tellurate Glass [D]. Dalian Institute of Light Industry, 2006.

[4] Ren Guangjun, Wei Zhen, Zhang Qiang, Yao Jianquan. Research on neodymium-doped polarization-maintaining fiber amplifier[J]. Acta PhysicaSinica, 2009,58(06):3897-3902.

[5] Kong Yong, Guo Mingxiu, Lu Yutian. Analysis of nonlinear refractive index of neodymium-doped fiber amplifier [J]. China Laser, 2004(07):789-792.

[6] Peng Zhaoliang, Ma Shanchao, Lu Sihua, Luo Changfei, Zhang Baofu, Jiao Zhongxing. Numerical simulation and experimental study of gain-modulated thulium-doped fiber laser [J]. Advances in Lasers and Optoelectronics, 2020,57(19):184-191.

[7] Yang Xingchen, Zhou Zhaoqin, Satisfaction, Xu Hui, Zhang Dan. Research on performance of Nd-doped polymer optical waveguide amplifier based on LED pumping[J/OL]1-14[2022-08-26].http://kns.cnki.net/kcms/detail/31.1339.TN.20220623.1534.002.html

[8] Gan Fuxi. Energy transfer process of neodymium ion Nd~(3+) in inorganic glass II. Nonradiative transition [J]. Science Bulletin, 1979(02):59-62.

[9] Jiao Licheng, Yang Shuyuan, Liu Fang, Wang Shigang, Feng Zhixi. Seventy Years of Neural Networks: Retrospect and Prospect [J]. Journal of Computer Science, 2016, 39(08): 1697-1716.

[10] Yang Baolai, Wang Xiaolin, Ye Yun, Zeng Lingfa, Zhang Hanwei, Xi Xiaoming, Shi Chen, Wang Peng, Han Kai, Wang Zefeng, Zhou Pu, Xu Xiaojun, Chen Jinbao. The output power of an all-fiber laser oscillator exceeds 6 kW[J]]. China Laser, 2020, 47(01): 338.

[11] Zhu Hongtao. Study on the lifetime model of ~4I_(11/2) energy level of neodymium ions [J]. Journal of Lasers, 2001(06):25-27.

[12] Lou Qihong, He Bing, XueYuhao, Zhou Jun, Dong Jingxing, Wei Yunrong, Wang Wei, Li Zhen, Qi Yunfeng, Du Songtao, Zhao Hongming, Chen Weibiao. 1.75kW domestic Yb-doped double-clad fiber laser[J] .China Laser, 2009, 36(05):1277.

[13] Kong Yong, Guo Mingxiu, Lu Yutian. Effect of bending loss on gain of neodymium-doped fiber amplifier [J]. Acta PhotonicaSinica, 2003(08):900-903.

[14] Yu Ling, Zhang Hao, Liu Yange, Yuan Shuzhong, Kai Guiyun, Dong Xiaoyi. Experimental study on an ultra-wideband Erbium-doped fiber amplifier [J]. Journal of Nankai University (Natural Science Edition), 2006(01):70-73 .

[15] Liu Yi, Guo Rongrong, Yi Xiaogang, Zheng Yongqiu, Chen Pengfei. Gain Flatness Characteristics of Erbium Doped Fiber Sagnac Ring Erbium Doped Fiber Amplifier [J]. China Optics, 2020, 13(05): 988-994.