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Study on high coupling efficiency Er-doped fiber laser for femtosecond optical frequency comb

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Abstract

The femtosecond laser is crucial to the operation of the femtosecond optical frequency comb. In this paper, a passively mode-locked erbium-doped fiber laser is presented with 91.4 fs pulse width and 100.8 MHz repetition rate, making use of the nonlinear polarized evolution effect. Using a 976 nm pump laser diode, the average output power is 16 mW from the coupler and 27 mW from the polarization beam splitter at the pump power of 700 mW. The proposed fiber laser can offer excellent temporal purity in generated pulses with high power, and provide a robust source for fiber-based frequency combs and supercontinuum generation well suited for industrial applications.

Keywords: mode-locked fiber laser, solitons, optical frequency comb

(Some figures may appear in colour only in the online journal)

1. Introduction

Fiber lasers were made in the 1960s by incorporation of trivalent rare-earth elements such as neodymium, erbium, and thulium into glass hosts [1]. Due to the high efficiency of the Nd^{+3} ion as a laser, early works focused on Nd^{+3} -doped silica fiber lasers operating at 1.06 μm [2, 3]. Doping of silica fibers with Er^{+3} ion were not achieved until the 1980s. Since then, Er-doped fiber (EDF) lasers, which are suitable for optical communications [4], have received much attention recently. Among EDF lasers, passively mode-locked EDF lasers also have applications in high-resolution spectroscopy, THz pulse generation, coherent tomography [5], optical clockworks [6], supercontinuum generation [7], and absolute distance measurements [8–10].

For passively mode-locked EDF lasers, there are such passive mode-locked techniques as the nonlinear polarization evolution (NPE) [11, 12], semiconductor saturable absorbers (SESAMs) [13] and saturable absorbers based on carbon nanomaterials (carbon nanotubes and graphene) [14–19].

However, the shortest pulses from fiber lasers have been achieved with NPE techniques. Using intra-cavity polarization elements, NPE techniques have been considered to be a promising mechanism to achieve femtosecond pulses with high repetition rate in ring-cavity lasers [20, 21].

There are two basic structures based on NPE mode-locked fiber lasers: the conventional ring cavity fiber laser and compact all-fiber laser [22, 23]. With the conventional ring cavity, the shortest pulse and highest repetition rate can be obtained. Reference [22] reported a 94 fs pulse duration with the repetition rate of 301 MHz and 3 dB spectral width of 60 nm. In 2010, [23] reported the shortest dechirped pulse width of 37.4 fs at a 225 MHz repetition rate after compression. However, in this scheme, the output light is extracted out from the polarization beam splitter (PBS), which further restricts the coupling efficiency and increases the coupling difficulty via free-space coupling. Conversely, the biggest disadvantage of all-fiber NPE mode-locked lasers is their relatively low repetition frequency, which is usually limited by the length of the cavity. The shortest pulse can be obtained, but the

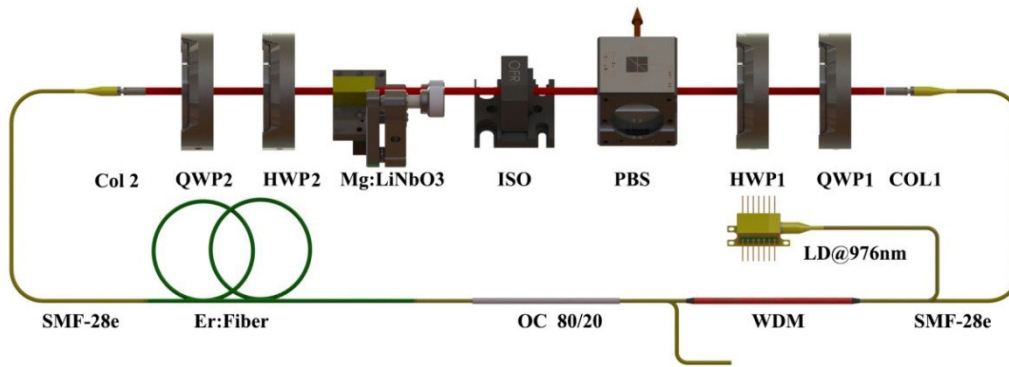


Figure 1. Configuration of the passively mode-locked EDF laser (COL: collimator; PBS: polarization beam splitter; ISO: polarization-dependent isolator; HWP: half-wave plate; QWP: quarter-wave plate; WDM: wavelength-division multiplexer).

fundamental repetition rate is typically limited to 30–50 MHz [24–27]. Furthermore, the average output power of the compact all-fiber laser is low. Thus, the conventional ring cavity fiber laser has the disadvantages of low coupling ratios of free-space, and the compact all-fiber laser has the disadvantages of low output power and low repetition frequency.

In order to improve the performance of passively mode-locked EDF lasers, we demonstrate a passively mode-locked EDF laser with two output ports: the free space output port and fiber output coupling port. The free space output port can be used for monitoring the mode-locking state, while the fiber output coupling port can be used to connect the optical fiber amplifier without loss. This kind of experimental design can increase the coupling efficiency for the conventional ring cavity fiber laser, and enhance the output power and repetition frequency for the compact all-fiber laser with the fiber coupler output. With proper dispersion management in the EDF laser cavity, the passively mode-locked EDF laser generates 91.4 fs pulses at 100.8 MHz repetition rate, and increases the coupling efficiency for application in amplification and supercontinuum generation systems. Besides, the passively mode-locked EDF laser does not introduce additional external noise to the amplified pulses, and the small volume and low noise fiber laser systems can be realized. In addition, the seed laser can achieve self-starting under low pump power, the mode-locked threshold is low, and stable operation of the seed laser can be achieved. Furthermore, due to the fiber output coupling port, power jitter for a femtosecond optical frequency comb can be effectively avoided.

2. Experiment setup

Configuration of the passively mode-locked EDF laser can be seen in figure 1. The polarizing beam splitter (PBS) acts as the polarizer to maintain linear polarized light. The first $\lambda/4$ wave plate (QWP2) controls the polarization state of the light entering the fiber, and changes the linear polarization to elliptical. This is a superposition of left and right hand circular modes of different intensity, experiencing different nonlinear phase shift through self-phase modulation (SPM) and cross-phase modulation (XPM) induced by the phase shift imposed on the orthogonally polarized component. The second $\lambda/4$ wave plate (QWP1) changes the elliptically polarized light

Table 1. Parameters of all fiber in the ring cavity.

	EDF	WDM	OC	Collimator1	Collimator2	LiNbO ₃ : MgO
Length (mm)	400	300	210	100	100	10
GDD (fs ² mm ⁻¹)	+12	-1.3	-22	-22	-22	+220

back to linear polarization; the different intensity of a signal leads to the different polarization direction. The $\lambda/2$ wave plate (HWP) adjusts the strongest polarization signals consistent with the polarization-dependent isolator; and finally, to harness the power of the saturable absorption effect—wherein higher intensities experience lower loss—the polarizing isolator lets the central intense part of the pulse pass, but blocks (absorbs) low intensity pulse wings, and forces unidirectional operation in the laser cavity. The result is that the pulse is slightly shortened after one round trip inside the ring cavity. The LiNbO₃:MgO crystal acts as a fast locking device in the mode-locked EDF laser. When the LiNbO₃:MgO crystal has a voltage between two poles, it can be used as the waveguide EOM with a servo bandwidth of more than 1 MHz for fast control of the cavity length, allowing for tight stabilization of the fiber laser repetition frequency.

The dispersion parameters of all fiber and LiNbO₃:MgO in the ring cavity are shown in table 1. The free space is composed of four wave plates, an ISO and a PBS; the component is fused quartz; the length of fused quartz is about 15 mm, the GDD of fused quartz at 1550 nm is -15 fs² mm⁻¹, the spatial dispersion of free space is -225 fs². Thus, the total GDD of the intracavity is about -2635 fs².

3. Experimental results and discussion

In the experiments, the self-start mode locking operation [28] of the laser is obtained at a pump power of 650 mW by adjusting the HWP and QWP. The corresponding oscilloscope trace is depicted in figure 2(a), illustrating equally spaced pulses emitted from the laser with the repetition rate of 100.8 MHz, which suggests no signal or dual-pulsing or Q-switched mode-locking operation of the laser oscillator.

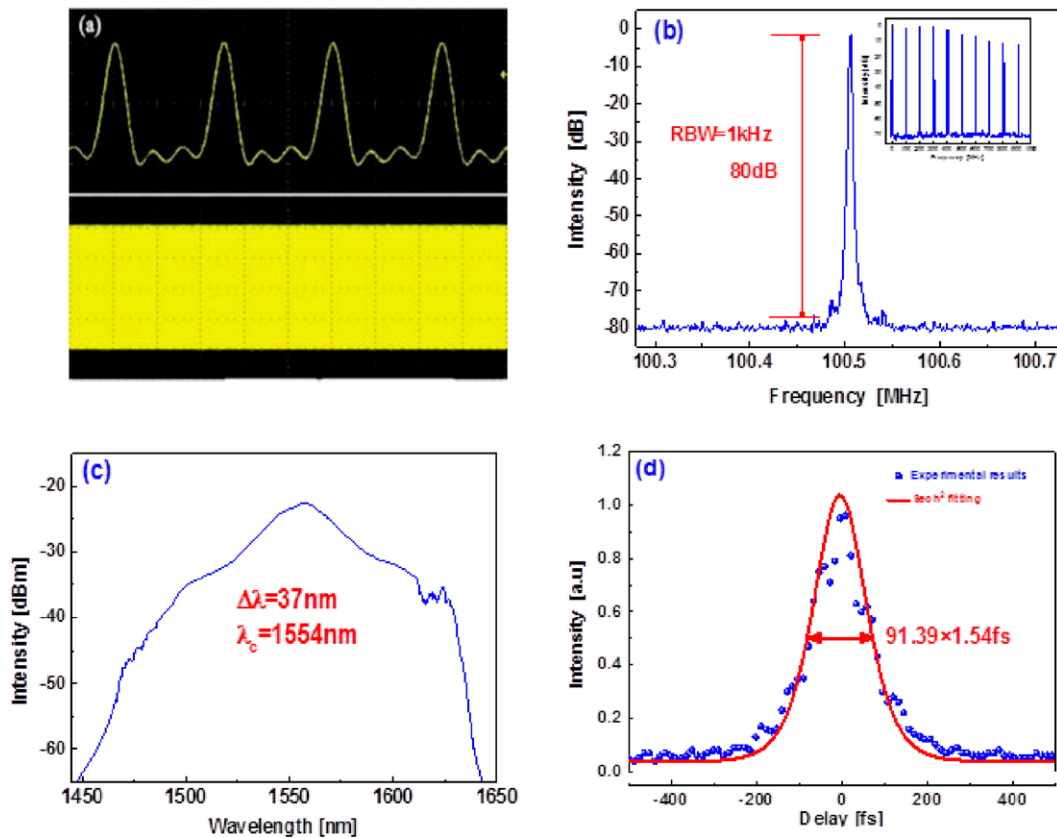


Figure 2. Experimental results. (a) Mode-locked pulse train in the oscilloscope, (b) radio frequency spectrum, (c) optical spectrum, and (d) intensity autocorrelation trace of the fiber laser pulses.

The pulse train was measured using a 1 GHz photo-detector and a 250 MHz oscilloscope (Tektronix TDS 714L). It is noted that there is a slight fluctuation of pulse intensity, which can be attributed to the insufficient band-width and resolution of the oscilloscope. The pulse trace on the oscilloscope maintains relatively uniform intensity, with a pulse to pulse interval of 10 ns corresponding to the cavity round trip time. The RF spectrum of the 100.8 MHz fundamental mode beat used by the RF spectrum analyzer (E4407B, Agilent Inc.) is illustrated in figure 2(b). The signal-to-background ratio of the fundamental frequency is up to 80 dB at a resolution bandwidth of 1 kHz, and no sideband is observed within a frequency range of 5 MHz. The inset graph of the upper right corner of figure 2(c) shows the RF spectrum of 15 harmonics (up to a frequency of about 3 GHz) at a resolution bandwidth of 1 kHz, which further verifies the high stability of our fiber laser.

The output spectrum is measured with an optical spectrum analyzer (AQ 6315A, ANDO). As shown in figure 2(c), the optical spectrum of mode-locked pulses is centered at 1555 nm and 3 dB spectral width is 37 nm. The measured dispersion compensated laser pulses had a time-bandwidth product (TBP) of 1.328, assuming a secant shape pulse. Figure 2(d) shows an autocorrelation trace of the dechirped pulse, which has a pulse duration of 91 fs. No pedestal beat can be observed in either side, indicating that temporal beat pedestals are successfully suppressed by nonlinear amplitude

modulation in the oscillator. From the fitted estimation, the pulse width can be deconvoluted to be 93.9 fs for a secant hyperbolic pulse. Theoretically supported Fourier transform limit FWHM pulse width is 69 fs. Although the addition of the optical coupler and $\text{LiNbO}_3\text{:MgO}$ crystal has increased the FWHM pulse width, an extra port with the possibility of further integration of fiber has been added. Moreover, due to amplitude modulation, the initiation of pulse generation has been simplified.

The EDF laser delivers an average output power of 16 mW from the optical coupler and 27 mW from the PBS at the pump power of 700 mW, corresponding to pulse energy of 0.3 nJ. Compared to the characteristics of pulses from PBS and fiber coupler outputs, we find that the pulse is more stable from fiber coupler output. The impact of the pump power on the output spectrum is also investigated as shown in figure 3. The average pump power changes from 400 mW to 625 mW. The spectral width broadens slightly with increasing pump power, and the resonant sidebands at both slopes are typical for passively mode-locked fiber lasers.

The laser is highly stable with several free-space bulk components and the NPE mode-locking scheme. Once mode-locked, the presented laser was capable of constant operation over four months. Additionally, if no change in the position of the polarization controller knobs was made after achieving stable mode-locked operation, the constructed lasers underwent self-starting when the pumping power was cycled on-off.

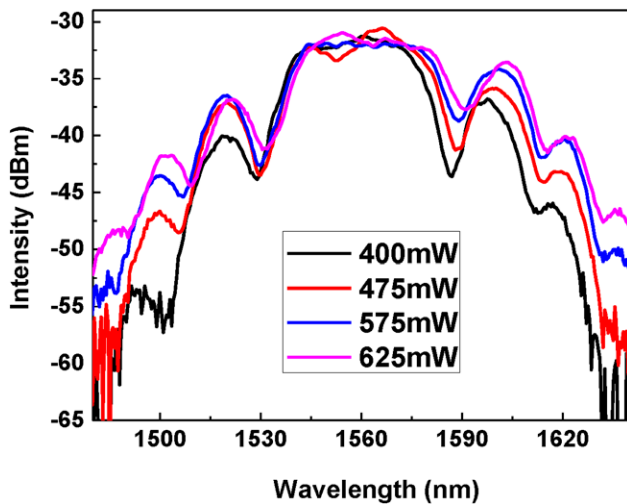


Figure 3. Experimental results. Output spectrum of the fiber laser pulses with different pump power.

Self-starting behavior of the system was observed even if the lasers underwent transportation among laboratories or were unpowered for several weeks.

4. Conclusion

In conclusion, we have demonstrated a passively mode-locked NPE-based EDF laser with fiber output. The passively mode-locked EDF laser generates a stable pulse as short as 91.4 fs without dechirping process at a 100.8 MHz repetition rate, and the fitted estimation of the pulse width can be deconvoluted to be 93.9 fs for secant hyperbolic pulse profile assumptions. The laser delivers an average output power of 16 mW from the optical coupler and 27 mW from the PBS at a pump power of 700 mW, corresponding to pulse energy of 0.3 nJ. The FWHM of the optical spectrum is 37 nm centered at 1555 nm. Mode locking can be self-starting, and the laser can work continuously for four months. The use of the fiber coupler in this fiber laser will allow for further integration with no change in strong laser characteristics. Besides, this compact passively mode-locked EDF laser with high coupling efficiency and repetition frequency has simple design and excellent stability, so that it can play an important role in femtosecond optical frequency combs as well as in supercontinuum generation.

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