Experimental optimization of an erbium-doped super-fluorescent fiber source for fiber optic gyroscopes

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Abstract: Double-pass forward and double-pass backward erbium-doped super-fluorescent fiber sources (ED-SFSs) were combined in one configuration. A 980 nm laser diode pumped the same erbium-doped fiber from both directions using a coupler as a power splitter. The double-pass configuration was achieved by coating the fiber end face. Firstly, an optimal fiber length was found to obtain a high stability of output light wavelength with pump power, and then 1530/1550 nm wavelength division multiplexing was used for spectrum planarization, which expanded the bandwidth to more than 22 nm. The final step was a test of temperature stability. The results show that the rate of the central wavelength change kept to below 3.5 ppm/℃ in the range of −40 to 60 ℃ and 1–2 ppm/℃ in the range of 20–30 ℃. Considering all the three factors of the fiber optic gyro applications, we selected 80 mA as the pump current, in which case the central wavelength temperature instability was calculated as 2.70 ppm/℃, 3 dB bandwidth 22.85 nm, spectral flatness 0.2 dB, output power 5.17 mW and power efficiency up to 9.92%. This experimental result has a significant reference value to the selection of devices and proper design of ED-SFSs for the application of high-precision fiber optic gyroscopes.

Key words: erbium-doped super-fluorescent fiber source; central wavelength stability; pump from both directions; spectrum planarization; coating on the fiber end; high-precision fiber optic gyroscope

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1. Introduction

The requirements of a light source for fiber optic gyroscopes (FOGs) are mainly reflected in three indexes: spectral width, output power and central wavelength stability. In applications of FOGs, broadband can reduce coherent noise, high power can improve measurement sensitivity and wavelength stability can improve the scale factor stability of the gyro, thereby enhancing precision[1, 2]. There are several kinds of light sources for FOGs, such as the laser diode (LD), light-emitting diode (LED), super luminescent diode (SLD) and the erbium-doped super-fluorescent fiber source (ED-SFS). As the LD has a high output power but narrow spectral bandwidth and the LED has a broad bandwidth but small output power, both of them can only be used for low-precision gyros. SLD and ED-SFS can be used in middle and high-precision gyros because of their higher output power and broader spectral bandwidth. Moreover the ED-SFS has better central wavelength stability than the SLD, which makes it to be the preferred source for navigation-grade high-precision FOGs.

The research on ED-SFS in the past twenty years has made great progress. Various kinds of configurations have been reported, some of which obtained up to 80 nm bandwidth or 1 W output power for applications such as dense wavelength division multiplexing (DWDM). The research on wavelength stability was mainly concentrated in the wavelength change with pump power, rarely in the change with temperature. In addition, with regard to wavelength stability with temperature, a lot of work has been done in the theoretical field but less in experiments. Wavelength instability of less than 3 ppm/℃ was achieved by Yang *et al.*[3] using a DPB configuration with a wavelength-selective reflector which has an unsatisfied spectral flatness. The difference between the peak and valley in the spectrum is about 5 dB, which makes the 3 dB bandwidth small, although its integral bandwidth is more than 28 nm. For FOG applications the 3 dB bandwidth is more sensible than the integral bandwidth. The temperature test is just for the erbium-doped fiber, not the whole configuration, which is another defect.

Central wavelength stability is the most critical index for high-precision FOGs, because the scale factor of a FOG is calibrated by the central wavelength of the light source. In other words, the central wavelength stability of the light source directly determines the stability of the scale factor stability of the FOG[4]. In engineering applications, the higher wavelength stability with temperature can also reduce temperature control precision. There are three main factors for the change of the central wavelength in ED-SFSs: the inherent temperature characteristics of the erbium-doped fiber, the change of pump wavelength and pump power with temperature. It can be expressed in mathematically as follows[5]:

$$\frac{\mathrm{d}\lambda_{\mathrm{s}}}{\mathrm{d}T}=\frac{\delta\lambda_{\mathrm{s}}}{\delta T}+\frac{\delta\lambda_{\mathrm{s}}}{\delta\lambda_{\mathrm{pump}}}\frac{\delta\lambda_{\mathrm{pump}}}{\delta T}+\frac{\delta\lambda_{\mathrm{s}}}{\delta P_{\mathrm{pump}}}\frac{\delta P_{\mathrm{pump}}}{\delta T}. \quad (1)$$

In the experiment, we found that the temperature coefficients $\frac{\delta\lambda_{\mathrm{pump}}}{\delta T}$, $\frac{\delta\lambda_{\mathrm{s}}}{\delta P_{\mathrm{pump}}}$ and $\frac{\delta P_{\mathrm{pump}}}{\delta T}$ can be positive or negative, which depends on the configuration parameters and working conditions. So, through the design of configuration parameters and optimization of working conditions we can make the three parts partially offset to achieve smaller $\frac{\mathrm{d}\lambda_{\mathrm{s}}}{\mathrm{d}T}$. This paper gives a double-pass configuration pumped from both directions uti-

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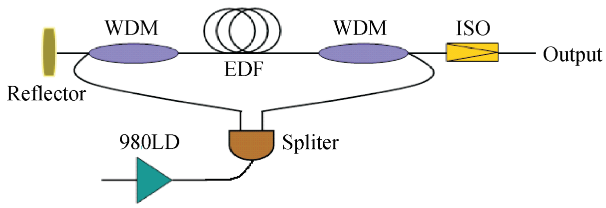

Fig. 1. A combined configuration of DPF and DPB.

lizing a coupler as a splitter. Firstly we found an optimal fiber length to obtain high stability of wavelength with pump power and relatively large output power, then utilized 1530/1550 nm wavelength division multiplexing (WDM) to make the spectrum much flatter and expand the bandwidth. Lastly, we gave the whole configuration a temperature test and ultimately got some excellent results, such as a more than 22 nm bandwidth, higher than 5 mW output power, 0.2 dB flatness and 1–2 ppm/℃ temperature stability.

2. Configuration selection

According to the propagation direction of the output light and the reflective properties at the fiber ends, there are four basic configurations for ED-SFSs[6]: single-pass forward (SPF), single-pass backward (SPB), double-pass forward (DPF) and double-pass backward (DPB). The double-pass configuration is always widely used because it makes use of the spontaneous emission of erbium ions from both directions at the same time, which has a high conversion efficiency and low pump threshold.

Based on previous experience, the DPF configuration is prone to produce light of long wavelength, especially for the configuration with high concentration erbium-doped fiber; while the DPB configuration is usually used to generate light of C-band[7, 8]. So putting these two configurations together may obtain a greater spectrum with a broad bandwidth. According to this idea, a double-pass configuration pumped from both directions is utilized in this paper as shown in Fig. 1. The pump light from a 980 nm laser is divided into two parts by a coupler (shown as the splitter in Fig. 1), both of which enter the erbium-doped fiber through WDM. The DPF and DPB configurations are achieved by the pump light from the left and right WDM respectively. The two configurations share the same erbium-doped fiber.

In a configuration pumped from only one direction, a different position of the erbium-doped fiber absorbs different pump light. The absorption of erbium-doped fiber decreases along the propagation direction of the pump light. The end near the pump laser has the maximum absorption and the other end has the least. The different absorption makes the erbium-doped fiber fail to take full advantage and also affects the wavelength stability with external factors such as the pump power and temperature. The configuration pumped from both ends of the fiber can achieve good pump uniformity, thereby enhancing stability. It can also be expected that by optimizing the fiber length, a good performance of output light will be obtained.

The double-pass configuration in Fig. 1 is achieved by a coating on the fiber end face, shown as the reflector in this

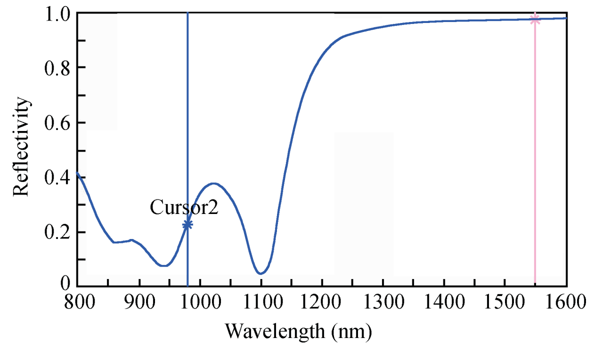

Fig. 2. Reflectivity curve of coating on the fiber end with Si and SiO_2.

figure. In this experiment, Si and SiO_2 films are coated alternately on the 1550 nm end of the 980/1550 WDM through electron beam evaporation, whose simulated reflectivity is shown in Fig. 2. It reaches larger than 97% in the range of 1500–1600 nm. By comparing the configurations with uncoated and coated fiber ends in this experiment, it is found that the latter has a significantly improved output power.

Below are some parameters of devices composed in the light configuration in this experiment:

(1) Erbium-doped fiber (EDF): erbium ion doping concentration is 5.4×10^{24} cm^{-3}; peak absorption coefficient is 6 dB/m and 3 dB/m at 1530 nm and 980 nm, respectively; Numerical aperture $N_A = 0.23$; single-mode cutoff wavelength is 920 nm. (2) 980 nm pump source: a laser diode; threshold current is 14 mA; power-current slope is 0.68; the peak wavelength is 978 nm. (3) 980/1550 nm WDM: Isolation at 980 nm and 1550 nm are 26.3 and 30.9 dB, respectively. (4) Optical power splitter: using an optical coupler, of which the insertion loss at 980 nm is about 3 dB. (5) Isolator (ISO): isolation is greater than 50 dB in 1550 nm.

3. Optimization of fiber length

After pre-calculation, the initial length of the erbium-doped fiber is selected as 15 m in the experiment. The output spectral information at different pump current conditions is measured, including the central wavelength, bandwidth, power and spectral shape. Then the measurement is repeated when decreasing the fiber length 1 m each time. All these measurements were carried out at room temperature.

Figure 3 shows the curve of the central wavelength change with pump current at different EDF lengths. The curve roughly shows a ladder shape as the central wavelength has a jump at some points with the increasing of pump power. We know that the output spectrum of an ED-SFS always shows a shape with two peaks: near 1530 nm and 1560 nm. The reason for the jump is that the 1560 nm peak plays a dominant role at low pump power and a 1530 nm peak plays a dominant role at high pump power. As can also be seen from the figure, the flat area of the central wavelength change increases while the EDF length decreases, and the curve is increasingly flat. The flatter curve means a greater stability of wavelength with the pump power. For the fiber length of 11 m, this flat area covers 50–140 mA, a wider range and better stability than other cases. Near a 100 mA pump current, the wavelength change with pump power is less

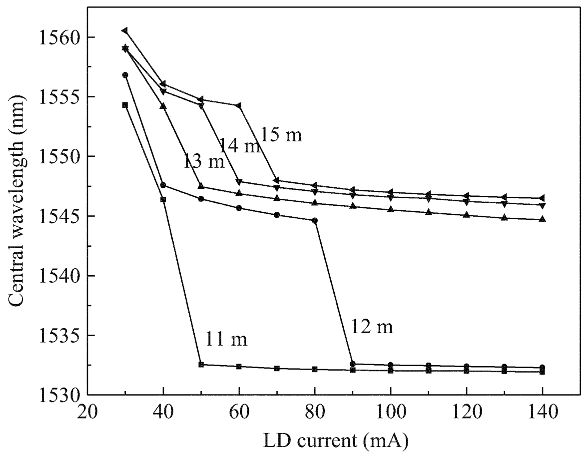

Fig. 3. Central wavelength versus LD current at different fiber lengths.

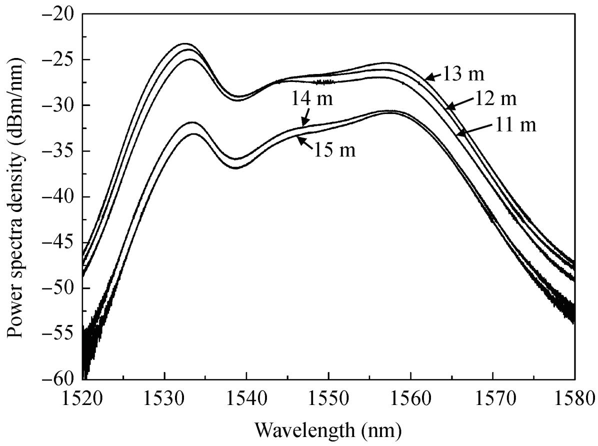

Fig. 4. Spectrum with 80 mA LD current at different fiber lengths.

than 1 ppm/mW.

Moreover, the spectral shape at 11 m fiber length is flatter than other lengths in the 1540–1560 nm range, as shown in Fig. 4 (the pump current of 80 mA). After a flattening process through filtering the 1530 nm peak, a 11 m fiber length will have the best spectrum.

Output power is also an important index that we consider. In the 15–12 m fiber length range, the output power decreases with the increase of fiber length. But when the fiber length is set as 11 m, the power begins to decline. So we can infer that the maximum output power should be obtained at a fiber length between 11–12 m, which can be explained as the erbium-doped fiber is fully pumped and has the smallest loss. In other words, erbium-doped fiber less than 11m will not be able to fully use the pump power. That is why we did not go on decrease the fiber length for more measurements.

In summary, we chose a fiber length of 11 m for further spectrum planarization experiments and temperature stability testing.

4. Spectrum planarization

The former experimental results tell us that no matter what light source configuration is used, the output spectrum has a double-peak near 1530 nm and 1560 nm. It is determined by

Fig. 5. Scheme of 1530/1550 nm WDM.

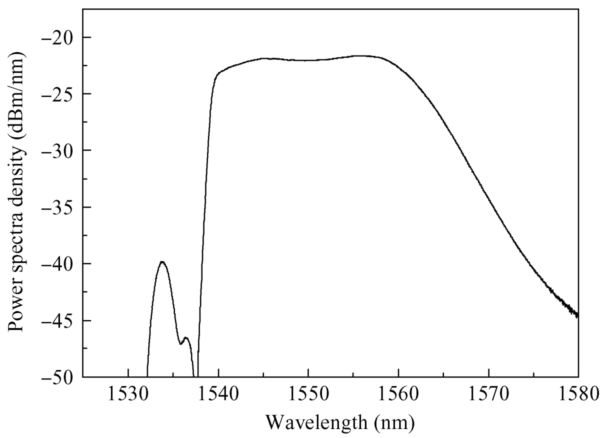

Fig. 6. Output spectrum with a 80 mA LD current after implanting 1530/1550 WDM.

Table 1. Changes of bandwidth and power after 1530/1550 nm WDM utilized.

Parameter	Bandwidth (nm)	Output power (mW)
Without WDM	6.94	7.24
WDM implanted	22.85	5.17

the internal configuration properties of erbium-doped fiber (i.e. the distribution in absorption and luminescence cross-section of erbium ion). The double peaks make the spectrum uneven and the bandwidth small, in particular, the larger gain of peak at 1530 nm directly narrows the 3 dB bandwidth. The spectrum in Fig. 4 shows that the 3 dB bandwidth is only 6.94 nm with a 11 m fiber length. In order to further expand the bandwidth, the spectrum needs a flattening process.

In this experiment a special device—1530/1550 nm WDM is utilized to flatten the spectrum, as shown in Fig. 5. It is implanted before the isolator (ISO) in the light source configuration shown in Fig. 1 with the two ends of common and reflect. The amplified spontaneous emission (ASE) light generated in the erbium-doped fiber propagates into the 1530/1550 nm WDM common side and then is divided into two parts. One part around 1530 nm wavelength is lost from the pass side, while the other around 1550 nm wavelength is reflected back from the Reflect side and is the last output light through the isolator.

The result shows that this method can obtain a fairly flat spectrum and a great bandwidth. Figure 6 shows the output spectrum pumped at a 80 mA LD current, in which the spectral flatness of the effective portion is 0.2 dB (difference between the peak and valley), and 3 dB bandwidth approximately 23 nm. However, the output power partly declines because the 1530 nm peak is filtered out. Table 1 shows the comparison of bandwidth and power before and after placing in the 1530/1550 nm WDM at a 80 mA pump current and at room temperature.

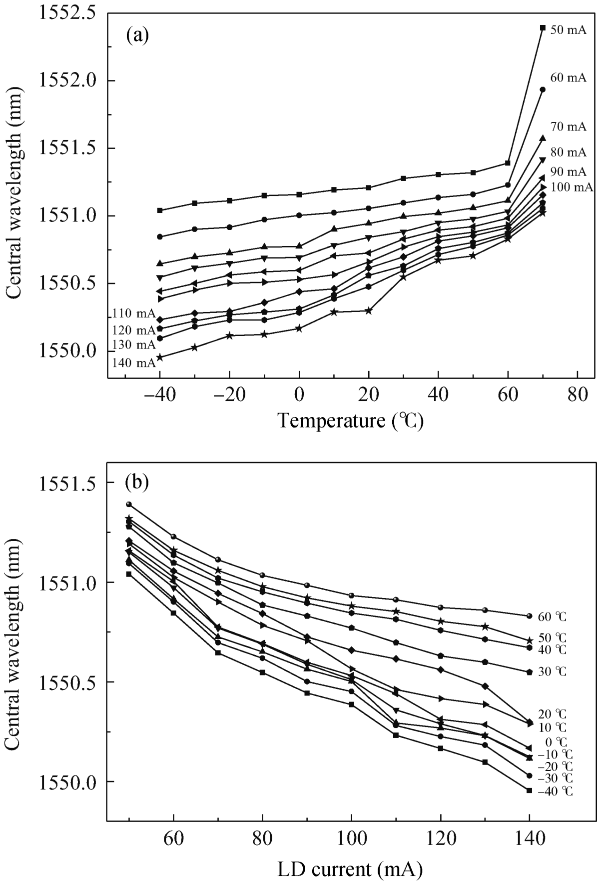

Fig. 7. Shift of central wavelength (a) with temperature at different LD currents and (b) with LD current at different temperatures.

There are still some glitches apparent around the 1530 nm wavelength in Fig. 6. These are attributed to light leakage from the 1530/1550 nm WDM, which is caused by its internal defects. It can be removed by improving the device performance through further optimization. Another way to avoid this is by adding a part of erbium-doped fiber at the output end by which the light leakage is absorbed because it has a high absorption rate around 1530 nm.

5. Temperature stability test

Based on the configuration in Fig. 1, we select 11 m as the fiber length and implant the 1530/1550 nm WDM in it. That is the last configuration we will give a temperature stability test. As mentioned earlier, the central wavelength changes with pump power and pump wavelength, both of which also change with the temperature. So the whole configuration is put into the temperature box for testing, including the pump source, fiber and all the passive components, to consider all factors for the changes of wavelength with temperature.

The temperature range is set from −40 to 70 ℃ and the measuring step as 10 ℃. Every test temperature point is kept 30 min in order to make all parts of the light source have the same temperature as the inside one. At every temperature point we test the output spectral information with different pump currents. Figure 7 shows the shift of central wavelength with temperature at different LD currents and with LD current at different temperatures.

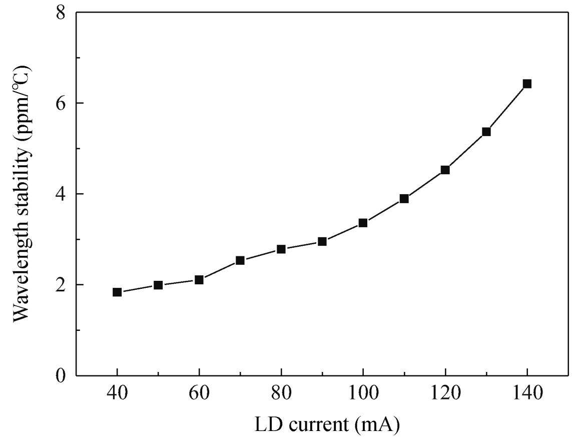

Fig. 8. Central wavelength stability versus LD current.

From Figs. 7(a) and 7(b), we can get the following information:

(1) The central wavelength decreases while the pump power increases, but increases with the increasing of temperature. This is determined by both of the internal structural characteristics of erbium-doped fiber and the light source configuration (such as the fiber length). It was reported that the sign of the temperature coefficient is closely related to the length of the erbium-doped fiber[9], which is not discussed here. The impact of pump power can be explained: the erbium-ion transition happens between the lower Stark splitting energy levels when the pump power is low, which corresponds to the longer wavelength of emitted light; and as the power increases, more and more high-level transition makes the output wavelength shift to short ones.

(2) The pump power is lower, the central wavelength changes more slowly with temperature, e.g. when the pump current is 50 mA, the central wavelength has a stability of 1.3 ppm/℃ in the range of 30–50 ℃. However, the pump power has a greater impact on the central wavelength shift in this case. As the power increases, the impact of temperature on the wavelength shift becomes bigger, but the impact of pump power is smaller, e.g. when the temperature is 60 ℃, the central wavelength shift with the pump power remains at 1.6 ppm/mW in the range of 80–120 mA pump current. Thus we should make different choices based on different requirements in the practical application or make a compromise.

(3) From Fig. 7(a) we can see the measured wavelengths are much higher at 70 ℃ than at 60 ℃. That is because 70 ℃ is close to the operating temperature limit of the pump LD and other passive components, which makes the work performance decline. It is also the reason why we choose 70 ℃ as the terminate temperature point. Furthermore, the central wavelength stability with temperature is worse at 140 mA than other pump currents too because 140 mA is close to the maximum operating current (150 mA) of the pump LD. Thus, excluding the measurements at 70 ℃, we calculate the central wavelength stability with temperature between −40 to 60 ℃ at different pump currents, as shown in Fig. 8. In the current range of 40–100 mA, the wavelength stability with temperature can be maintained less than 3.5 ppm /℃. The smallest shift happens

Table 2. Wavelength stability between 40–50 ℃ for different LD currents.

Pump current (mA)	50	60	70	80	90	100	110	120	130
Stability (ppm/℃)	0.90	1.54	1.70	1.74	1.67	2.19	2.51	2.90	3.55

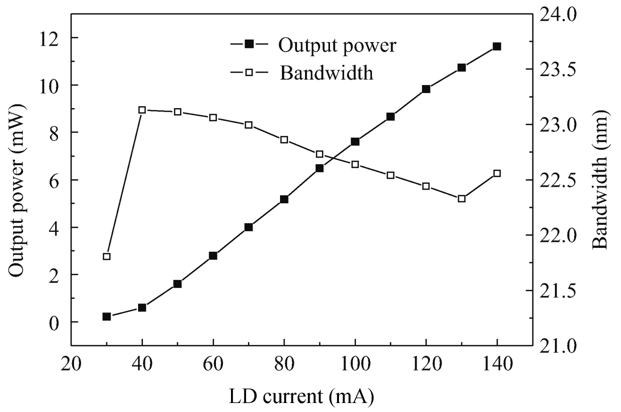

Fig. 9. Output power and bandwidth versus LD current at room temperature.

at 40 mA pump current, which is only 1.83 ppm /℃.

(4) The light source shows good temperature stability in 40–50 ℃ range, no matter what the pump current is. Table 2 gives the calculated result.

(5) Figure 9 is the curve of output power and spectral bandwidth with the pump current at room temperature. The output power is almost proportional to the pump current, the same as the four basic configurations of ED-SFS we measured before. The spectral bandwidth is slightly affected by the pump current after the 1530/1550 nm WDM is implanted and essentially keeps to between 22–23 nm.

Considering all the three key indicators of the output power, bandwidth and central wavelength temperature stability we select 80 mA as the pump current, at which the temperature stability is calculated as 2.70 ppm/℃, bandwidth 22.85 nm, spectral flatness 0.2 dB and output power 5.17 mW. This working condition in the configuration of this paper has a good reference value for the application of high-precision FOGs.

6. Conclusion

In this paper, we use a special coupler as a power splitter to make an erbium-doped fiber pumped from two directions by only one 980 nm laser; and alternate deposition of Si and SiO_2 on the fiber end as the reflector of double-pass configuration; then a 1530/1550 nm WDM to flatten the spectrum and broaden the bandwidth. As changes of output wavelength with pump power is closely related to the erbium-doped fiber length, we optimize the fiber length experimentally and obtain 11 m, which makes the light source obtain high stability. Finally we give the whole configuration a temperature stability test. In the −40 to 60 ℃ range the stability of the output wavelength with temperature can be controlled below 3.5 ppm/℃, while it can be 1–2 ppm/℃ in the range of ±5 ℃ room temperature. This result is a good reference for the applications of high-precision optical fiber gyros.

Through the selection of configuration, optimization of fiber length and temperature stability test we get some satisfactory results. However, there are also some shortcomings to be further improved. For example, the introduction of the 1530/1550 nm WDM causes the output power to significantly decrease although it is beneficial for the spectral characteristics. In later experiments, we will design a new configuration to make the leaked light from the Pass side of the WDM reinject into the erbium-doped fiber and pump the fiber a second time, in which the output power is expected to increase.

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