Experimental and theoretical analysis on pump spectral propriety of single frequency Erbium-Ytterbium co-doped fiber amplifier

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Abstract
The pump spectral propriety of three types of commercial 915 and 976 nm LDs on single frequency Erbium-Ytterbium co-doped fiber amplifier (EYDFA) is theoretical and experimental analyzed. The slope efficiency, ASE intensity and linewidth broadening of the wavelength stabilized or un-stabilized LDs pumped amplifier are compared in detail. The results demonstrate that 976 nm LD pumping exhibits superior to 915 nm LD in efficiency and SNR. Comparing with wavelength stabilized 976 nm LD, the wavelength un-stabilized 976 nm LD with center wavelength deviating from Yb absorption peak and over 4 nm linewidth has better performance in Yb-ASE suppression but slightly lower in efficiency and linewidth broadening. The difference between the two 976 nm LDs could be taped off by increasing the seed power or output power. This work indicate that wavelength un-stabilized 976 nm LD is more suitable for pumping high power single-frequency EYDFA to avoid the bottlenecking effect, and provide reference for the optimal pump selection.

1. Introduction
The single-frequency fiber laser at 1.5 μm band has many applications on the LIDAR, coherent communication and so on [1–3]. Up to now, the Erbium-Ytterbium co-doped fiber master oscillator power amplifier (MOPA) is more suitable configuration to realizing hundreds of watts of output power and narrow linewidth of kHz-level than others [4, 5]. In 2005, Jeong et al obtained 151 W single frequency fiber laser with Er/Yb co-doped fiber MOPA [6]. We also got 56.4 W single-frequency fiber laser with 4.21 kHz linewidth by using the cascaded Er/Yb co-doped fiber amplifier (EYDFA) [7]. The single frequency laser also can be obtained in silicon oscillators [8]. However, the power scaling of EYDFA is limited by either stimulated Brillouin scattering (SBS) or amplified spontaneous emission (ASE) [9]. The SBS effect can be suppressed by using large-mode-area fiber [8], temperature gradient [10], stress gradient [11], or modulating seed laser spectrum [12]. Due to the Er/Yb co-doped energy system, the Yb-ASE of EYDFA, whose wavelength mainly around 1000–1100 nm, has obvious limitation on output power and slope efficiency. When the pump rate exceeds the Yb-to-Er energy transfer rate, the gain of signal at 1.5 μm decreases through rapid increasing of Yb-ASE. This phenomenon named as ‘bottlenecking effect’ was reported in literature [9] in 2007 by the first time. The Yb-ASE suppression can be achieved by injecting an auxiliary light with a wavelength of 1 μm into the gain fiber via fiber grating [13] or another laser system [14]. The auxiliary signal can be amplified together with the signal while avoiding Yb-ASE accumulation. But this method increased in complexity and costs as well. Choosing the appropriate pump laser diode (LD) whose center wavelength deviated from Yb absorption peak (976 nm) for pumping also can lessen the impact of Yb-ASE. In 2016, D. Creeden et al used a 940 nm LD pumped single frequency EYDFA, and realized the recorded maximum 264 W single frequency laser output at 1560 nm [15]. And then the pump wavelength dependence of ASE and SBS in single-frequency EYDFA was investigated theoretically by P. Booker et al in 2018 [16]. The wavelength off-peak pump laser can reduce the thermal loading and Yb inversion per unit length of the gain fiber, which can improve overall efficiency at 1.5 μm band by suppressing the Yb-ASE. However, the center wavelength shifting of semiconductor laser is hard to control due to the challenge of pump...
In this letter, the pump spectral propriety of three typical commercial 915 and 976 nm LDs on single frequency EYDFA is theoretical and experimental analyzed. The wavelength stabilized and un-stabilized LDs are used for fiber laser amplification and their output performance, i.e. slope efficiency, signal-to-noise ratio (SNR) are measured. The influence of pump spectral propriety on Yb-ASE suppressing and output linewidth broadening are studied in experiment also. The results demonstrate that 976 nm LD pumping exhibits superior to 915 nm LD in efficiency and SNR. The efficiency and linewidth broadening of wavelength un-stabilized 976 nm LD is slightly lower than that of wavelength stabilized 976 nm LD while the wavelength un-stabilized 976 nm LD has weaker Yb-ASE intensity. The results indicate that wavelength un-stabilized 976 nm LD is more suitable for pumping high power single-frequency EYDFA to avoid the bottlenecks effect. This work provides a possible technical route to break through the EYDFA power limitation.

2. Experimental setup

The schematic diagram of the experimental setup is shown in figure 1. The single frequency seed laser is a homemade ring fiber laser with 1.5-m-long un-pumped Erbium doped fiber (Nufern, SM-ESF-7/125) as saturable absorber. The maximum launched power is 35 mW. The output spectra at maximum output are recorded in figures 2(a) and (b) by optical spectrum Analyzer (Anritsu, MS9710C).

The center wavelength of seed laser is 1550.14 nm, corresponding to the reflection wavelength of 0.5 nm bandwidth fiber Bragg grating (FBG). The laser with a center wavelength of 1550 nm has the lowest transmission loss in quartz fiber and be used as seed laser to test performance of EYDFA. The linewidth of seed laser at maximum output is measured by delayed self-heterodyne method. The linewidth measure system contains 70-MHz acousto-optic modulator, 50-km-long delay fiber, and optic-electric detector (Thorlabs, DET01CFC). The line shape and Lorentz fitting line of seed laser is shown in figure 2(c). According to the measured 20 dB linewidth of 12.63 kHz, the calculated 3 dB linewidth of seed laser is about 630 Hz. A pre-amplifier, which is consisted of wavelength stabilized 976 nm pump LD, double-cladding Er/Yb co-doped fiber (Nufern, SM-EYDF-6/125) with length of 2 m, (2 + 1) x 1 combiner and cladding light stripper (CLS), boosts the seed laser so that the signal power injected into the power amplifier can be adjusted within the range of 10 mW to 1 W. The core and cladding diameter of gain fiber is 6 and 125 μm, respectively. After being launched from pre-amplifier, the signal laser is injected into the power amplifier via an isolator and combiner. The gain fiber of main amplifier is 3-m-long EYDF-6/125 fiber and placed on a heat sink. Three kinds of common commercial semiconductor LDs are selected as pump sources: the wavelength stabilized 976 nm LD (WS-976 nm) with center wavelength of 976.4 nm and linewidth of 0.7 nm, the wavelength un-stabilized 976 nm LD (WUS-976 nm) with center wavelength of 968.0 nm and linewidth of 4.8 nm, the wavelength un-stabilized 915 nm LD (WUS-915 nm) with center wavelength of 905.2 nm and linewidth of 5.3 nm. The normalized output spectra of these pump LDs are shown in figure 2(d). These pump LDs are all coupled into the gain fiber from the same pump port of the (2 + 1) x 1 combiner with over 97% efficiency to avoid pump port coupling difference. The end of amplifier is
connected sequentially with a CLS to remove the residual cladding pump and a piece of passive fiber with angle-cleaved end to launch the signal.

3. Results and discussion

3.1. Theoretical analysis

The single-frequency EYDFA pumped by three types of commercial 915- and 976 nm LDs are numerically analyzed based on rate equations and power transfer equations [17–19]. The theoretical model of the power amplifier is the same as the experimental structure in figure 1. The length $L$ of EYDF is assumed to be 3 m. The signal and pump laser are assumed forward coupled into the EYDF-6/125 gain fiber from left end together. The amplified signal is launched from the right end of gain fiber. To simulate the influence of spectral profile on the output characteristics of EYDFA, the pump spectra of wavelength un-stabilized 976 and 915 nm LD are divided into discrete channels with a sampling width of 1 nm and the pump power should be allocated to each separated channels before the simulation. For example, as shown in figure 3(a), the pump power of wavelength un-stabilized 976 nm LD is distributed to five separate channels symmetrically distributed around 968 nm. The wavelength of channels can be ranged sequentially from 966 to 970 nm. The pump power allocation from center to edge channel is set to be 26%, 22% and 16% according the relative intensity of pump spectral profile at each center wavelength. The pump power evolution can be simulated by substituting the corresponding wavelength, absorption and emission cross sections of each channels into following equations (1)–(2).

\[
P_p(z) = \sum_{n=1}^{s} r_n P_n(z, \lambda_n) \tag{1}
\]

\[
\frac{dP_n(z, \lambda_n)}{dz} = \left\{ \begin{array}{l}
\Gamma_p \sigma_{65}(\lambda_n) + \sigma_{65}(\lambda_n) N_0(z) - \sigma_{56}(\lambda_n) N_{10} \end{array} \right\} P_n(z, \lambda_n) - \Gamma_p \alpha P_n(z, \lambda_n) \tag{2}
\]

In this work, only the forward transmitted pump light is considered. The $P_p(z)$ in equation (1) is the pump power at $z$ position of EYDF. The pump power $P_p(z)$ is allocated to $n$ simulated channels, and the values of $n$ is 5 according to the channel division assumption mentioned above. $\lambda$ and $r_n$ are the center wavelength and corresponding power distribution ratio of each channels, respectively. The $P_n$ is the pump power distributed on the channel with $\lambda_n$. The power of wavelength stabilized 976 nm LD does not need to be divided because the output linewidth is narrow than 1 nm. For simplicity, the power of wavelength un-stabilized 915 nm LD is also distributed in the same way of WUS-976nm LD. This calculation method is also used to estimate the carrier distribution for reflecting the tendency of photons emitted angle in Si gate-controlled light-emitting device [18].

![Figure 2.](image-url)
Figure 3. (a) Schematic diagram of pump spectrum segmentation in simulation. (b) Output power performance of signal with 10 mW and 1 W seed power under three kinds of pumping. (c) The ASE intensity evolution in Er-band and Yb-band. (d) Evolution of output power and ASE power along fiber length with pump spectral width.
The equation (2) is the power evolution equation of pump light. The $\sigma_{67}(\lambda)$ and $\sigma_{68}(\lambda)$ in equation (2) are the absorption and emission cross section of Yb-ions at the wavelength of $\lambda_6$, respectively. The $N_y(\lambda)$ is the upper-level population of Yb-ions at $z$ position. The $N_p$ is the total Yb doping concentration and the value is $3.305 \times 10^{26} \text{ m}^{-3}$ according to $[19]$. The influence of pump spectral profile on output of the amplifier can be calculated by adding the equations (1) and (2) to the rate equation groups. To improve readability, other equations of the rate equation groups referred to literatures $[19, 20]$ are not listed here. The values of cladding overlap factors $\Gamma_p$, scattering loss $\alpha$ and other parameters are also referred to literatures $[19, 21]$. We solved the equations numerically with finite difference method which is reported by Zheng in 1994 $[22]$ and Han in 2014 $[21]$.

The output power performance of amplifier with 10 mW and 1 W seed power under three kinds of pumping is simulated, and plotted in figure 3(b). If seed power is set to be 10 mW, the slope efficiency of WUS-976 nm LD pumped amplifier is 19.6%, which is 0.8% higher than that of WUS-976 nm LD pumping. When seed power is increased to 1 W, the slope efficiency can improve to 31.2%. Comparing with the simulation results of the 976 nm pump LD, the efficiency of 915 nm LD pumping is only 11.3% at 10 mW seed power and 17.8% at 1 W. The advantage of wavelength stabilized pump LD in amplification efficiency can be attributed to its high absorption coefficient. The center wavelength of wavelength stabilized LD can match the peak of Yb-ions absorption cross-section curve. However, when the pump power exceeds 25 W, the output power of 1 W seed under WS-976 nm pumping is saturated, and the slope efficiency is dropped to 4.3%. This power saturation will also occur until the pump power of wavelength un-stabilized 976 nm LD exceeds 30 W, which leads to the reduction of slope efficiency to 9%. Although the 976 nm pump with narrow spectral width can obtain higher amplification efficiency at low pump level, the amplifier pumped by WUS-976 nm can obtain higher output power than others at high pump level. To explain this results, the ASE intensity at Yb- and Er-band are simulated and plotted in figure 3(c). When the pump power is less than 30 W, the Yb-ASE of WS-976 nm LD pumped amplifier is $1.1 \sim 2.8$ dB higher than that of the un-stabilized 976 nm pumped amplifier, while the Er-ASE is only $0.5 \sim 0.8$ dB higher. It means that wavelength un-stabilized 976 nm LD can not achieve Yb-ASE suppression by changing pump wavelength to reducing pump absorption. However, as the pump power increases, the difference in Yb-ASE intensity will tend to disappear and form new differences in the opposite direction. The Yb-ASE intensity of 40 W WUS-976 pumped amplifier is $-25.4$ dB, which is $5.4$ dB higher than that of narrow linewidth 976 nm pumped at same power level. It demonstrates that the suppression of Yb-ASE by using wavelength un-stabilized 976 nm pump LD only has limited effective in a relatively low pump power level. In order to obtain better suppression effect, the pump wavelength needs to be further optimized $[15]$. A typical amplification process is choosed to analysis the influence of pump spectrum on output power. The output power and Yb-ASE intensity evolution of the amplifier with 10-mW seed is simulated and show in figure 3(d). The pump power is set to be 10 W. The center wavelength of pump light is assumed to be 976 nm, which is matched to Yb absorption peak. The spectral width of the pump light varies from 1 to 4 nm by setting the $r_n$ value in equation (1). For example, assuming that the pump spectral width $\Delta \lambda$ is 1 nm, the number of virtual channels $n = 1$ and $r_n = 100%$ are setted. When the $\Delta \lambda = 2$ nm, $n$ is set to be 3. The wavelength of channels ranges sequentially from 975 to 977 nm. The corresponding $r_n$ of each channels are 10%, 80% and 10%, respectively. When $\Delta \lambda = 3$ nm, the corresponding $r_n$ of each channels change to be 20%, 60% and 20%, respectively. When $\Delta \lambda = 4$ nm, $n$ increases to 5 and two new virtual channels with wavelengths of 974 and 978 nm are added. The power allocation ratio $r_n$ of the five channels is 10%, 20%, 40%, 20%, 10%, respectively. The simulated results shows that the narrower the pump spectral width is, the stronger Yb-ASE will be produced in the front segment of gain fiber, which makes the output power quickly reach saturation. When the pump spectrum becomes wider, the distribution of Yb-ASE is smoother in the whole fiber, which helps to block the premature power saturation and obtain higher output power by extending the gain fiber.

In particular, although the intensity of Er-ASE and Yb-ASE is very low when 915 nm pump power exceeds 15 W, the wavelength un-stabilized 915 nm pump LD is not an ideal choice for EYDFA due to the low amplification efficiency. In this work, we mainly discusses the pump source with wavelength around 976 nm.

3.2. Experimental results

When the signal power of power amplifier is set to 10 mW. The power scaling under different pump sources are recorded by power monitor (Thorlabs, S425C-L), which are shown in figure 4(a). Under the WS-976 nm pump, the slope efficiency of amplifier is measured to be 16.0%, which is higher than that of WUS-976 nm pumping by 1.6%. The WUS-915 nm has obtained the minimum slope efficiency which is only 7.1%. When the gain fiber length is fixed, the amplification efficiency depends on the pump absorption, and the absorption is related to Yb-ions absorption cross-section.

To further compare the pump wavelength propriety on the output spectra, the output power are maintained to be 1 W by carefully adjust the pump power when measuring the spectra. The output spectra at 1 W output are
plotted in figure 2(b). The SNR in 1.5 μm band under WUS-915 nm pumping is only 18.8 dB, which is far lower than that of WS-976nm (39.8 dB) and WUS-976 nm (37.4 dB). It should be noted that WS-976 nm pumping has less 1.5 μm ASE intensity than wavelength un-stabilized LD pumping due to the high slope efficiency. However, as shown in the insertion of figure 4(b), the WUS-976nm pumping has lowest intensity of Yb-ASE than others. The Yb-ASE intensity of WS-976 nm pumping is −59.89 dB, which is 1 dB more than that pumped by WUS-976 nm, and far lower than 915 nm (−58.87 dB). Because of low pump absorption, the 915 nm pumped LD has no advantages in amplification efficiency and output SNR. Comparing the results of wavelength stabilized and un-stabilized LD, it is indicated that the wavelength un-stabilized 976 nm LD pumping has potential in suppressing Yb-ASE.

When the seed power of power amplifier is increased to 1 W, the output power evolution with different pump sources are shown in figure 5(a). Because of the increasing of seed power, the slope efficiency is universally improved and the trend of relative efficiency is the same as that of 10 mW seed. The slope efficiency of the amplifier pumped by WS-976 nm LD is 29.1% in this seed level. Meanwhile, the efficiency of WUS-976 nm and WUS-915 nm pump are 28.4% and 20.8%, respectively. The output spectra at 5 W output power with different pump are shown in figure 5(b). It can be seen that 976 nm has the maximum output SNR (40 dB) in 1.5 μm band. The SNR under WUS-976 nm and WUS-915 nm are 37.4 and 18.4 dB, respectively. The trend of relative ASE intensity at 1.5 μm band is the same as that of 1 W seed power also. The insertion of figure 5(b) illustrates the relative Yb-ASE intensity trend has no obvious change. WUS-976 nm pump still has the minimum Yb-ASE intensity, corresponding value is −50.6 dB. The Yb-ASE of WS-976 and WUS-915 nm are −49.5 dB and −47.9 dB, respectively.

It can be inferred from the above experimental results that the central wavelength and linewidth of the pump source have obvious influences on the amplification efficiency and ASE when the gain fiber length is fixed. Due to the low efficiency and SNR, the 915 nm LD is not the best choice for EYDFA. The WS-976 nm and WUS-976

![Figure 4.](attachment:image.png)

Figure 4. (a) The power scaling of main amplifier under different pump sources with 10 mW seed power. (b) the output spectra at 1 W output power. The insertion is zoomed spectra from 1000 to 1100 nm.
nm pumping are excellent candidates of EYDFA because of the great output efficiency, SNR, and Yb-ASE performance. Comparing with the wavelength un-stabilized 976 nm pumping, the WS-976 nm pumping has more advantages in efficiency and Er-band ASE, but poor in Yb-ASE intensity. This experimental results is consistent with the theoretical analysis results mentioned above. By shifting the pump center wavelength away from Yb absorption peak, the pump absorption can be reduced properly to avoid the raptly rising of Yb-ASE. Then the overall efficiency of the amplifier can be improved by increasing the length of gain fiber.

However, we found this advantage of wavelength stabilized 976 nm pump was reduced with the increasing of seed and output power in experiment. The measured relationship between slope efficiency with seed power of WUS- and WS-976 nm pumping is plotted in figure 6(a). The slope efficiency with these 976 nm pumps shows a general ascending trend with the seed power. While the difference between them (mark as hollow dot) is reduced from 1.6% at 10 mW seed to 0.7% at 1 W seed. We consider the reason is increasing of seed power can promote the Er/Yb energy transfer and avoid the Yb-ASE accumulation. This explanation can also be obtained by comparing the output ASE intensity. The function between ASE and output power with 1 W seed is shown in figure 6(b). The overall trend of ASE intensity at 1 or 1.5 μm band raises up with the increasing output power. In 1.5 μm band, the ASE intensity difference between the WS-976 nm and WUS-976 nm pumping is almost constant. However, the 1 μm ASE intensity difference decreases continuously with output power. This demonstrates that the wavelength un-stabilized 976 nm pump LD can only reflect its advantage in limited power range. When the pump power is lower than the bottleneck effect threshold, choosing WS-976 nm pump source with narrow linewidth can obtain high quality 1.5 μm laser output. If the pump power over the threshold, the wavelength un-stabilized pump LD with low pump absorption can be used as the pump source to suppress Yb-ASE and maintain the slope efficiency at an acceptable level. This power limitation is related to seed power, absorption coefficient at pump center wavelength, linewidth of pump laser, and so on.

In addition, we measured the output linewidth at 5 W output power. The line shapes and Lorentz fitting lines are shown in figure 7. The measurement results are averaged 100 times to reduce the measurement error. The 20

![Figure 5](image-url). (a) The power scaling of main amplifier with 1 W seed power. (b) The output spectra at 5 W output power. The insert is zoomed spectra from 1000 to 1100 nm.
dB linewidth of WS-976 nm and WUS-976 nm pumping measured are 28.4 and 31.0 kHz, corresponding to 3 dB linewidth of 1.43 and 1.55 kHz, respectively. We infer that the linewidth difference is caused by the 1.5 μm ASE. Under WS-976nm pump, the signal laser has a lower 1.5 μm noise, which leads to a smaller broadening of linewidth during amplification [23].

**Figure 6.** (a) The relationship between slope efficiency with seed power of WUS- and WS-976 nm pumping. (b) The function between ASE and output power with 1 W seed.

**Figure 7.** The line shapes and Lorentz fitting lines with WS-976 nm and WUS-976 nm pumping at 5 W output power.
4. Conclusions

In conclusion, the application potential of wavelength stabilized and wavelength un-stabilized LDs with center wavelength at 915 nm or 976 nm in suppressing the bottlenecking effect of EYDFA are theoretical and experimental analyzed by comparing the efficiency and output spectra. Reducing pump absorption per unit length by selecting appropriate pump spectral propriety can effectively suppress Yb-ASE to overcome the bottleneck effect. Although the wavelength un-stabilized 915 nm LD has the minimum pump absorption among the three types of commercial pump LDs, the strong ASE intensity in either 1 or 1.5 μm band and low efficiency limit its application in EYDFA. Therefore, the 976 nm pump laser is a good candidate for single frequency EYDFA. Comparing with wavelength stabilized 976 nm LDs, wavelength un-stabilized 976 nm LD with center wavelength deviating from Yb absorption peak and over 4 nm linewidth has slight reduction of efficiency, but has relative low Yb-ASE intensity in favor of suppressing the pump bottlenecking effect. Meanwhile, the difference between the two 976 nm LDs could be taped off by increasing the seed power or output power. In addition, reducing the amplification efficiency will also make 1.5 μm ASE enhanced, resulting in the linewidth broadening. Roughly speaking, in the fiber length fixed EYDFA, there is a contradiction between the Yb-to-Er energy transfer efficiency and the amplification efficiency caused by the spectral propriety of the pump source. Only by considering the length of gain fiber and the spectral propriety of pump source at same time, can optimize the output characteristics of EYDFA. This work provides a reference for the optimal selection of pump source for single-frequency EYDFA.

Acknowledgments

This work is supported by Natural Science Foundation of Inner Mongolia Autonomous Region of China (2020BS06002).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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