# Tunable all normal dispersion erbium-doped fiber laser

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**Abstract**: We experimentally demonstrated an all normal dispersion erbium-doped fiber oscillator, producing pulses of 121 fs, 3.8 nJ at 1562 nm. The central wavelength and bandwidth are tunable by using an intracavity Fourier transform pulse shaper.

## 1. Introduction

Dissipative solitons in self-similar and all normal dispersion (ANDi) lasers have attracted much attention in recent years because of the increased intracavity pulse energy [1]. In stretched pulse mode-locked lasers, the pulse width is minimized at two intracavity positions where strong nonlinear chirp and even wave breaking could occur [1]. In contrast, the large positive chirp of an ANDi laser prevents the intracavity pulse compression, suppressing the peak power, nonlinear chirp, and wave breaking. The achievable pulse energies of femtosecond fiber oscillators can thus be increased by one order of magnitude. ANDi lasers are further distinguished from soliton and stretched pulse lasers in terms of the pulse formation mechanism. In the presence of large linear chirp, the temporal pulse shape will imitate the power spectrum. As a result, a spectral filter can suppress the pulse wings in the time domain, behaving like an effective saturable absorber. Stable mode-locking can be achieved if the spectral filter bandwidth, net group velocity dispersion (GVD), and nonlinear phase accumulation are properly managed.

The ANDi laser was first proposed and implemented with Yb-doped fiber amplifier around 1 μm wavelength [2] where the standard single-mode fiber (SMF) exhibits normal dispersion. So far, only a limited number of ANDi Er-doped fiber lasers have been demonstrated [3-5] because of the anomalous GVD of standard SMF at the telecommunications band and the lower dopant concentration of the Er-doped fiber (EDF). Chichkov et al. achieved an ANDi Er-doped fiber laser around 1552 nm with 750 fs duration and 20 nJ pulse energy [3]. However, they needed to use a very short (59 cm) EDF and very long (57 m) passive fibers to balance the nonlinear chirp and normal GVD, and the compressed pulse had oscillatory tail due to the residual cubic phase. In this work, we demonstrated an ANDi Er-doped fiber laser producing 121 fs, 3.8 nJ (limit by the pump power), oscillatory tail-free pulses using only EDF and standard SMF. An intracavity Fourier transform (FT) pulse shaper allows for tuning of central wavelength and bandwidth by simply moving the blades placed on the Fourier plane. Experiments about more sophisticated manipulation of the generated pulses by using a spatial light modulator is ongoing.

## 2. Experiments

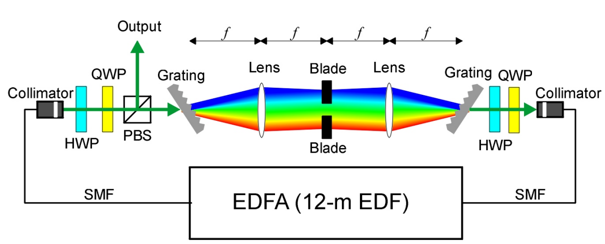


Fig. 1. Experimental setup of the ANDi Er-fiber laser: QWP: quarter waveplate; HWP: half waveplate; PBS: polarization beam splitter. SMF: Single-mode fiber.

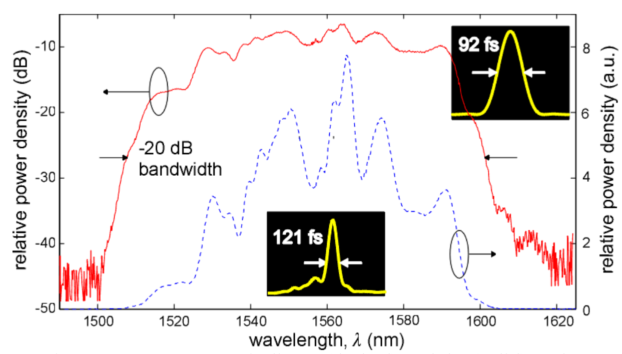


Fig. 2. Power spectrum in linear (dashed) and dB (solid) scales. The temporal intensity profiles of the transform-limited (right inset) and roughly dechirped (middle inset) pulses.

The ANDi Er-doped fiber laser setup is shown in Fig. 1. A customized erbium-doped fiber amplifier (EDFA) was employed as the gain medium, and an FT pulse shaper was used as a tunable spectral filter. The EDFA consists of 12-m-long EDF with $\beta_2$=17.5 ps$^2$/km, and 2-m-long SMF with $\beta_2$=-22 ps$^2$/km, contributing to a net cavity dispersion of ~0.17 ps$^2$. SMF longer than 2 meters will introduce excessive anomalous dispersion and destabilize the mode-locking mechanism. The nonlinear polarization evolution (NPE) effect in the fibers and the polarizationdependent optics behave as a saturable absorber to initialize mode-locking. Some optical power is output-coupled by the polarization beam splitter. The mode-locking can self-start and sustain by properly adjusting the waveplates when the pump power is above 100 mW. We got a stable pulse train with 12.5 MHz repetition rate, 48 mW averaged power (3.8 nJ pulse energy) when using 336 mW pump power and 10 nm filter bandwidth. The mode-locked power spectrum (Fig. 2) extends from 1510 nm to 1600 nm (-20 dB bandwidth), corresponding to an FT-limited pulse width of 92 fs (right inset) and an FWHM time-bandwidth product (TBP) of 0.68. The output pulse was roughly dechirped by 2-m-long SMF and measured by frequency-resolved optical gating [6]. The measured temporal intensity (middle inset) has a larger FWHM (121 fs) and TBP (0.89) due to the residual spectral phase.

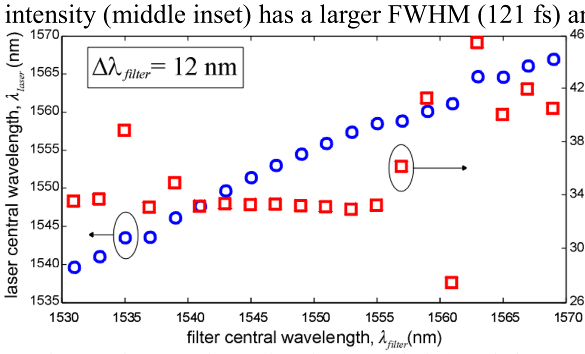


Fig. 3. The central wavelength (open circles) and the rms bandwidth (open squares) of the output pulse versus the central wavelength of the filter at fixed $\Delta\lambda_{filter}$ =12 nm.

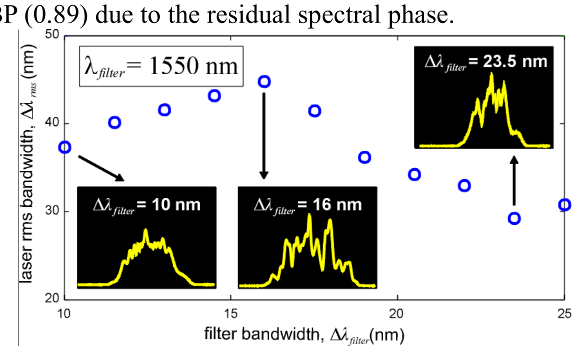


Fig. 4. The rms bandwidth of the pulse versus the filter bandwidth when the filter is centered at 1550 nm. Insets: Representative power spectra.

The intracavity FT pulse shaper consists of two 1100 gr/mm gratings and two lenses with *f*=20 cm. A tunable spectral filter with central wavelength $\lambda_{filter}$ and bandwidth $\Delta\lambda_{filter}$ can be achieved by changing the positions and separation of the two blades on the Fourier plane. Since the mode-locked power spectrum $I(\lambda)$ is typically structured, the central wavelength and bandwidth of the output pulse are better estimated by the weighted average values $\lambda_{laser} = \langle\lambda\rangle = \int_{-\infty}^{\infty} \lambda \cdot I(\lambda) d\lambda \Big/ \int_{-\infty}^{\infty} I(\lambda) d\lambda$ and $\Delta\lambda_{rms} = 2\sqrt{\langle\lambda^2\rangle - \langle\lambda\rangle^2}$, respectively. Fig. 3 shows that the central wavelength of the output pulse $\lambda_{laser}$ (open circles) could be tuned from 1540 nm to 1567nm (limited by the clear aperture of the lenses) as the central wavelength of the filer $\lambda_{filter}$ varies from 1531 nm to 1569 nm. The rms bandwidth $\Delta\lambda_{rms}$ (open squares) is nearly constant as $\lambda_{filter}$ falls within 1541-1555 nm, but tends to broaden when $\lambda_{filter}$ is beyond this wavelength range. The primary reason is that the filter could block more power when its center is away from the laser spectral center. After the EDFA, the peak power and the induced nonlinear phase shift become higher, supporting a broader laser bandwidth. Fig. 4 shows the rms bandwidth $\Delta\lambda_{rms}$ of the pulse versus the intracavity filter bandwidth $\Delta\lambda_{filter}$. The corresponding FT-limited pulse width (FWHM) lies within 77-115 fs. In principle, a narrower $\Delta\lambda_{filter}$ enables a stronger pulse shortening effect, causing a higher peak power (after amplification) and broader laser bandwidth $\Delta\lambda_{rms}$ (through self-phase modulation) [7]. However, the mode-locking mechanism will be overcome by the nonlinear chirp and evolves into wave breaking if $\Delta\lambda_{filter}$ is too small. Our experimental data meet with this trend and showed a maximum output pulse bandwidth of 44.5 nm when the filter bandwidth was 16 nm (Fig. 4, middle inset).

## 3. Conclusions

We have experimentally demonstrated an all normal dispersion Er-doped fiber laser at 1.56 μm with 121 fs pulse width and 3.8 nJ pulse energy (limited by the maximum pump power of 350 mW). The built-in FT pulse shaper allows for stable mode-locking with widely tunable central wavelength (1540-1567nm) and bandwidth (29-45 nm).

## 4. References


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