



Generation of 2- μ J 410-fs pulses from a single-mode chirped-pulse fiber laser operating at 1550 nm

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Abstract

We report on a simple, robust, femtosecond chirped-pulse-amplification system, based on Er- and Er-Yb-doped fibers, operating at a central wavelength of 1555 nm. The entire system is constructed from commercially available fiber components, except the grating compressor, for easy duplication by other researchers. The laser system produces chirped pulses with up to 4 μ J of pulse energy at 250 kHz. After dechirping, the pulse duration is 410 fs and the pulse energy is reduced to 2 μ J. The repetition rate of the laser is electronically tunable between 125 kHz and 60 MHz, limited by strong amplified spontaneous emission (ASE) generation at the low end. The amplifier system is almost completely fiber integrated, except for the pump delivery into the final amplifier stage, which is free-space backward-pumped to reduce undesired nonlinear effects, and the compressor which was designed using the gratings. The laser is practically free of misalignment and has exhibited excellent long-term stability during its use in various experiments for more than 600 working hours.

1 Introduction

In the past decade, several new applications areas of high-energy and high-power femtosecond laser sources around 1.5 μ m central wavelength have been developed. These include, in addition to well-known scientific applications [1], medical surgery [2, 3], industrial micromachining [4], micromachining in transparent materials [5], and most recently, silicon [6–8]. However, development of compact fiber-based laser sources have lagged far behind those in Yb-doped and Tm-doped fiber lasers. Various ultrashort fiber laser systems operating at 1.5 μ m with different design have been reported so far. The combination of chirped pulse application (CPA) technique with large-mode-area (LMA) clad pumping fiber technology is a common factor among

them [9]. These reports cover a wide range of pulse energies, durations and repetition rates: A 156-MHz-repetition-rate system with 450 fs pulse duration and average power of 10 W was demonstrated in [10]. In [11], generation of 175-fs pulses at 3.5 W of average power at a repetition rate of 43 MHz was reported. The paper [12] describes a system based on a single-mode EY- fiber, with a maximum average power of 10 W at repetition rates from 600 kHz to 100 MHz and the pulse durations 400–600 fs. Femtosecond pulses with 1.5 μ J energy and 605 fs duration at 300 kHz were reported in [13]. In [14], the authors reported on the generation of 2- μ J, 880-fs pulses at repetition rates ranging from 100 kHz to 1 MHz. These results were obtained by readily available, splicable fibers producing diffraction-limited outputs. A parallel development has seen the use of specially designed fibers and in-band pumping to reduce the effective nonlinearity by orders of magnitude, and as a result, considerably higher pulse energies have been achieved, albeit at the expense of much more complicated setups. In [15], an Er-fiber laser system operating at 50 kHz and generating 25 μ J pulse energies and a pulse duration of 800 fs was demonstrated. At the high end of the energy scale, a fiber laser system generating 636-fs pulses with pulse energy of 100 μ J was reported [16] and a similar system reporting sub-500 fs pulses with 913 μ J pulse energy and average output power of 4.4 W was presented in [17]. However, the need for specialty components appear to have limited the impact of these reports, judging by that no

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other groups appear to have duplicated them. We believe that there continues to be strong demand for simple designs, which can easily be duplicated by researchers without access to specialty components.

Here, we report on a simple CPA system that uses only commercially available fibers and fiber components, achieving $2 \mu\text{J}$ pulse energy with 410 fs pulse duration. The repetition rate of the system is adjustable from 60 MHz (the repetition rate of the seed oscillator) down to 250 kHz, limited by the growing presence of spontaneous emission (ASE) at low repetition rates. The amplifier system is fully fiber integrated, except for delivery of pump power to the last amplifier, which is free-space backward-pumped in order to avoid excessive nonlinear effects, and the compressor which was designed using the gratings. The presence of this free-space part notwithstanding, the system has demonstrated excellent long-term stability during its use in various experiments in our laboratory over the course of one year, including the work reported in [8].

2 Experiments and results

Schematics of the experimental setup is shown in Fig. 1. The laser system consists of a mode-locked seed oscillator, three pre-amplifiers, a main amplifier and a diffraction grating-based dispersive delay line, based on the all-fiber femtosecond fiber laser-amplifier architecture first reported in [18]. We performed numerical simulations of pulse generation and propagation to help understand the influence of nonlinear effects and gain narrowing, to help determine the optimal placement and length of the stretching fibers, as well as to interpret the experimental measurements. The

simulations are fairly standard in terms of the included effects and the numerical method, having been used in numerous reports from our group. Further details can be found in [7, 19]. The results of modeling the evolution of spectral width and pulse duration in the amplifier system as described above are shown in Fig. 2.

Next, we describe the experimental setup in detail. The oscillator is passively mode-locked using nonlinear polarization evolution. The gain fiber of the oscillator is 1 m of single-mode Er-doped fiber (Er80 4/125, Thorlabs Inc.), which is backward pumped by a standard single-mode laser diode at 976 nm through a wavelength division multiplexer (WDM). The rest of the fibers are of standard SMF-28 type. The entire length of the fibers comprising the cavity is approximately 3.6 m, with a corresponding total dispersion of -19700 fs^2 . This length estimate is consistent with the measured repetition rate of 56.8 MHz. The average power, extracted from the cavity through a 20% fiber-coupler was 7.3 mW. Thus, the intra-cavity power and pulse energy were calculated to be 36.5 mW and 0.65 nJ, respectively. The (full-width at half-maximum, FWHM) bandwidth of the oscillator output measured at this port was 40.8 nm (Fig. 3a), centered at 1564.8 nm. The pulses were negatively chirped, but still of sub-picosecond duration. The radio frequency (RF) spectral measurement with 10 GHz scan range and 50 kHz resolution bandwidth, coupled with long-range autocorrelation scans confirmed single-pulsed operation (inset of Fig. 3a). A similar RF measurement for a 1-kHz scan range and 10-Hz resolution bandwidth, centered at the frequency of the fundamental harmonic of the oscillator, exhibited ~ 70 dB signal-to-noise ratio, which indicates excellent short-term stability.

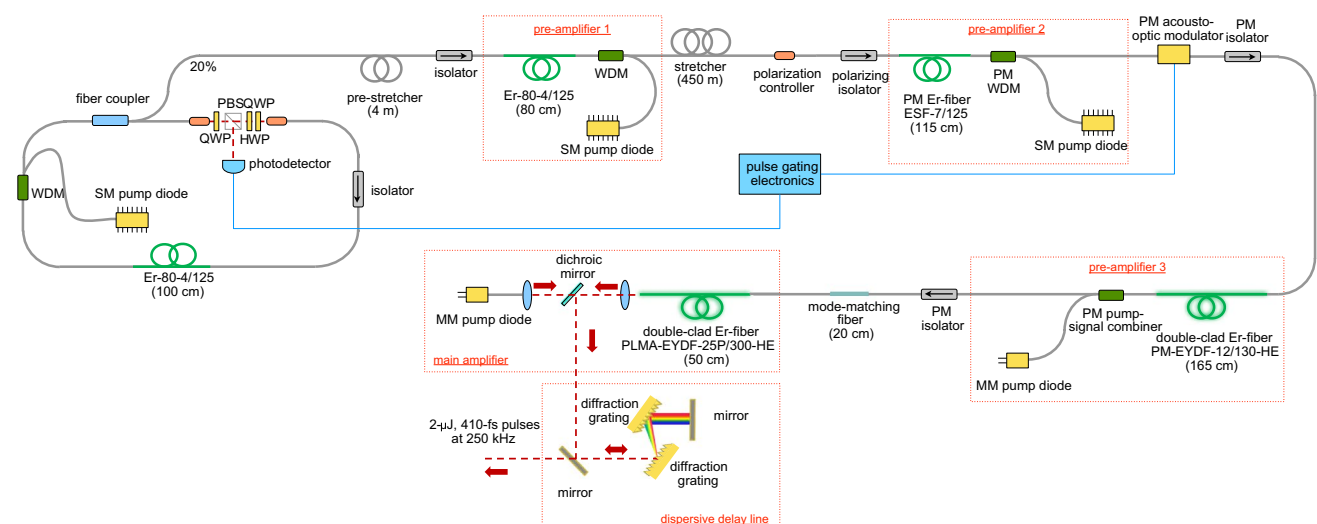


Fig. 1 Schematic of Er-Yb femtosecond laser system: *QWP* quarter waveplate, *HWP* half waveplate, *PBS* polarizing beamsplitter, *WDM* wavelength division multiplexer, *SM* single-mode, *MM* multimode, *PM* polarization maintaining

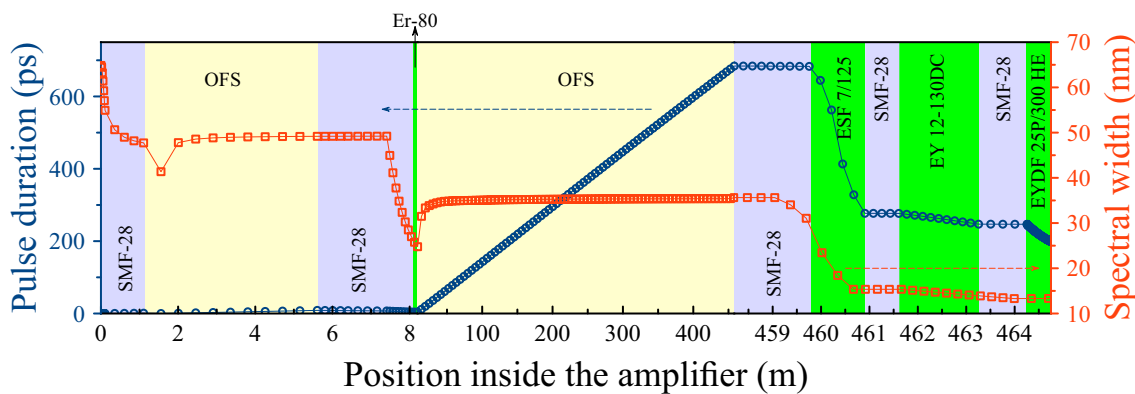
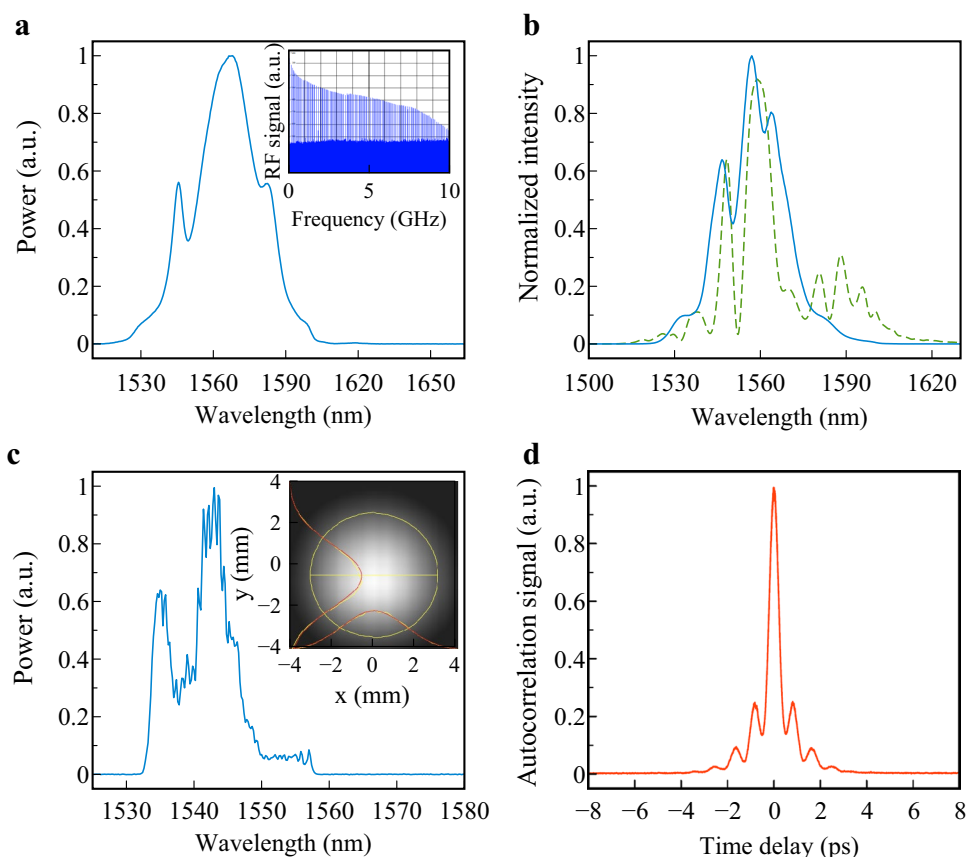


Fig. 2 Simulation results for evolution of the pulse duration and spectral width along the amplifier system

Fig. 3 **a** Measured optical spectrum of the oscillator output, where the inset shows the RF spectrum, **b** measured optical spectra after the first pre-amplifier without pre-stretcher (green dashed line) and with pre-stretcher (blue solid line), **c** measured optical spectrum of the final output after dechirping in the dispersive delay line for a pulse energy of $2 \mu\text{J}$, and **d** the measured autocorrelation trace corresponding to the results shown in **c**. Inset of **c** shows the spatial profile of the beam



The pulses extracted from the oscillator’s fiber port are directed into the first pre-amplifier based on 80 cm-long gain fiber (Er80-4/125, Thorlabs, Inc.), which is backward-pumped through a WDM (pre-amplifier 1 in Fig. 1). However, in order to reduce nonlinearity during the pre-amplification, a short segment of a normal-dispersion stretch fiber (4 m, $D = -44 \text{ ps/nm.km}$, OFS Ocean fiber) is used before the preamplifier (the pre-stretcher in Fig. 1). While the approximate length of the pre-stretcher to obtain the

broadest spectral width with minimal modulations was estimated from numerical simulations, its precise values was determined experimentally, using the cut-back method. In essence, we arrange for the balancing of gain narrowing with self-phase modulation [20] at the output of this pre-amplifier. The measured optical spectra with and without the pre-stretcher are shown in Fig. 3b. The nonlinear phase shifts at the output of the pre-amplifier with and without the pre-stretcher were estimated as 1.3π and 2.4π , respectively.

The optimal output spectrum had a bandwidth of 25.6 nm and is centered at 1557 nm (black solid line in Fig. 3b). The output power after the pre-amplifier was 118 mW, which corresponds to 2 nJ for the pulse energy.

After the first preamplifier, the pulses traverse the main stretcher, which consists of 450 m of the single-mode fiber with $D = -44$ ps/(nm.km). The estimated pulse duration after the stretcher was 520 ps. Since all of the fiber components and gain fibers after the stretcher are polarization maintaining (PM), we used a polarization controller, followed by a polarizing isolator (fast axis is blocked). The polarization controller was adjusted to maximize the signal obtained after the isolator, which was 50 mW. The second preamplifier (pre-amplifier 2 in Fig. 1) consists of 1.15 m of PM single-mode Er-doped fiber (ESF - 7/125, Nufern, Inc.) backward-pumped in core by a 976-nm diode through a PM WDM. The signal power after the second preamplifier was 213 mW (for a pump power of 580 mW). After the second preamplifier an acousto-optic modulator (AOM) is used to decrease the repetition rate of the laser. The AOM is controlled with a homemade electronic card based on a field-programmable gate-array (FPGA), triggered by a photodetector signal obtained from one of the oscillator outputs. Due to the low duty cycle of pulse picking at low repetition rates and relatively high internal losses of the AOM (3 dB), the signal power after the AOM decreases precipitously. For example, for a repetition rate of 250 kHz, the signal power after the AOM is merely 0.4 mW. For this reason, an additional pre-amplifier is included before coupling into the main amplifier. This pre-amplifier (pre-amplifier 3 in Fig. 1) is made of 165 cm-long PM Er/Yb co-doped double-clad fiber (PM-EYDF-12/130-HE, Nufern, Inc.). It is cladding pumped in the backward direction by multimode diode operating at 976 nm through PM multimode pump combiner. The output power of this pre-amplifier (pre-amplifier 3) at 1 MHz repetition rate was 303 mW at a pump power of 2.65 W. Due to gain narrowing, the signal had a bandwidth of 13.6 nm centered at 1543 nm at this power level. This suggests that decreasing the length of the stretch fiber would be the optimal way to compensate the gain narrowing in pre-amplifier 2 by spectral broadening due to self-phase modulation. In fact, ideally a dedicated stretcher should be placed preceding each amplifier, i.e., four segments of stretcher fiber in this laser, each of which would be of optimal length for balancing of gain narrowing. However, this would require placement of two other stretchers, approximately matching the length to be removed from the currently 450 m-long stretcher. Unfortunately, this was not possible in our work due to lack of any readily available PM fibers with large normal dispersion at 1550 nm, given that pre-amplifier 3 and the main amplifier are built from PM fibers. Nevertheless, a similar experimental optimization was performed on the length of the second stretcher and the minimum achievable pulse duration after

this stage (obtained with an external grating compressor) was 356 fs with a pulse energy of nearly 300 nJ. This result already compares favorably to our recent report in terms of peak power [11], where the pulse was shorter (175 fs), but for a lower pulse energy of 80 nJ.

The main amplifier (main amplifier in Fig. 1) consists of 50 cm-long large mode area PM Er/Yb co-doped fiber (PLMA-EYDF-25P/300-HE, Nufern, Inc.) with a core diameter of 25 μ m. Before the gain fiber, a piece of 20 cm passive fiber with 20- μ m core and 125- μ m cladding diameters is placed to act as a simple, but effective mode field adapter. The amplifier is backward pumped by a high-power multimode diode at 976 nm through free space. The pump diode output from MM fiber (105/125) is collimated by a 20 mm focal length lens and focused into the 8° angle-cleaved facet of the gain fiber by a high-power compatible focusing objective (LMH-10X-1064, Thorlabs, Inc.). The same objective is used for collimating the amplified signal beam from the gain fiber. The signal and pump are separated by a dichroic beam splitter mirror (DMSP1180, Thorlabs, Inc.). After the main amplifier, the output pulses are dechirped with a dispersive delay line, which comprises of a pair of 900 line/mm transmission diffraction gratings (WP-900/1550-50.8, Wasatch Photonics, Inc.). The transmission efficiency of the compressor was measured to be 65%. The output parameters of the system at different repetition rates are shown in Table 1.

The output spectrum and the autocorrelation trace of the system measured during operation at 250 kHz are shown in Figure 3c, d. At this repetition rate, the average power was measured to be 540 mW, which corresponds to 2 μ J of pulse energy after taking into account ASE content (see detailed discussion below). The measured pulse duration is inferred to be 410 fs based on the autocorrelation measurements, assuming a deconvolution factor corresponding to a Gaussian pulse shape. The inset of Fig. 3c shows the spatial profile of the output beam, which is nearly Gaussian. The beam quality was measured, yielding $M^2 = 1.4$.

We have intentionally kept the gain fiber of the final amplifier short to reduce the accumulated nonlinear phase shift. A consequence of this decision is the reduction of the efficiency of the amplifier to $\sim 15\%$, whereas an optimal length would achieve an efficiency as high as $\sim 45\%$. Although we did not observe saturation of the output power

Table 1 Parameters of the dechirped pulses produced by the laser system at different repetition rates

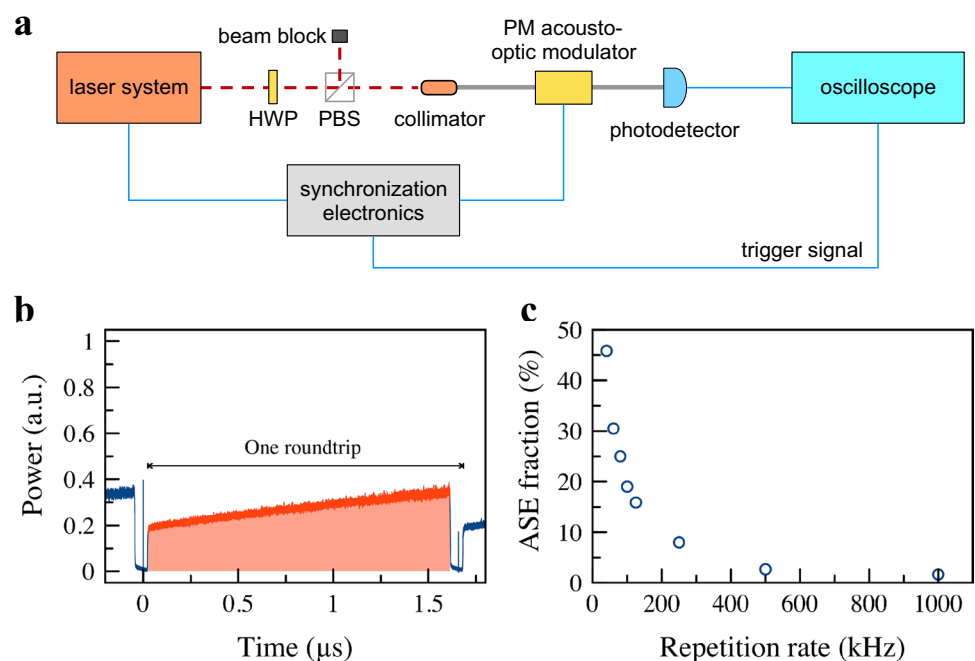
Repetition rate (MHz)	Average power (W)	Duration (fs)	Energy (μ J)
1	1	370	1
0.5	0.8	400	1.6
0.25	0.54	410	2

with increasing the pump power, the low efficiency of the amplifier indirectly imposes limitations to the achievable average power in our case. The first mechanism is due to the significant amount of unabsorbed pump light after the gain fiber, which thermally damages the coating of the mode-matching passive fiber placed before the gain fiber beyond a certain pump power. The second mechanism is the thermal damage of the tip of the gain fiber at the output of the system at high pump power. Both of these limitations can be overcome by introducing a commercial-grade cladding-mode stripper before the gain fiber and by introducing an end-cap comprised of a piece of coreless fiber at the output end. However, it is these limitations that presently limit the average powers for safe, long-term operation. Additionally, the collimating objective in our system was B coated, with nearly 30% loss at 1.5 μm . Replacing the objective with proper coating would immediately increase the output pulse energy by 30%, to 2.6 μJ , without any changes in the pulse duration.

Given the present limitations to average power, the ultimate limitation for pulse energy arises from the limit to reducing the repetition rate. This value, itself, is limited by the onset of significant ASE generation between the pulses. It is important to note that presence of large amounts of ASE can easily be overlooked and we strongly suspect that it has accompanied several of the high-energy results reported in the literature. In our case, we carefully measured the ASE content with a setup similar to those described in [21–23].

The schematic of the ASE measurement setup is shown in Fig. 4a. A small portion of the output light (20 mW) is coupled into a single-mode fiber and passed through a second AOM. The second AOM is triggered with the complement of the signal for the AOM in of the system, such that when the latter is high (transmitting) the former is low (blocking), which allows us to block the laser pulses, and pass only the temporal region between them, where the ASE content resides. Thus, we are able to directly and accurately measure the ASE power, even when it is a small fraction of the laser output. Fig. 4b shows the oscilloscope trace of the electrical signal taken from the photo-detector when the pulses are blocked by the second AOM, where the shaded region indicates the ASE generation between the temporal gates applied by the AOM. By measuring the ratio of the energy within this region to the energy within an entire roundtrip when the AOM is set to pass all signal, we obtain the fraction of ASE within the output signal. We note that since the suppression ratio of the AOM is limited to 50 dB, a small portion of the blocked pulses leak through and are visible under high magnification on the oscilloscope. However, their integrated contribution is negligible. The measured ASE ratios for different repetition rates are shown in Fig. 4c. The minimum ASE amount was measured at 1 MHz (1.64%), and it increases sharply when the system is operating at a repetition rate below 100 kHz, reaching 45% at 40 kHz. At 250 kHz, it was 8%. Therefore, we decided to limit operation to 250 kHz, while noting that this is not a hard limit.

Fig. 4 **a** Schematics of the ASE measurement setup: *HWP* half-waveplate; *PBS* polarizing beam splitter. **b** Oscilloscope trace showing the buildup dynamics of ASE (shaded region) for 600 kHz repetition rate. **c** Fraction of ASE as a function of repetition rate



3 Conclusion

We report on a simple, robust, compact and highly integrated fiber laser system operating at a central wavelength near 1.5 μm . The repetition rate of the system is adjustable from 60 MHz to down 250 kHz, limited by significant ASE content at low repetition rates. At 250 kHz, the system delivers 2- μJ de-chirped pulses with 410-fs duration. However, the pulse energy can easily be increased to 3.4 μJ without changing the pulse generation at all, but simply replacing the lossy objective at the output and also replacing the lossy gratings with the typical values routinely obtained at 1 μm [21]. Finally, we would like to note that the operation of the system in the range between 1 MHz to 250 kHz was highly stable over a long period of time (more than 600 working hours over the course of 1 year) without any reduction of the output power or misalignment. It was successfully applied to writing waveguides deep inside Si chips [8], as well as time-resolved pump-probe measurements of filament-inducing pulse propagation in Si (manuscript is under preparation). In contrast to many reports on Er-fiber lasers in recent years, the laser reported here is built using only commercially available components, the details of which have been provided in this report. Thus, we expect it to be duplicated easily by any researcher, who is interested in using this low-cost, reliable laser source of microjoule-level femtosecond pulses.

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