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1 083 nm 窄线宽单频掺镱光纤激光器

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摘 要:提出了一种低噪声、线宽小于 4 kHz、波长为 1 083 nm 的线形腔单频光纤激光器.该激光器引入了偏振控制器来消除线形腔内的空间烧孔效应,从而抑制了多纵模振荡.实验结果表明:泵浦功率在 40～200 mW范围内时,可获得稳定的单纵模振荡,且最大输出功率可达 46 mW,光学信噪比大于 60 dB,其光光转换效率和斜率效率分别为 23%和 33.3%;经过 1 h 的观察,测得的激光输出功率以及光谱不稳定性分别小于 3%和 0.9%;在整个观察期内,没有出现模式跳跃和模式竞争现象.

关键词:光纤激光器;单频光纤激光器;可饱和吸收体;环形滤波器;掺镱光纤;线宽
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Narrow-linewidth Single-frequency Yitterbium-doped Fiber Laser at 1 083 nm

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Abstract: A low noise single-frequency 1 083 nm fiber laser with a linear cavity was presented and demonstrated with a linewidth of 4 kHz. A polarization controller was introduced to eliminate the spatial hole burning effect in the linear cavity to suppress the multiple longitudinal mode oscillation. The results show that, when the pump power is in the range of 40 mW～200 mW, the single-frequency oscillation is very stable, the maximum output power can reach to 46 mW, the optical signal to noise ratio is larger than 60 dB, the maximum optical-to-optical conversion efficiency and the slope efficiency is 23% and 33.3%, respectively. The stable single-frequency operation can be maintained more than 1 hour with the instability of the output power and the spectrum fluctuations less than ±3% and 0.9% respectively. There are no mode hopping and mode competition during the entire observation.

Key words: Fiber laser; Single-frequency fiber laser; Saturable absorber; Loop mirror filter; Yitterbium-doped fiber; Linewidth
OCIS Codes: 060.2420; 140.3510; 140.3570; 140.3615; 260.3060

0 Introduction

Single-Frequency (SF) lasers are applied in a wide range of areas, such as telecommunications, optical fiber sensors, laser ranging, materials processing and so on[1-4]. Due to their excellent characteristics of

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narrow linewidth, good beam quality, low intensity noise and wide tuning range of wavelength, they have been attracted intense interest of investigators in the last two decades. Most previously presented SF solid-state lasers are based on the intracavity crystal, etalons and a monolithic nonplanar ring oscillator[5-7], which have the advantages of stable structure, good reliability, high efficiency and high output power. Nevertheless, the linewidth of SF solid-state lasers are about MHz level[7]. Consequently, several new methods have been used to realize a narrow linewidth all-fiber laser in the past few years. Morkel *et al*. used the traveling-wave ring cavity to eliminate the spatial hole burning effect and obtained the SF laser with the linewidth of less than 7 kHz at 1.95 μm[8]. Meng *et al*. employed an Er-doped fiber as both Brillouin and gain media in a ring cavity SF fiber laser and achieved an output power of 6mW at 1550nm with the ultra-narrow linewidth of 40 Hz[9]. Obviously, the ring cavity fiber laser exhibits excellent characteristics in the linewidth and the output stability. Nevertheless, the complicated structure and rather low slope efficiency limit its extensive applications[8-9]. Besides, the short linear-cavity structures (Distributed Bragg Reflector (DBR)[10-11] and Distributed-Feedback (DFB)[12-13]) are beneficial to SF laser emission for mode-hop-free, narrow linewidth and low noise. Due to the simple and compact configurations, these fiber lasers have been studied widely. Mo *et al*. reported a 1014nm DBR linearly polarized low-noise SF fiber laser with a linewidth of less than 7 kHz, in which the 5-mm-long ytterbium-doped phosphate was employed as the active media[10]. Shi *et al*. reported a 30-cm-long Roman DFB laser, which exhibited a performance of SF with a linewidth <2.5 kHz at 1 109.5 nm[13].

Moreover, the narrow linewidth SF lasers at 1 064 nm and 1 083 nm also attracted much attention due to their significant applications in gravitation wave detection, atomic and molecular spectroscopy[14-16], the ytterbium-doped fiber is widely employed as the gain material in the lasers[17-19] and laser amplifiers[20-24]. Deng *et al*. reported a 1064nm linear cavity with a saganc Loop Mirror Filter (LMF), which introduced a graphene film acting as the saturable absorber into the LM[23]. Guan *et al*. demonstrated a high power hybird Brillouin/ytterbium ring cavity SF laser with the output power of 1W at 1 080 nm[18]. Xu *et al*. reported a 1 083 nm DBR fiber laser, which employed a 1.8-cm-long ytterbium-doped phosphate single mode fiber as the gain media and the maximum output power was over 100 mW[19].

Due to the low slope efficiency and expensive costs, these fiber lasers of ring cavity and short linear cavity have been limited extensive research. In the paper, the linear cavity (around 2 m) with the Loop Mirror Filter (LMF) is adopted for generating a high efficiency Single Frequency (SF) fiber laser, which introduces three Polarization Controllers (PC) and 10m-long un-pumped ytterbium doped fiber embedded in a fiber loop mirror acting as a saturable absorber. Three Polarization Controllers (PC) is employed to adjust the polarization state in order to suppresses the Spatial Hole Burning (SHB) in the linear cavity and optimize the reflectivity of the Loop Mirror Filter (LMF). Due to the 1 μm wide range of the gain spectrum in near infrared, the ytterbium-doped fiber is used as the gain medium to generate a Single Frequency (SF) 1 083 nm laser. The structure of our configuration is simple, compact, low insertion loss and high reliability.

1 Experimental setup

The experimental schematic of the SF all-fiber laser is shown in Fig. 1. As we know, the linewidth of SF lasers is an important parameter and can estimate based on the famous Schawlow-Townes equation modified by Melvin Lax, as follows [25-27]

$$\Delta v_{\mathrm{laser}}=\frac{hv\theta I_{\mathrm{tot}}T_{\mathrm{oc}}}{4\pi T_{\mathrm{rt}}^{2}P_{\mathrm{out}}} \tag{1}$$

where hv is the photon energy, θ denotes the spontaneous emission factor, I_{tot} is the losses of total resonator, T_{oc} denotes the transmission of output coupler, T_{rt} is the cavity round-trip time and is proportional to the cavity length, P_{out} denotes the output power. Under the same parameters (θ, T_{oc}, P_{out}), the longer length of cavity can achieve much narrower linewidth based on the Eq. (1) and $T_{\mathrm{rt}}=2\,nL/c$(L is the length of cavity, n is the refractive index of fiber, c is the speed of light), comparing to the ultra-short cavity (DBR and DFB) SF fiber laser. Thus even if the resonator loss I_{tot} will grow with the increasing of L, the linewidth will be reduced evidently and is inversely proportional to L^2. In order to achieve the narrow SF fiber laser, the linear cavity is composed of a LMF and a narrow-band Fiber Bragg Grating (FBG). T he optical path length of our laser cavity is about 2m (without the length of LMF), then the space of adjacent longitudinal mode of the fiber laser is approximately 50 MHz. The reflectivity spectrum of FBG is shown in Fig. 2. The central wavelength and the reflectivity of FBG is about 1 083 nm and 70%, respectively. The 3 dB bandwidth of FBG is about 0.1 nm. The LMF acts not only as the longitudinal mode selector but also as the high reflection mirror to construct an integral resonator in the linear cavity. A continuous wave laser at 975 nm is used as the pump beam and then is imported into the cavity by Wavelength Division Multiplex (WDM_1, 980/1 080 nm, 1×2). Two single-mode single-clad ytterbium-doped fibers (INO Yb 501, mode filed diameter of 6 μm, an ytterbium-ion-doped concentration of 21000 ppm, the numerical aperture of 0.13) are used separately as the gain medium and the Saturable Absorber (SA) material in the LMF. The length of the gain medium and the SA is optimized to 20 cm and 10 m, respectively. Polarization controllers (PC_1 and PC_3) are used to control the polarization state of the counter-propagating waves in order to optimize the reflectivity of the LMF. As we know, the spatial hole burning (SHB) effect could not be avoid in the gain material for the linear laser cavity, which generated by the nonlinear wave mixing of the two counter-propagating waves and was a serious obstacle for generating SF laser. So the PC_2 is introduced to adjust the polarization state and suppresses the Spatial Hole Burning (SHB) in the linear cavity[28-29]. Considering that the residual pump beam would be absorbed by the SA fiber, which may stimulate other absorption dynamic grating at 1 083 nm, in addition, if the residual pump light is not completely absorbed by the LMF, then another dynamic grating at 975 nm would be induced. The complex situations would affect the select of longitudinal modes, so the WDM_2 (980/1 083 nm, 1×2) is employed to output the residual pump beam. The generated laser beam at 1 083 nm is finally exported from the other port of WDM_1.

In our fiber laser, the LMF is the core design, as shown in the Fig. 1, which plays the key role in the mode selection and the linewidth narrowing. The LMF is consisted of a 3 dB coupler, PC_1, PC_3 and a 10-m-long un-pumped high-doped ytterbium fiber SA. The principle of LMF for generating narrow single longitudinal mode is based on the mechanism of a Sagnac interferometer with the fiber SA. At first, the entering optical field is split into two counter-propagating parts by the 3 dB coupler, which shares the same optical path and engenders a series of interference fringes in the SA fiber. These interference patterns induce the variation of refractive index and create a dynamic absorption Bragg grating. This is an absorption-induce grating, which is more effective than the normal grating[30]. Besides, the bandwidth of the LMF could cover from the sub-MHz to GHz regimes. In our experiment, a 10-m-long high concentration ytterbium doped fiber with large absorption coefficient is adopted as the SA, so the bandwidth of the LMF would be much narrower than adopting a shorter fiber, which is used to benefit select the laser longitudinal modes effectively.

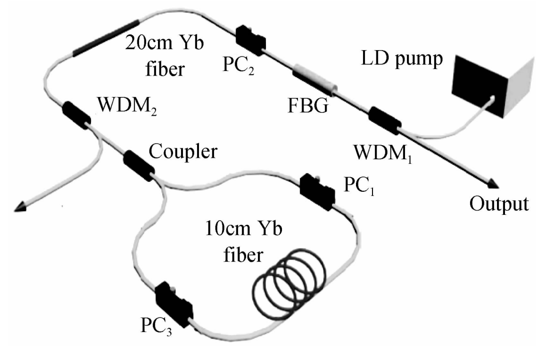


Fig. 1 Experimental setup of the SF fiber laser based on the LMF

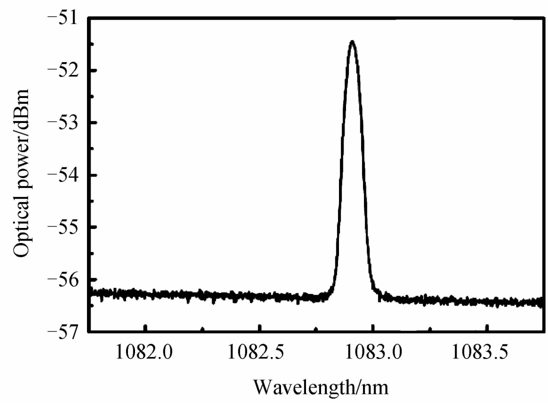
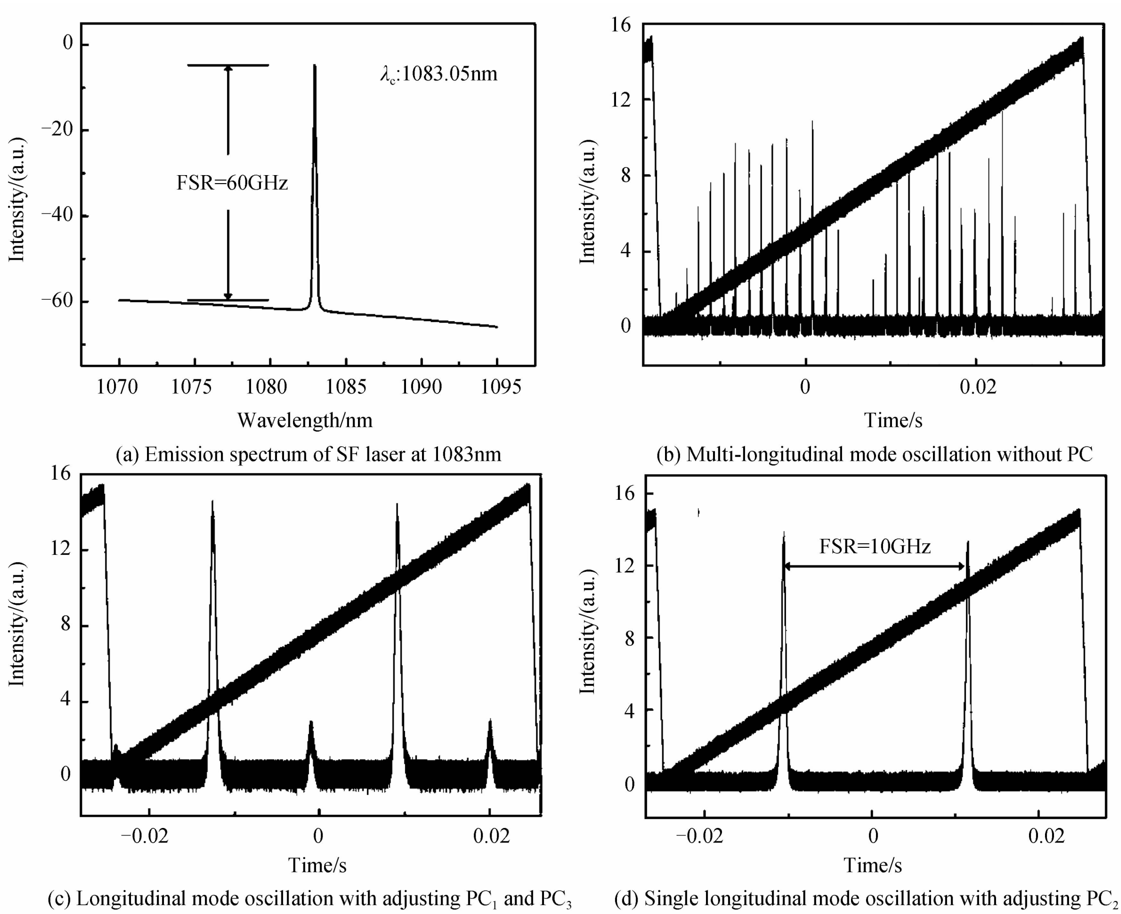


Fig. 2 Reflectivity spectrum of FBG

2 Experimental results and analysis

The output laser at 1 083 nm from WDM_1 is measured and scanned by a Fabry-Perot (F-P) interferometer (Thorlabs, SA201, with a FSR of 10 GHz and a resolution of 67 MHz), which is analyzed by an oscilloscope (OSC, Agilent Infiniium 9000, with a resolution of 0.02 nm). The function generator is introduced to provide a sweep signal (Thorlabs, SA201 F-P controller). The spectrum information of the SF fiber laser is recorded by an optical spectrum analyzer (OSA, YOKOGAWA AQ6370B, with a resolution of 0.02 nm) and the optical power of the output laser is measured by a power meter (Gentec PH100-Si-HA).

In the experiment, the 1 083 nm laser is generated by increasing the pump power to an appropriate value. Fig. 3(a) illustrates the emission spectrum of SF laser at the room temperature, when the output power is 46 mW and shows the output spectrum over a range from 1 070 nm to 1 095 nm. The central wavelength of the signal peak is about 1 083.05 nm, in addition, there is no other emission peaks existing. The signal-to-noise ratio approximate to 60 dB is obtained. The SF characteristics are also confirmed by the scanning Fabry-perot interferometer, and the multi-longitudinal mode oscillations without adjusting three PCs are observed (Fig. 3(b)). In Fig. 3 (b), the sawtooth wave is the F-P ramp voltage, which provides approximately two Free Spectral Range (FSR). The curve of longitudinal was the wave signal of the laser passing through F-P interferometer in a FSR voltage. According to the design principle and structure of resonant cavity, we adjust PC_1 and PC_3 to optimize the loop mirror reflection and raise laser output power. Then the number of longitudinal modes is decreased obviously, only a few modes operated in one FSR (Fig. 3(c)), this phenomenon shows that the dynamic absorption Bragg grating has formed in LMF. So only when the frequency of longitudinal mode is exactly inside the pass-band, the longitudinal mode will transmit through the grating; otherwise, the other frequency can be reflected by the grating. Besides, except the strong signal peak, there is a weak envelope in a FSR, as shown in Fig. 3(c). The reason might be that the PC_1 and PC_3 are not adjusted very well, thus forming two dynamic absorption gratings at the different center frequency. In addition, the influence of SHB in the linear cavity will cause the adjacent longitudinal mode oscillation and will not be suppressed. So the PC_2 is employed to adjust the wave polarization to restrain Spatial Hole Burning (SHB) effect. Then we adjust the three PCs carefully and increase the pump power, when the pump power is increased to 200mW, we obtain the maximum output power for 46 mW SF laser at 1 083 nm. A standard graph of single longitudinal mode oscillation spectrum information is observed, as shown in Fig. 3(d). There is only one longitudinal mode presented in a FSR (10 GHz) of the F-P interferometer, which confirms the SF oscillation is attained. The SF oscillation is very stable, there is no mode hopping during one hour of observation. Nevertheless, the multi-longitudinal mode oscillations and mode hopping appear when the pump power is increased more than 200 mW, as shown in Fig. 3(c).



(a) Emission spectrum of SF laser at 1083nm

(b) Multi-longitudinal mode oscillation without PC

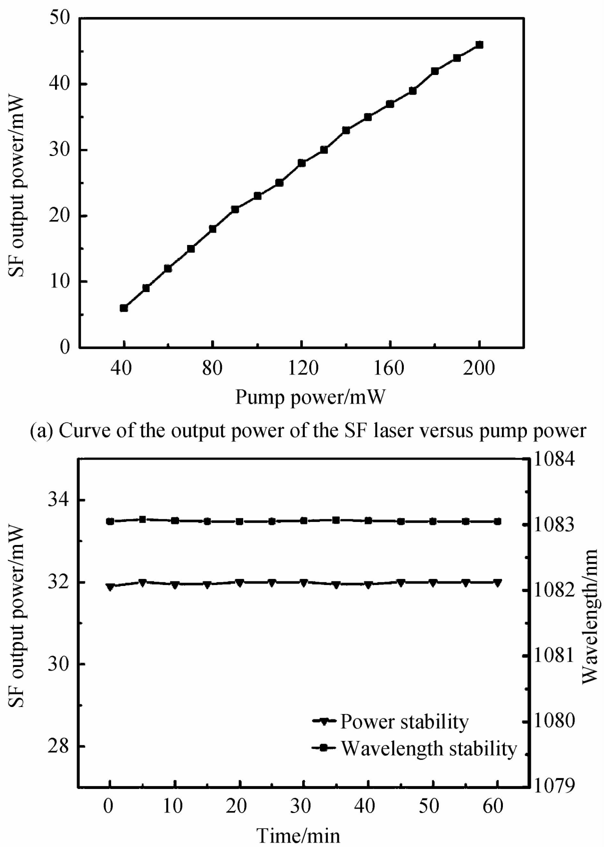
(c) Longitudinal mode oscillation with adjusting PC_1 and PC_3

(d) Single longitudinal mode oscillation with adjusting PC_2

Fig. 3 Longitudinal mode oscillations over one FSR scanned by a F-P interfermeter

That can be attributed to the SHB effects induced by the high light intensity in the cavity, which can't be suppressed by the adjustment of PC_2 and the LMF.

The curve of the SF laser output power at 1 083 nm is shown in Fig. 4(a). The lasing threshold is around 40 mW. When the pump power is above the threshold, the laser output power enhances linearly. The maximum output power of SF laser reaches about 46 mW when the pump power is 200 mW. The optical-to-optical conversion efficiency and the slope efficiency is 23% and 33.3%, respectively. After the fiber laser works for half an hour, the output power of the laser becomes very stable obviously. The stability curves of the output power at 32 mW and wavelength at 1 083.05 nm are shown in Fig. 4(b), respectively. The power instability of < ±3% of the average power during 1 h is observed (triangle line in Fig. 4(b)). The wavelength instability of the center wavelength is less than 0.9% (marked with red square line in Fig. 4(b)). The instabilities of the output power and wavelength are caused by the small fluctuations in the pump laser power and small changes of ambient temperature.



(a) Curve of the output power of the SF laser versus pump power

(b) Power and wavelength stabilities of the fiber laser for an hour

Fig. 4 Curve of the output power and stabilities of the SF laser

To furtherly investigate the characteristics of the SF laser, we measure the linewidth of the laser by the delayed self-heterodyne method[31]. Firstly, the SF laser beam is split into two beams by 3 dB coupler, one beam as the reference light is delayed by 30 km single mode delay fiber and another beam as the signal light is through an acousto-optical modulator (AOM, Gooch S-M150-0.4C2G-3-F2S, with a carrier frequency of 150 MHz). Next, the two beams are recombined by a 3 dB coupler to obtain the beat frequency spectrum signal and go through the photoelectric detector with a bandwidth of 2 GHz (THORLABS DET01CFC). Finally, the signal is analyzed by a Radio Frequency (RF) spectrum analyzer (KEYSIGHT N9320B). Fig. 5 shows the result of the measurement. From the heterodyne signal, we take 3 dB down from the maximum value to estimate its bandwidth, which is about 8 kHz. The laser linewidth is equal to the half-width of the heterodyne signal, which is about 4 kHz.

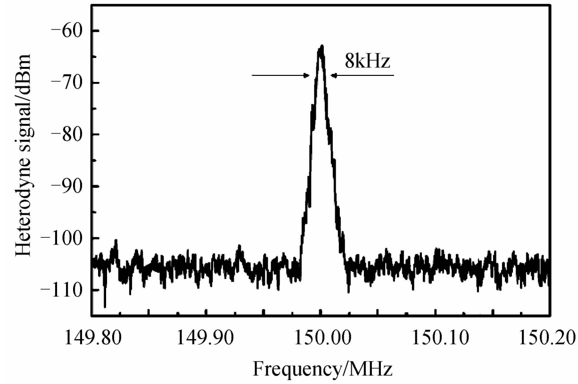


Fig. 5 Lineshape of the heterodyne signal measured with a 30 km fiber delay

In order to furtherly verify the role of the SA Yb fiber, we get rid of the fiber in the LMF and other parts keep the same, simply breaking the LMF and splicing the two ports of the 3 dB coupler directly. Then we repeat the same experiment operation as before, the tanglesome and irregular multi-mode oscillations are observed from the Oscilloscope (OSC). No matter how we adjust the three PCs, there is no SF signal all the time, only the multi-longitudinal mode oscillations can be observed through the OSC. But beyond that, the beat frequency spectrum of the laser is also measured by the delayed self-heterodyne method, as shown in Fig. 6. There are a lot of signal peaks in Fig. 6, indicating that the fiber laser is in multi-longitudinal mode oscillations. This phenomenon demonstrates the crucial role of the Yb fiber as the SA in the experiment.

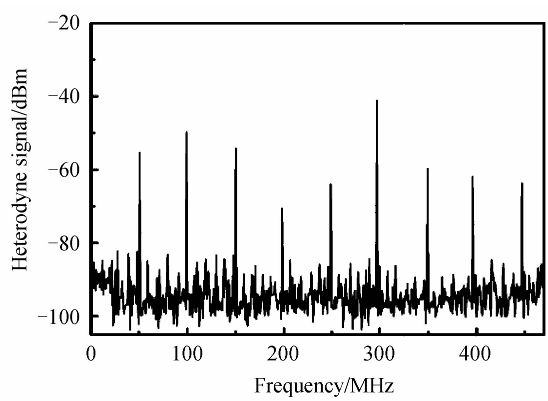


Fig. 6 Lineshape of the heterodyne signal measured without the SA Yb fiber

3 Conclusion

We have studied a stable single-frequency 1 083 nm laser with an all-fiber linear cavity. The Yb-doped fiber is employed as the gain medium and the saturable absorber in the loop mirror fiber. Three polarization controllers are used to adjust the state of the light polarization. The maximum output power of single-frequency laser reaches 46 mW, when the pump power is 200 mW. The optical-to-optical conversion efficiency and the slope efficiency of single-frequency laser oscillation approaches 23% and 33.3%, respectively. The signal noise ratio is approximate to 60 dB. The laser linewidth is 4 kHz, which is measured by the delayed self-hetrodyne method with a 30 km single mode delay fiber. The stability of the output power and spectral for an hour are less than ±3% and 0.9%, respectively. There are no mode hopping and mode competition in the entire observation time. Moreover, it can be a very good single frequency seed laser to achieve higher output power. In the future, the master oscillator power amplification system will be employed and several different lengths of yitterbium doped fiber (2 m, 5 m, 10 m) will be introduced as the working medium in the amplification system. By comparing the experimental results, we select the optimum fiber length for the amplification system.

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