Experimental study of an ultra narrow linewidth fiber laser by injection locking

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An ultra narrow linewidth fiber laser is presented, which is composed of a ring cavity laser and a linewidth-narrowing module. The fiber laser is introduced in detail and the single mode operation of the laser is verified. Using a revised self-heterodyne detection method, experimental data of the laser linewidth against the pump power are presented. The narrowest linewidth is measured to be 109 Hz, whereas the output power is 1.1 mW.

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Fiber lasers have attracted increasing interest due to their relatively high gain, compactness, and flexibility[1]. Recently, narrow linewidth fiber laser has become more attractive with its great potential in high resolution optic coherent detection, remote sensing, and wavelength division multiplexed networks[2]. The narrow linewidth is typically realized using semiconductor saturable absorption mirrors (SESAMs). However, the fabrication program of SESAMs is complex[3,4] and costly, thus preventing the wide use of SESAMs. In this letter, an ultra narrow linewidth Er^{3+}-doped fiber (EDF) laser, created using a fiber saturable absorber, is investigated experimentally. A single mode fiber (SMF) laser with linewidth of 109 Hz is obtained by optimizing the parameters of saturable absorber. The relationship between the laser linewidth against the pump power is also studied.

The schematic diagram of the ultra narrow linewidth fiber laser is shown in Fig. 1. It was constructed with a basic ring cavity and a linewidth-narrowing module. In the basic ring cavity, the pumped EDF was 4 m long with a doping concentration of 900 ppm. A fiber resonant ring (FRR) filter was used for mode control (18-cm long). The linewidth-narrowing module included a segment of un-pumped EDF and a fiber Bragg grating (FBG). The un-pumped EDF used as the fiber saturable absorber had a length of 2.5 m with a doping concentration of 200 ppm. The FBG was used not only as a narrow-band filter, but also as a reflecting mirror. The reflectivity and the bandwidth at –3 dB of the FBG were 93% and 0.16 nm, respectively. The total cavity length was about 10–11 m, corresponding to a free spectral range (FSR) of 18.7–20.5 MHz.

The EDF in the ring cavity was pumped as the pump light was conducted into the ring cavity through a 980/1550-nm wavelength division multiplexer (WDM). The main function of the filter in the ring cavity is to increase the FSR. The filter was based on a 2×2 coupler, which was connected by a rather short piece of fiber (18 cm). The FSR of this filter was about 1 GHz. Then, the lights were inserted into the linewidth-narrowing module, which was constructed using a piece of EDF and a FBG. The piece of EDF (2.5 m long with a doping concentration of 200 ppm) was placed between an optical circulator and a Bragg grating acting as a saturable absorber. The incident light passes through this segment of EDF and reaches the FBG. At this time, the light is reflected and filtered by the Bragg grating immediately. Due to the interaction between the incident light and reflected light, a dynamic modulation of the refractive index takes place in the un-pumped EDF[5,6]. This modulation can cause very large losses at neighboring longitudinal modes, while allowing high transmission at the favored longitudinal mode, thereby resulting in the narrow linewidth of the laser output[7].

Single mode operation was verified in this letter by utilizing an optical spectrometer (Anritsu Ms96A) and a self-making sweeping ring[8]. Figure 2(a) shows the spectrum of the fiber ring laser. It also shows that the minimum resolution of the spectrometer is neither enough for viewing the operating status (single mode/multimode), nor for measuring the linewidth. In this situation, a self-making sweeping ring was used to verify single mode operation. This sweeping function is realized by a PZT with a sawtooth wave. The total length of the sweeping ring was about 1 m, corresponding to a bandwidth of 200 MHz. Figure 2(b) shows the sweeping spectrum taken by an oscilloscope (Tektronix TDS33052B).

In one single sweeping period, more than one peak should appear if the laser is operating in multimode state, and only one peak for the single mode operation. The phenomenon showing that only one peak exists in each sweeping period can be easily seen from Fig. 2(b),

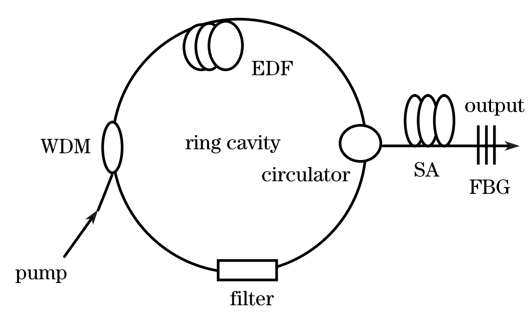

Fig. 1. Experimental setup of the narrow linewidth single-longitudinal-mode fiber laser. SA: saturable absorber.

indicating that the fiber laser exhibits a good characteristic of single mode operation. During the experiments, mode hopping did not take place. Thus, it is safe to say that this fiber laser operated in a single mode state.

The methods of laser spectrum linewidth measurement can be classified by the range of optical linewidth. Generally, an optical spectrum analyzer is used to measure the linewidths of over 0.01 nm; but for those narrower than 0.01 nm, a frequency spectrometer must be used along with an optical coherent system or a beat frequency system. A Fabry-Perot interferometer is commonly used to measure linewidth when the latter is at the MHz level; however, when it becomes narrow enough to be beyond the resolution capability of the Fabry-Perot interferometer, then beat frequency detection is used. Beat frequency detection is typically used in two technical ways, namely, homodyne and heterodyne beat frequency detections; of the two, the latter method can better avoid the $1/f$ electronic noise at zero position. In 1980, Okoshi *et al.* first proposed the self-heterodyne technique to measure the laser linewidth[9]. Currently, this technique has been widely used by many researchers for narrow linewidth determination. In this letter, a revised self-heterodyne detection was also used to measure the linewidth of the presented fiber laser.

The experimental setup for the revised self-heterodyne detection is shown in Fig. 3. The output of the laser was split into two beams by an optical coupler, one beam went through a fiber delay line, and the other was modulated by a PZT with a cosine signal. These two beams were combined by another optical coupler, such as a Mach-Zehnder interferometer. The optical heterodyne signal of the two beams was detected by a photodiode (PIN), and then transferred to an electronic signal. Finally, the electronic signal was received by a spectrum analyzer (Stanford Research SR785) and an oscilloscope (Tektronix TDS33052B).

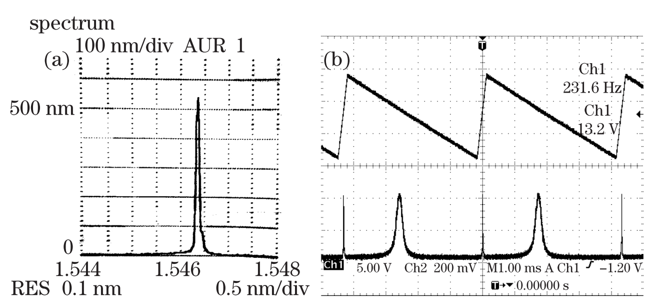

Fig. 2. Spectra verifying the single mode operation of the fiber laser. (a) Output spectrum directly taken by an optical spectrometer; (b) sweeping spectrum taken by an oscilloscope.

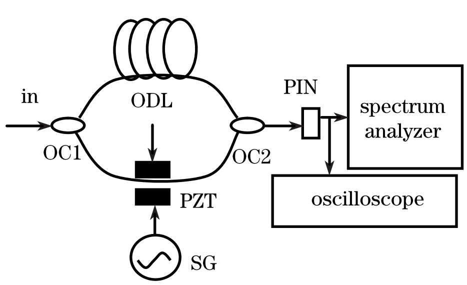

Fig. 3. Schematic diagram of self-heterodyne detection. SG: signal generator; OC: optical coupler.

In the scheme, the optical field going through the optical delay line (ODL) can be expressed as

$$\widetilde{E}(t) = A \cdot \exp\{\mathrm{j}\left[\omega\left(t-\tau\right)+\varphi(t-\tau)\right]\}. \tag{1}$$

The other part of the light is modulated by a PZT with a cosine signal. PZT provides a phase modulation. The field can be expressed as

$$\widetilde{E}(t) = A \cdot \exp\{\mathrm{j}\left[\omega t+\varphi(t)+\cos\Omega t\right]\}. \tag{2}$$

Based on the coherent theory, the self-heterodyne signal received by the PIN is mathematically described as

$$P(t) = P_0 + P_0\cos\left[\omega\tau+\cos\Omega t+\Delta\varphi\left(t,t-\tau\right)\right], \tag{3}$$

where τ is the delay time of one path with respect to the other, ω is the laser frequency, P0 is the output power of the fiber laser, Ω is the modulated frequency, and the phase jitter $\Delta\varphi$ is assumed to have a Gaussian distribution, and can be expressed as

$$\Delta\varphi(t,t-\tau) = \varphi(t)-\varphi(t-\tau). \tag{4}$$

Expanding Eq. (3), we obtain

$$\begin{aligned} & P_0\{1+\cos\left(\omega\tau+\cos\Omega t+\Delta\varphi\left[t,t-\tau\right]\right)\} \\ = {} & P_0\{1+J_0\left(\Phi_0\right)\cos\left[\omega\tau+\Delta\varphi\left(t,t-\tau\right)\right]\} \\ & -2P_0J_1(\Phi_0)\sin\left[\omega\tau+\Delta\varphi\left(t,t-\tau\right)\right]\cos\Omega t \\ & -2P_0J_2(\Phi_0)\cos\left[\omega\tau+\Delta\varphi\left(t,t-\tau\right)\right]\cos 2\Omega t \\ & +2P_0J_3(\Phi_0)\sin\left[\omega\tau+\Delta\varphi\left(t,t-\tau\right)\right]\cos 3\Omega t \\ & +2P_0J_4(\Phi_0)\cos\left[\omega\tau+\Delta\varphi\left(t,t-\tau\right)\right]\cos 4\Omega t \\ & +\cdots, \end{aligned} \tag{5}$$

where $J_n(\varPhi_0)$ is the nth order Bessel function. Neglecting the harmonic components, the power density spectrum of optical intensity $S(\omega)$ can be expressed as

$$\begin{aligned} S(\omega) &= \lim_{T\to\infty}\frac{\left|-2J_1(\varPhi_0)\pi\{X(\omega)\left[\delta\left(\omega-\Omega\right)+\delta\left(\omega-\Omega\right)\right]\}\right|^2}{T} \\ &= \left[2J_1(\varPhi_0)\pi\right]^2 G\left(\omega-\Omega\right)+\left[2J_1(\varPhi_0)\pi\right]^2 G(\omega+\Omega), \end{aligned} \tag{6}$$

where $X(\omega)$ refers to the Fourier transform of $P_0\sin\left[\omega\tau+\Delta\varphi\left(t,t-\tau\right)\right]$, and $G(\omega)$ is the Fourier transform of the autocorrelation function $\gamma(\delta\tau,\tau)$, which means the power density spectrum. This is expressed as

$$\begin{aligned} & G(\omega)\leftrightarrow r(\delta\tau,\tau) \\ & r(\delta\tau,\tau) = \frac{1}{2}P_0^2\exp\left[\frac{-|\tau|}{\tau_c}\right]\exp\left[-\frac{\delta\tau-|\tau|}{\tau_c}\right]. \end{aligned} \tag{7}$$

Finally the frequency shifted spectrum $\mathrm{G}(\omega\pm\Omega)$ can be observed as

$$G(\omega \pm \Omega) = \frac{\frac{1}{2}P_0^2\tau_c}{1+(\omega \pm \Omega)^2\tau_c^2}\left\{1-\left[\cos(\omega \pm \Omega)|\tau| + \frac{\sin(\omega \pm \Omega)|\tau|}{(\omega \pm \Omega)|\tau_c|}\right]\times\exp\left[-\frac{|\tau|}{\tau_c}\right]\right\} + \frac{1}{2}\pi P_0^2\exp\left[-\frac{|\tau|}{\tau_c}\right]\delta(\omega \pm \Omega). \tag{8}$$

Introducing Eqs. (6) to (8), the conclusion that the laser linewidth can be observed by measuring the full-width at half maximum (FWHM) of the Lorextzian $S(\omega)$[10−12] can be drawn easily. PZT used in the structure provides a phase modulation, and after a series of signal processing, the shifting of the frequency spectrum of the coherent light is observed. The shifted frequency is equal to the modulation frequency.

By utilizing Origin 6.0 for data analysis and smoothing, the corresponding linewidths against different pump powers (60, 80, 140, and 160 mA) are shown in Fig. 4. The experimental data show that the FWHM of the observed Lorextzian ranges from 377 to 218 Hz, indicating that the measured fiber laser linewidths range from 188.5 to 109 Hz. The minimum linewidth of our EDF laser is 109 Hz, which means that, in this case, the pump power is 74.7 mW, and the laser output is 1.1 mW.

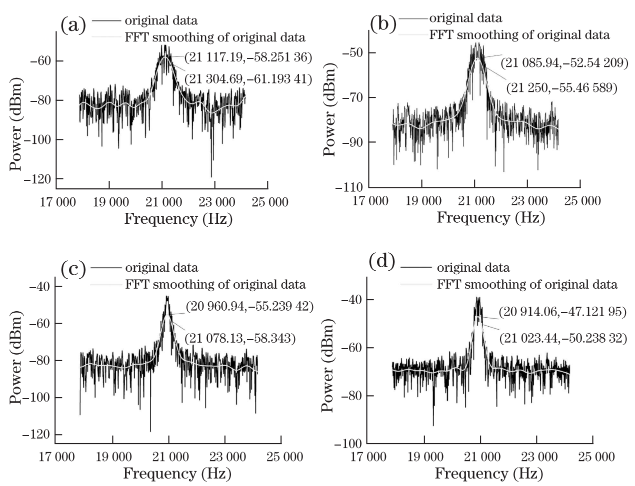

Fig. 4. (Color online) Heterodyne spectra of the fiber laser for different pump power levels. (a) Pump power is 60 mA, linewidth is 188.5 Hz; (b) pump power is 80 mA, linewidth is 164.06 Hz; (c) pump power is 140 mA, linewidth is 117.19 Hz; (d) pump power is 160 mA, linewidth is 109.08 Hz.

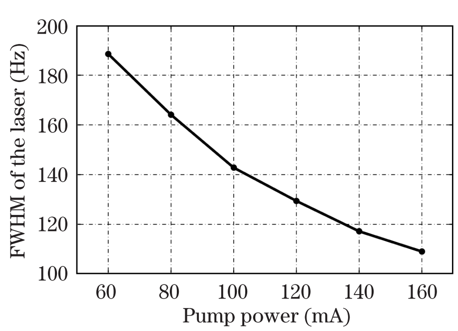

Fig. 5. FWHM of the fiber laser against the pump powers.

Figure 5 shows the experimental results of laser linewidth against the pump power. As the pump power increases, the laser linewidth becomes narrower. According to our knowledge, this result is contributed to the stronger positive feedback formed in the saturable absorber. The mechanism of induced saturable absorbing grating has been introduced in many studies[13]. If higher pump power is injected, stronger positive feedback would form in the cavity, which would lead to improved coherence and promotion of the single mode operation. A stronger mono frequency light would pass through the pumped EDF in the ring cavity and induce the EDF to excite photonics with the same frequency preferably. Finally, a narrower output is obtained.

In conclusion, an ultra narrow linewidth fiber laser incorporating a fiber saturable absorber is studied and demonstrated experimentally. This laser is operated in a single mode state. The narrowest linewidth observed in our experiments is 109 Hz. Compared with other reported results[14,15], our findings prove exciting. Moreover, experimental data of the laser linewidth against pump power indicate that the laser linewidth becomes narrower as the pump power increases.

References

1. R. Zhou, B. Ibarra-Escamilla, J. W. Haus, P. E. Powers, Q. Zhan, Appl. Phys. Lett. **95,** 191111 (2009).
2. C. H. Yeh, and C. W. Chow, Laser Phys. Lett. **7,** 158 (2010).
3. H. Zhang, Q. Bao, D. Tang, L. Zhao, and K. Loh, Appl. Phys. Lett. **95,** 141103 (2009).
4. J. Zhang, D. Bauer, F. Konig, T. Dekorsy, X. Zhang, and Y. Chen, Chin. Opt. Lett. **8,** 676 (2010).
5. H. S. Kim, S. K. Kim, and B. Y. Kim, Opt. Lett. **21,** 1144 (1996).
6. I. A. Kostko and R. Kashyap, Opt. Express **14,** 2706 (2006).
7. N. J. C. Libatique, L. Wang, and R. K. Jain, Opt. Express **10,** 1503 (2002).
8. J. Qian, J. Su, X. Wang, and B. Zhu, Chin. Opt. Lett. **5,** 229 (2007).
9. T. Okoshi, K. Kikuchi, and A. Nakayma, Electron. Lett. **16,** 630 (1980).
10. L. E. Richter, H. I. Mandelberg, M. S. Kruger, and P. A. Mcgrath, IEEE J. Quantum Electron. **22,** 2070 (1986).
11. L. B. Mercer, J. Lightwave Technol. **9,** 485 (1991).
12. Y. Jia, P. Ou, Y. Yang, and C. Zhang, J. Beijing University of Aeronautics and Astronautics (in Chinese) **34,** 568 (2008).
13. M. Horowitz, R. Daisy, B. Fischer, and J. L. Zyskind, Opt. Lett. **19,** 1406 (1994).
14. Y. Cheng, J. T. Kringlebotn, W. H. Loh, R. I. Laming, and D. N. Payne, Opt. Lett. **20,** 875 (1995).
15. Z. Meng, G. Stewart, and G. Whitenett, IEEE J. Lightwave Technol. **24,** 2179 (2006).