

# Hybrid mode-locked Er-doped fiber femtosecond oscillator with 156 mW output power

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**Abstract:** We report on an Er-doped fiber oscillator that produces 146 fs pulses with 156 mW average power at a repetition rate of 49.9 MHz. The pulse energy reaches 3.13 nJ, surpassing the conventional power limit in the dispersion-managed soliton regime. Such high pulse power is obtained by devising a hybrid mode-locking scheme that combines saturable absorption with nonlinear polarization evolution. The oscillator also offers excellent temporal purity in the generated pulses with high power, providing a robust fiber-based frequency comb well suited for industrial uses.

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## 1. Introduction

Fiber pulse lasers offer advantages over solid-state pulse lasers in the pumping efficiency, beam quality, power scalability, system robustness and easy operation [1,2]. Since the first demonstration of the frequency-stabilized octave-spanning comb using crystal-based femtosecond lasers [3,4], much attention has been paid to Er- and Yb-doped fiber lasers to replace the crystal-based comb with the fiber-based comb that can conveniently be used with superior immunity to environmental disturbance for precision spectroscopy and optical clocks [5–10]. Nowadays the fiber-based comb is widely used in diverse applications such as astronomical spectrograph calibration, remote distance ranging, coherent LIDAR, and arbitrary waveform generation [11–13]. Despite the remarkable progresses made in the last few decades, more efforts are needed to improve the fiber-based comb particularly in the design of fiber oscillator so as to produce shorter pulse duration, higher average power and less jitter noise to compete with the crystal based comb.

Formation of ultrashort pulses inside a fiber oscillator can be explained by the interplay between the group-velocity dispersion (GVD) and the nonlinear self-phase modulation (SPM). Continuous balancing between the GVD and SPM all over the cavity of the fiber oscillator gives rise to clean sub-picosecond pulses. This simple way of pulse generation called the soliton mode-locking is, however, not suitable to achieve high pulse energy over 0.1 nJ, because the fiber oscillator filled with high energy pulses over its entire cavity tends to split or destabilize the pulses due to various intra-cavity nonlinear side effects [14,15]. On the other hand, pulse generation in the dispersion-managed (DM) soliton regime (also called the stretched-pulse regime) permits accommodating stronger pulse energy up to 2.7 nJ together with pulse duration shorter than 100 fs and high average power up to 95 mW [16–18]. This improvement is enabled by controlling the pulse duration alternatively to be stretched and compressed following a designed dispersion profile, rather than being held constant, to reduce the nonlinear side effects causing pulse degradation inside the oscillator. Recently a new technique called the self-similar or all-normal dispersion was introduced to generate sub-100 fs with 200 mW average power and 14 nJ pulse energy by letting only strongly chirped pulses to circulate inside the cavity [19–21]. However, to date, this method of pulse generation in the all-normal dispersion regime, suffers large timing jitter coupled with phase noise, making it difficult to obtain high frequency stability in the resulting comb [22,23].

In this investigation, we demonstrate a new design of fiber oscillator that operates on a hybrid scheme devised by incorporating two distinct mode-locking mechanisms; nonlinear polarization evolution (NPE) and saturable absorption (SA). The NPE mode-locking adopted here is intended to shape ultrashort pulses in the DM soliton regime. The SA mode-locking is added to perform nonlinear filtering of the pulse amplitude to avoid excessive intra-cavity nonlinear side effects. At the same time, the SA facilitates pulse initiation [24] and also suppresses the parasite waves separated from the main pulses. This combined mode-locking scheme consequently permits generating ultrashort pulses with high average power and temporal purity, thereby enabling construction of a robust fiber-based comb with a large spectral bandwidth and high frequency stability.

## 2. Hybrid mode-locked Er-doped fiber femtosecond laser

Figure 1 illustrates the system layout of the fiber oscillator configured in this investigation. An Er-doped fiber (Er80-4/125, Liekki) is used as the gain medium. The normal dispersion of the gain fiber is compensated by use of a single-mode fiber (SMF-28, Corning) of anomalous dispersion. A 500 mW pump power is supplied from a laser diode at a 980 nm wavelength. Mode-locking is achieved by devising a nonlinear polarization evolution (NPE) unit to be combined with a transmission-type saturable absorption (SA) unit. The NPE unit consists of four waveplates whose rotations are individually adjusted with an angle resolution of 0.07 degree by use of step motors and reduction-gear mounts. The SA unit is made of a saturable absorber (SA-1550-25-FC/PC, Batop) that operates with a 2 ps relaxation time for 300  $\mu\text{J}/\text{cm}^2$  saturation fluence.

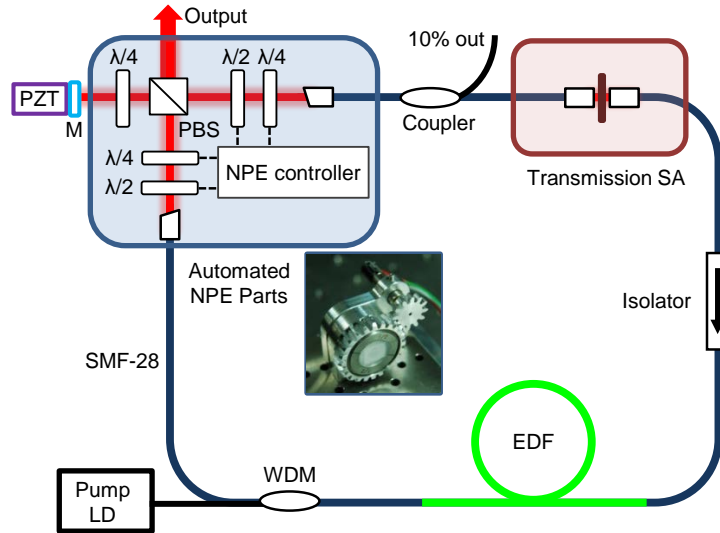


Fig. 1. System layout of the hybrid mode-locked Er-doped fiber oscillator configured in this investigation. M: mirror, NPE: nonlinear polarization evolution, SA: saturable absorber, LD: laser diode, WDM: wavelength division multiplexer, SMF: single mode fiber, and EDF: erbium-doped fiber.

The net dispersion of the oscillator cavity is managed to be  $-0.009 \text{ ps}^2$  so that pulses are generated in the DM soliton regime; the Er-doped gain fiber ( $-26 \text{ ps}/\text{nm}/\text{km}$ ) has a length of 1.4 m and the single-mode fiber ( $+17 \text{ ps}/\text{nm}/\text{km}$ ) is fine-tuned to a length of 2.52 m to achieve the targeted net dispersion. The total cavity length results in a pulse repetition rate of 49.92 MHz. The NPE unit is adjusted under computer control to search for the optimum polarization combination of the waveplates; the waveplates are rotated with different incremental steps until mode-locked pulses are clearly observed. Two different modes of pulse generation are found to exist; a hybrid mode and a NPE-dominating mode as summarized in Table 1. In order to monitor not only the output power but also the intra-cavity power simultaneously, a tap coupler (9:1) is connected right in front of the SA unit as shown in Fig. 1. The hybrid mode produces an average power of 156 mW at the output port and an intra-cavity power of 6.0 mW for a 450 mW pump power. The intra-cavity power is converted to a fluence of  $138 \mu\text{J}/\text{cm}^2$ , which is well below the fluence limit ( $300 \mu\text{J}/\text{cm}^2$ ) of the SA unit. This power measurement result confirms that the SA unit performs its intended functions through nonlinear attenuation of the pulse amplitude. The pulse power is reduced by the SA unit and gradually built up within the Er-doped gain fiber without excessive nonlinear side effects. Then the amplified pulse is compressed within the single-mode fiber of anomalous dispersion to a short pulse before entering the NPE unit. Consequently, the combined scheme

of mode-locking is well realized as expected with a strong average power of 156 mW at the output port located at the exit of the NPE unit.

In contrast, the NPE-dominating mode is not an intended result from the hybrid mode-locking scheme. In this mode, the intra-cavity fluence is measured to be 423  $\mu\text{J}/\text{cm}^2$  far above the fluence limit of the SA unit. Without proper functioning of the SA unit, this NPE-dominating mode shows multiple pulses per round trip for a given pump power of 450 mW. Single pulse is seen only when the pump power is reduced to 220 mW as the intra-cavity fluence falls below the SA fluence limit. The average output power reaches only 41 mW. This NPE-dominating mode is basically similar to the case of pure NPE mode-locking that would be observed with the SA unit eliminated from the oscillator.

**Table 1. Power Characteristics of Two Distinct Modes Existing in the Hybrid Mode-locking**

* SA fluence limit: 300 $\mu\text{J}/\text{cm}^2$			
Mode-lock scheme	Output power (mW)	Pump power (mW)	Pulse fluence at SA ( $\mu\text{J}/\text{cm}^2$ )
Hybrid (NPE + SA)	156	450	138
NPE-dominating (multiple pulses)	103	450	423
NPE-dominating (single pulse)	41	220	201

### 3. Suppression of temporal pedestal in femtosecond soliton pulses

Soliton mode-locked lasers with anomalous net dispersion are known to yield parasite waves due to the periodic perturbation of dispersion inside the oscillator cavity [25]. This unwanted phenomenon results in sharp Kelly sidebands in the spectral domain and a beat pedestal in the time domain. This also observed in our NPE-dominating mode as shown in Fig. 2(a) and 2(b); two Kelly peaks separated 39 nm apart from each other – one at 1551 nm and another at 1590 nm in the spectral domain. The spectral side peaks correspond to the pedestal beats of 210 fs in the time domain, causing a significant leak of pulse energy out from the main peak. Various methods have been reported to remove these pedestal beats, but they all accompany a serious loss in the spectral bandwidth together with temporal broadening of the main lobe [25,26]. However, our hybrid mode-locking, using the SA unit as a nonlinear filter, allows the main lobe of high power to pass through with less attenuation but suppresses dispersive waves of lower peak power. As a result, the pulse energy is concentrated in the main lobe with a much smaller beat pedestal as shown in Fig. 2(d). No noticeable Kelly sidebands are detected in the spectrum shown in Fig. 2(c). The hybrid mode produces pulses of 6.85% broader than the NPE-dominating mode, but the average power increases by a factor of 3.63 which sufficiently compensate for the slight power spreading due to pulse broadening.

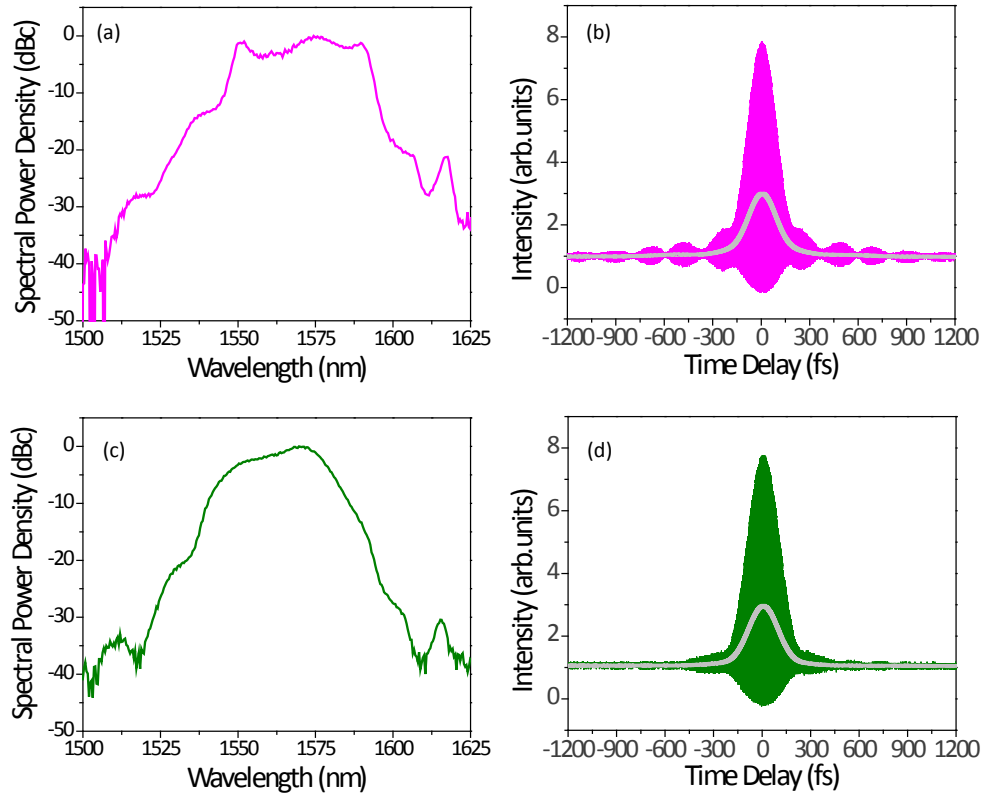


Fig. 2. Spectral and temporal characteristics of generated femtosecond pulses. (a) Spectrum of the NPE-dominating mode showing Kelly side bands. The spectral bandwidth is measured 42 nm. (b) Interferometric and intensity auto-correlation of NPE-dominating 135 fs pulses ( $\text{sech}^2$ , FWHM). The measured pedestal beat period agrees well with the Kelly side bands of Fig. 2(a). (c) Spectrum of the hybrid mode showing no noticeable side bands. The spectral bandwidth is 30 nm (d) Interferometric and intensity auto-correlation of hybrid-mode 146 fs pulses ( $\text{sech}^2$ , FWHM).

#### 4. Energy concentration and RF spectrum of the generated femtosecond pulses

The pulse energy concentrated on the main peak is quantitatively assessed by integrating the pulse energy from the peak to the side of a single pulse. As shown in Fig. 3, the hybrid-mode pulses contain 98.5% energy within the main lobe of 320 fs duration (99.9% energy in 1.13 ps duration), whereas the NPE-dominating pulses have only 94.0% energy within the same duration (99.9% energy in 2.94 ps). This calculation conforms that the hybrid mode-locking offers high energy concentration as well as strong average power. These energy characteristics are beneficial to construct a fiber-based comb that requires efficient nonlinear spectral broadening and second-harmonic generation for a self-referenced f-2f interferometer.

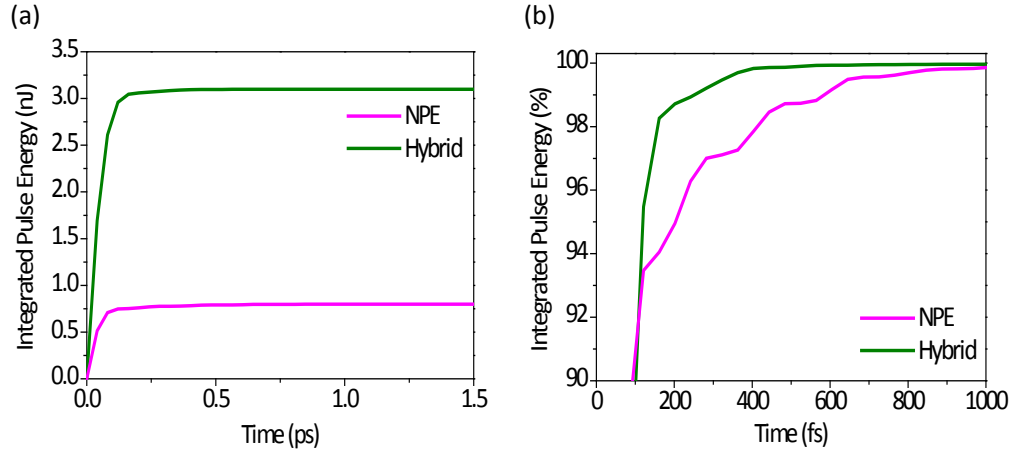


Fig. 3. Energy concentration of the mode-locked femtosecond pulses. (a) Accumulated pulse energy from the central peak of a pulse. (b) Normalized relative power concentration. More than 98.5% of the power is concentrated within 320 fs near the pulse peak in the hybrid mode-lock, compared to 94% in the NPE mode-lock case.

Figure 4 shows the RF spectrum of the hybrid mode pulses measured using a spectrum analyzer (R3267, Advantest). The spectral amplitudes of higher harmonics of the repetition rate appear to be even up to 200 MHz within the 3 dB bandwidth of the used photo-detector (FPD510, Thorlabs). No sub-harmonics or spurious RF noise peaks are observed. The 20th harmonic of the repetition rate located at  $\sim 1$  GHz (measured with SIR5-FC, Thorlabs) shows a clean instrument-limited linewidth less than 10 Hz (see Fig. 4(b) and 4(c)). The repetition rate of the oscillator was locked to the Rb atomic clock by phase-locked loop (PLL) control as shown in Fig. 4(d). The control signal was regulated using a servo controller (LB1005, New Focus) and then amplified and fed to an intra-cavity PZT actuator having a 10  $\mu\text{m}$  translation range to tune the repetition rate over a range of 167 Hz. Long-term stability was evaluated in terms of Allan deviation as 1.5 parts in  $10^{12}$  at a 10 s averaging. Finally, the phase noise of the resulting comb structure was monitored by beating it with a narrow-linewidth cw semiconductor laser (Thorlabs, SFL1550S). As shown in Fig. 4(e), the four beat notes observed in the rf-domain all had S/N ratios more than 35 dB in free-running state from the noise floor of the comb. This confirmed that the hybrid mode-locking scheme yields low phase noise so that the resulting comb can robustly be used for industrial uses.

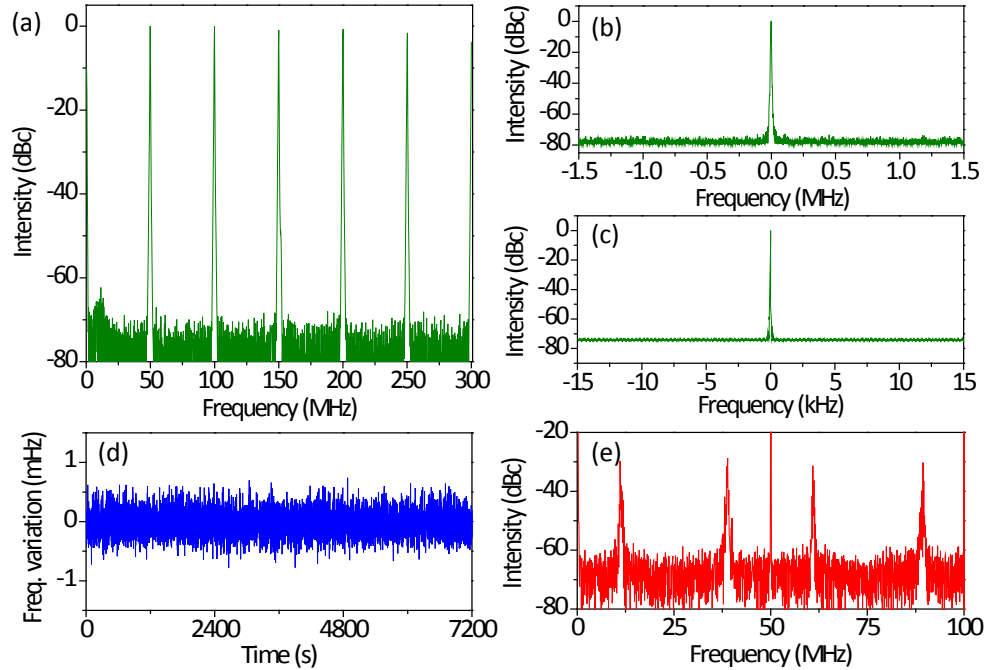


Fig. 4. RF spectra of the repetition rate of femtosecond pulses. (a) Harmonic spectrum of the pulse repetition rate (RBW & VBW: 300 kHz). No noticeable sub-harmonics or spurious peaks are detected. (b) Linewidth measurement of the 20th harmonic of the repetition rate at  $\sim 1$  GHz with 3 kHz RBW. (c) Measurement of the same linewidth with 10 Hz RBW. (d) Time trace of the stabilized repetition rate over a period of 2 hours. (e) RF beat notes with a narrow linewidth continuous-wave (cw) laser (RBW & VBW: 100 kHz).

## 5. Conclusion

The hybrid mode-locked femtosecond laser oscillator proposed in this study offers a 156 mW average power with 3.13 nJ pulse energy in the dispersion-managed soliton regime. Temporal beat pedestals are successfully suppressed by nonlinear amplitude control in the oscillator with the aid of a saturable absorber, resulting in concentration of 98.5% of the pulse energy in a 320 fs time duration. This achievement will facilitate the use of the fiber-based comb for industrial uses such as broadband spectroscopy, remote sensing, and bio-medical imaging.

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