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# Microjoule femtosecond fiber laser at 1.6 $\mu\text{m}$ for corneal surgery applications

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We report on chirped-pulse amplification in a large-mode-area erbium-doped fiber emitting in a water transparency window. 1.5  $\mu\text{J}$  605 fs pulses are generated at 1.6  $\mu\text{m}$  with a repetition rate of 300 kHz; this corresponds to an average power of 460 mW. Nonlinearities are adjusted on the global system to compensate for the dispersion mismatch between the fiber stretcher and the grating compressor. This new compact and robust source targets medical applications such as surgery in highly scattering corneas. © 2009 Optical Society of America

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Ultrafast lasers have attracted significant interest, as their potential for a wide range of applications has been demonstrated [1]. Femtosecond lasers are used in ophthalmology to correct myopia, hyperopia, or astigmatism in the most commonly performed medical laser procedure: LASIK (Laser in-Situ Keratomileusis). Nowadays, ytterbium- or neodymium-based microjoule class subpicosecond lasers operating near 1.05  $\mu\text{m}$  are successfully used for this procedure.

Femtosecond laser microkeratome is now well established in ophthalmology, but its use could be further extended to corneal transplants in edematous corneas. However, at 1.05  $\mu\text{m}$ , propagation of the focusing laser beam into highly scattering tissues results in high losses and distortion of the pulses. As a result, the fluence obtained at the focal spot is not sufficient to reach the ablation threshold and perform quality incisions. Further increase of the pulse energy would damage the corneal tissue by the process of heat accumulation. Femtosecond lasers operating near 1.05  $\mu\text{m}$  are therefore not adapted for surgery in highly scattering corneas that can reach a thickness of 1.1 mm [2].

Increasing the wavelength is a well-known technique to enhance the penetration depth in tissues, and it has been successfully used to improve subsurface cut quality in human sclera [3]. A femtosecond laser based on erbium-doped fibers operating near 1.55  $\mu\text{m}$  would allow substantial reduction of scattered energy while potentially providing a compact and highly reliable optical source suited to medical standards. In human corneas, the absorption behavior is dominated by water above the wavelength of 1  $\mu\text{m}$  [4]. As water absorption peaks at 1450 nm and decreases towards a minimum near 1.7  $\mu\text{m}$ , maximum penetration depth would be obtained by shifting the erbium-doped laser at the edge of the erbium spectrum. In this Letter we present a microjoule class subpicosecond fiber laser operating at 1.6  $\mu\text{m}$ , which is designed to reduce scattering as well as absorption to allow surgery in edematous corneas.

The combination of large-mode-area (LMA) fibers and chirped-pulse amplification (CPA) has been extensively studied over the past few years to overcome

the energy limitation due to inherent fiber nonlinearities. Using these techniques, several groups have demonstrated high energy subpicosecond generation from erbium-doped LMA fibers [5–7]. However, to our knowledge, all subpicosecond erbium fiber lasers reaching the microjoule level emitted between 1530 and 1565 nm, i.e., near the maximum of erbium gain. Transposing those systems to 1.6  $\mu\text{m}$  is far from being straightforward, as the small signal gain at 1.6  $\mu\text{m}$  is about 5 times lower than it is at 1555 nm. This leads to the need for longer fibers and results in increased nonlinear phase accumulation and reduced maximum achievable peak power.

The experimental setup is depicted in Fig. 1. The seed of our system is a sub-100 fs all-fiber oscillator emitting 400 pJ pulses. The spectrum of the oscillator has an FWHM of 57 nm and is centered at 1576 nm. This spectrum extends to about 1610 nm towards the long wavelengths, and a bandpass filter allows selection of a 25 nm wide spectrum centered at 1600 nm. The pulses are stretched to 200 ps in 100 m of dispersion-compensating fiber (DCF) with  $\beta_2=0.22 \text{ ps}^2/\text{m}$ . A first preamplifier with a 24 m erbium/ytterbium codoped fiber is used mostly to compensate for the insertion losses of the bandpass filter (−1.8 dB) and acousto-optic modulator (AOM, −6 dB). At the output of this section, pulses centered at 1600 nm are generated. A second, low-gain 29 m fiber amplifier is used to easily tune the energy at the input of the power amplifier, while a second filter ensures that minimum amplified stimulated emission

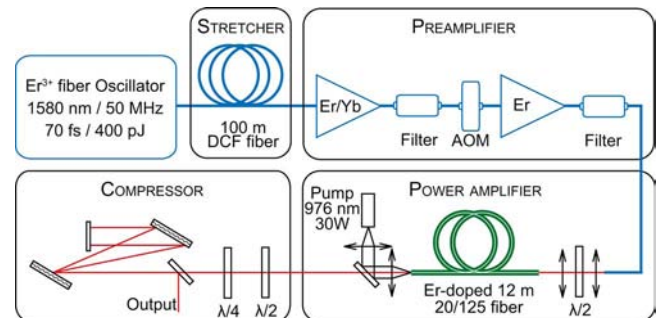


Fig. 1. (Color online) Experimental setup.

(ASE) is injected in the final amplification stage. Both amplifiers are monomode diode-pumped long-wavelength-optimized telecom-based units and include input and output optical isolators. The typical pulse energy at 200 kHz at the input of the power amplifier is 0.1 to 1 nJ. Up to this point, all components are fiber coupled and alignment free. The power amplifier is made of a 12 m long 20/125  $\mu\text{m}$  LMA erbium-doped fiber pumped by a 976 nm 30 W pump diode. The fiber is coiled with a 20 cm diameter and its  $V$  parameter is calculated at 3.14. High-energy pulses are finally compressed in a grating compressor.

It has been shown that high flat gain at 1600 nm can be obtained by imposing the average population inversion to 37% [8]. However, this requires very long fibers, which introduce significant nonlinearities when dealing with high-energy short pulses. The choice of the 12 m fiber length thus results from the interplay between the ASE owing to strong gain at 1550 nm with short fibers and the nonlinear phase accumulated along long fibers, which deteriorates the pulse temporal shape.

Figure 2 shows the evolution of the compressed pulse energy and total ASE power generated by the power amplifier as a function of the emitted pump power. As expected, while the signal exhibits a 36 dB gain (taking into account the measured 60% efficiency of the compressor), strong ASE generation is observed despite the angled-cleaved ends of the fiber. Nevertheless, this ASE is almost exclusively restrained to wavelengths below 1580 nm and is easily filtered in the gratings compressor, leading to almost ASE-free compressed pulses. This is confirmed by suppressing the power amplifier input signal while pumping at 15 W, roughly corresponding to the maximum energy obtained in Fig. 2. The ASE power at 1.6  $\mu\text{m}$  measured after the compressor is only 22 mW, which largely overestimates the ASE power in the presence of the input signal and would therefore, in the worst case, represent a pulse energy overestimation of 7.8%.

The stretcher DCF ( $\beta_3/\beta_2 = -5.4$  fs) and the compressor's gratings (830 lines/mm) have been chosen to minimize the stretcher/compressor dispersion mismatch. However, residual third-order dispersion and spectral shape modifications cause temporal broad-

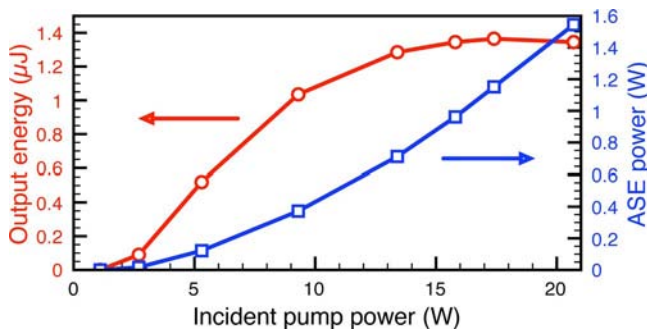


Fig. 2. (Color online) Evolution of the pulse energy after the grating compressor and the ASE power generated by the power amplifier versus pump power and for input pulse energy of 500 pJ.

ening of the compressed pulses, even without nonlinear effects. In this Letter, as the spectral shape is complex and variable, we assume a deconvolution factor of 1.4 to give an estimate of the pulse width. At high repetition rate/low energy the minimum compressed pulse width is 532 fs, which is 2.3 times longer than the pulse width of the oscillator after the bandpass filter.

To illustrate the effects of nonlinearities on the pulse compression we measured, at fixed pump power (15.8 W), the evolution of the energy and FWHM duration versus the energy of the input pulses of the power amplifier, as shown in Fig. 3(a). In this experiment, the repetition rate was set to 200 kHz and the compressor was not realigned when changing the input energy. The total dispersion introduced by the system is therefore fixed. As expected, at low output energy the pulse FWHM is comparable to the high repetition rate case. As the output energy increases from 0.3 to 1  $\mu\text{J}$ , self-phase modulation-induced (SPM) phase distortion leads to pulse broadening. It is well known that for highly stretched pulses the temporal shape mimics the spectrum, and the SPM-induced spectral phase thus strongly depends on the spectrum shape. As shown in Fig. 3(b)–3(d), the interplay between gain and nonlinear effects results in an energy-dependent shaping of the spectrum with a redshift for higher input energies. The spectral shaping is translated into a spectral phase change through SPM, and the compressor matches this spectral phase only at a given energy [9,10]. This results in pulse energy and duration of 1.37  $\mu\text{J}$  and 625 fs. The roll-off of the output energy is probably caused by nonlinear polarization rotation in the nonpolarization-maintaining fiber, which leads to higher loss in the highly polarizing gratings compressor. Optimizing the polarization state using wave plates before the compressor shows saturation of the

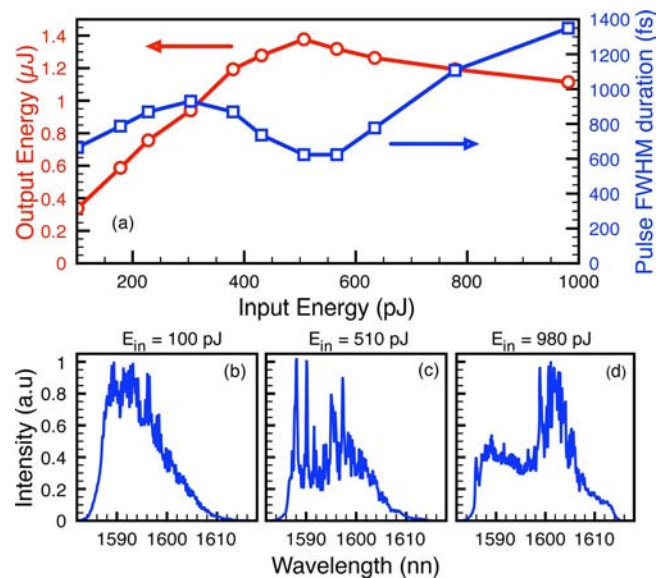


Fig. 3. (Color online) (a) Output energy of compressed pulses and corresponding FWHM duration versus energy of input pulse for the final amplifier with a pump power of 15.8 W. (b), (c), and (d) represent the spectrum of the compressed pulses for different input energies.

output energy at about  $1.4 \mu\text{J}$ . Beatings between the fundamental mode and residual higher-order modes are responsible for the fast spectral modulations observed in Fig. 3. Careful injection of the signal into the LMA fiber while monitoring the autocorrelation of the compressed pulses allows minimization of the energy spread out in higher-order modes, which is estimated to be less than 1% of the pulse energy. Slower spectral deformations are believed to arise from nonlinearities including SPM and four-wave mixing

The pulse width optimum can be obtained for a wide range of input energies by adjusting the pump power in the power amplifier to obtain the same accumulated nonlinear phase. The global optimum finally results of the trade-off between the input pulse energy, which defines the output pulse energy needed to reach the right amount of nonlinear phase, and the ASE, which limits the output pulse energy for low input power.

Following this argument, we adjusted the repetition rate to obtain the maximum energy for the maximum pump power in the final amplifier. As expected, a slight improvement has been obtained by decreasing the input energy while increasing the repetition rate to 300 kHz in order to reduce ASE generation. Figure 4 shows the autocorrelation corresponding to  $1.52 \mu\text{J}$  and 605 fs pulses. The autocorrelation of the oscillator after the bandpass filter is indicated for comparison in the dashed curve. The inset shows the corresponding spectra. The FWHM time-bandwidth product (TBP) is 0.32 but is not representative of the pulse quality for these complicated shapes. We therefore prefer to compare the pulse duration to the Fourier-transform-limited pulse corresponding to the measured spectrum. The pulse duration is 2.1 times longer than the flat spectral phase pulse. Based on

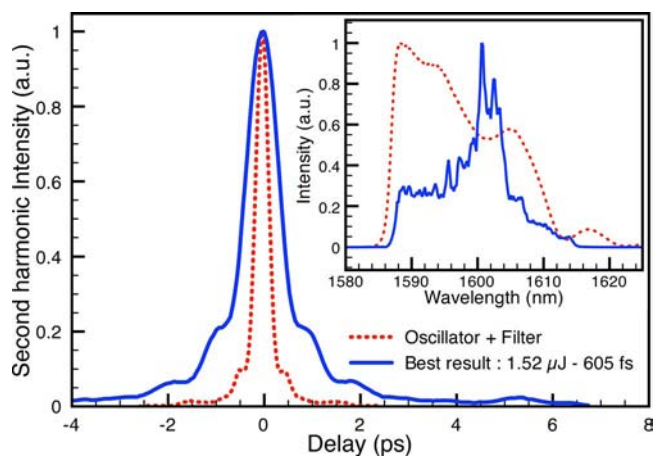


Fig. 4. (Color online) Output autocorrelation and spectrum (solid line) compared to the oscillator after the filter (dashed line).

the autocorrelation, we estimate that the main 605 fs pulse contains 80% of the pulse energy.

In conclusion, we have demonstrated, for the first time to our knowledge, a femtosecond microjoule CPA system based on erbium-doped fibers operating at  $1.6 \mu\text{m}$ . Large-mode-area erbium-doped fiber and nonlinear compensation of the dispersion were used to optimize pulse duration and energy.  $1.5 \mu\text{J}$  and 605 fs pulses were obtained at a repetition rate of 300 kHz and a central wavelength of  $1.6 \mu\text{m}$  in a nearly diffraction-limited beam. This is, to our knowledge, the highest energy ever obtained for subpicosecond pulses in erbium-doped fibers above 1565 nm. The setup robustness and compactness potential as well as the results obtained in terms of pulse duration and energy are suitable for corneal surgery applications.

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