High power, single mode, all-fiber source of femtosecond pulses at 1550 nm and its use in supercontinuum generation

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Abstract: We present a source of high power femtosecond pulses at 1550 nm with compressed pulses at the end of a single mode fiber (SMF) pigtail. The system generates 34 femtosecond pulses at a repetition rate of 46 MHz, with average powers greater than 400 mW. The pulses are generated in a passively modelocked, erbium-doped fiber laser, and amplified in a short, erbium-doped fiber amplifier. The output of the fiber amplifier consists of highly chirped picosecond pulses. These picosecond pulses are then compressed in standard single mode fiber. While the compressed pulses in the SMF pigtail do show a low pedestal that could be avoided with the use of bulk-optic compression, the desire to compress the pulses in SMF is motivated by the ability to splice the single mode fiber to a nonlinear fiber, for continuum generation applications. We demonstrate that with highly nonlinear dispersion shifted fiber (HNLF) fusion spliced directly to the amplifier output, we generate a supercontinuum spectrum that spans more than an octave, with an average power 400 mW. Such a high power, all-fiber supercontinuum source has many important applications including frequency metrology and bio-medical imaging.

OCIS codes: (140.3510) Lasers, fiber; (320.0320) Ultrafast optics; (060.4370) Nonlinear optics, fibers

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1. Introduction

Erbium-doped fiber lasers are a reliable source of sub-100 fs pulses at 1550 nm; however, nonlinearities in optical fibers make generation of multi-nJ pulses difficult. Multi-mode fibers can be used in amplifiers, to reduce the effect of nonlinearities, and compression of chirped pulses after the amplifier is frequently performed with bulk-optic components [1].

In addition to large-mode area fiber amplifiers, single mode amplifiers operating with anomalous dispersion at 1.5 μm [2] and with normal dispersion at both 1 μm [3] and 1.5 μm [4] have been demonstrated. However, the soliton amplifier suffers from multi-colored solitons at high powers, and the normal dispersion amplifiers have used bulk optics for pulse compression after amplification.

For applications such as supercontinuum generation in fibers, it is desirable to generate compressed pulses in single mode fibers and fusion splice the supercontinuum generating fiber directly to the amplifier output [5, 6]. A single-mode fiber laser plus amplifier with supercontinuum fiber fusion spliced to the amplifier output have recently been demonstrated to be ideal as all-fiber phase locked frequency combs covering the wavelength region from 1.1 to 2.3 microns [7]. Therefore, in this work we investigate a high power single-mode, erbium-doped amplifier for fs pulses, generating compressed fs pulses in the single-mode fiber pigtail. This system demonstrates, to the best of our knowledge, the highest reported peak-power femtosecond pulses in a single mode fiber from a single-mode erbium amplifier to date.

A brief outline of the paper is as follows. First, Section 2.1 details the experimental setup of the amplifier. Autocorrelation measurements show that the amplifier, although operating at high power, is free of pulse breakup, and modeling using a nonlinear Schrödinger equation (NLSE) suggest that the amplifier is operating close to the parabolic pulse regime.

Section 2.2 investigates the effect of pulse pre-chirp on the amplifier output. The pulse shape and chirp strongly governs how quickly a pulse in a fiber amplifier approaches the self-similar regime of operation [8]. Furthermore, the spectral width of the amplifier output depends strongly on the temporal chirp of the input pulse. Therefore, in order to optimize the amplifier output we investigate the effect on the amplifier of the length of pre-chirp fiber. Interestingly, these experiments show that, depending on the desired pulse width, the system can be easily configured to output either broad-bandwidth, strongly-chirped pulses suitable for temporal compression down to sub-50 fs pulses, or for generating nearly bandwidth-limited picosecond pulses.

Section 2.3 presents results of the temporal compression of the amplified pulses in SMF fiber. 34 fs pulses are generated at the end of the SMF pigtail. Furthermore, measurements of the pulse train and RF spectra after the amplifier show that, in spite of the strong nonlinearities taking place in the SMF pigtail, a good pulse train is maintained in the amplifier.

Finally, Section 3 presents measurements made when HNLF is fusion spliced directly onto the amplifier output. The supercontinuum spanned from 850 nm to wavelengths longer than 2.6 μm, with an average power of 400 mW.

2. High power, single mode, femtosecond, erbium-doped fiber amplifier

2.1. Amplifier setup

The amplifier schematic is shown in Fig. 1. The pulses from a passively modelocked, figure eight, erbium-doped fiber laser [7] (2 mW, 250 fs pulses at 46 MHz) were launched into a 2 m length of erbium-doped fiber. The amplifier was forward and backward pumped by four 1480 nm diode lasers. Because the forward and backward pumps faced each other, the pump lasers included integral isolators, to prevent the possibility of destabilization by unabsorbed 1480 nm radiation. Polarization multiplexing combined two pump lasers onto a single fiber. The maximum launched power of the forward (backward) pumps was 610 mW (571 mW). The amplifier consisted of three sections. An input length of single mode fiber (SMF) controlled the amount of pre-chirp of the pulses before being launched into the erbium-doped fiber. The erbium doped fiber provided gain, as well as pulse stretching from the normal dispersion and spectral broadening from nonlinearities. Finally the output lead of SMF was used for temporal pulse compression. The output SMF lead was angle cleaved to prevent reflections back into the amplifier.

The SMF fiber used in this work for both pre-chirping before amplification and pulse compression after amplification was a single-mode matched clad fiber from OFS. It had a dispersion

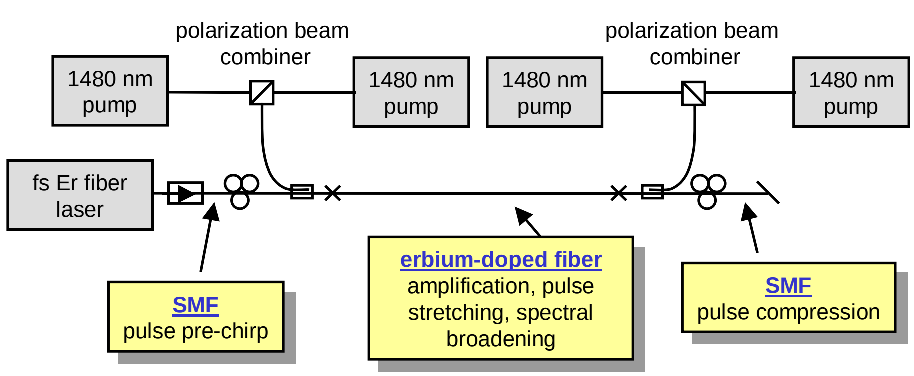

Fig. 1. Schematic of the amplifier setup.

#4483 - $15.00 US
Received 1 June 2004; revised 21 June 2004; accepted 23 June 2004

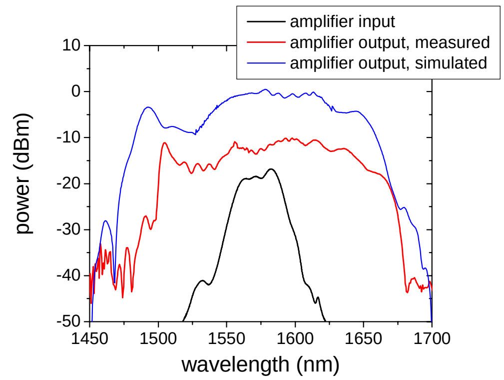

Fig. 2. Measured input and output spectra from the amplifier, compared to simulated spectra output from the amplifier. Spectra have been offset for clarity.

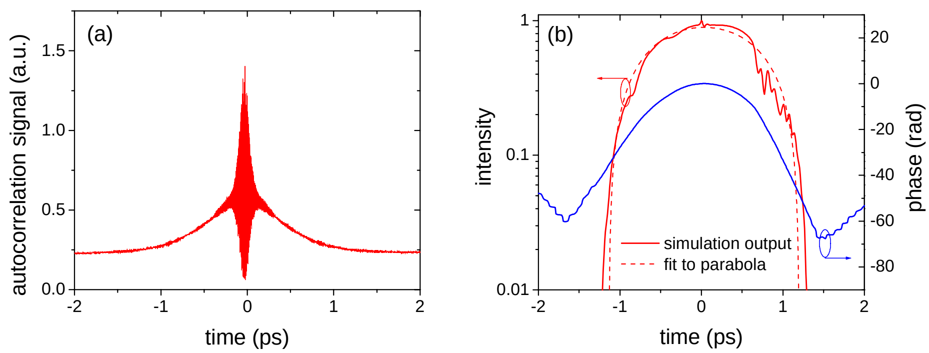

Fig. 3. (a) Measured autocorrelation of a picosecond pulse immediately after the amplifier. (b) Simulations of the pulse in the time domain.

at 1550 nm of 15 ps/(nm-km) and an affective area of 60 μm^2. The erbium doped fiber had a dispersion of approximately -17 ps/(nm-km) and an affective area of 10 μm^2, estimated by modeling the measured refractive index profile.

The measured spectra are shown in Fig. 2. The pre-chirp fiber length was 2 m. The spectrum from the oscillator is shown as a solid line, and the spectrum from the amplifier is shown as a dashed line. For these experiments, the output SMF lead was kept as short as possible ($<$ 24 cm) to minimize temporal pulse compression effects. The maximum output power of the amplified pulses was 400 mW, corresponding to a pulse energy of 8.7 nJ. Clearly a significant amount of spectral broadening due to nonlinearity occurs in the amplifier fiber. A calculation of the amplifier output spectrum, from a nonlinear Schrödinger equation (NLSE) model [9] including gain, is also plotted in Fig. 2. The model used the measured oscillator spectrum, assuming bandwidth limited pulses, as its starting condition. The measured and simulated spectra show good agreement.

The erbium-doped fiber had normal dispersion. The combination of distributed gain, normal dispersion, and SPM leads to self-similar propagation, where pulses acquire a parabolic shape in time and linear chirp [10]. The measured auto-correlation in Fig. 3(a), shows that the output does indeed consist of a single, highly-chirped pulse. NLSE simulations (Fig. 3(b)) also show that the pulses are approximately parabolic with quadratic phase.

#4483 - $15.00 US
Received 1 June 2004; revised 21 June 2004; accepted 23 June 2004

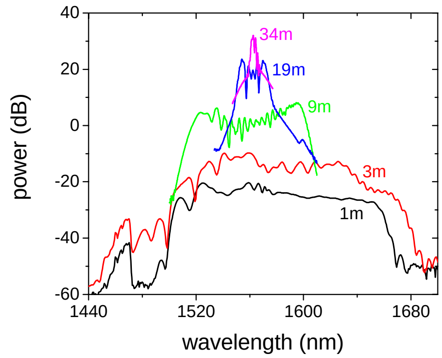

Fig. 4. Measured amplifier output spectrum as a function of input pre-chirp SMF length. The spectra have been offset vertically for clarity.

2.2. Spectral compression in an erbium-doped fiber amplifier

The amplifier with the setup described in the previous section was operating close to the parabolic regime. However, the speed with which the pulses approach the asymptotic parabolic solution depends strongly on factors such as spectral width and chirp [8]. Broader pulses have lower peak power and consequently evolve toward a parabolic pulse more slowly. Temporal compression due to an initial pre-chirp further complicates the picture. Therefore, in order to optimize the amplifier to ultimately generate the shortest possible pulses we investigated the effect of the length of pre-chirping SMF fiber on the amplifier output.

Self-phase modulation (SPM) due to n_2 in optical fibers is normally associated with spectral broadening. However, for a pulse whose chirp is initially negative the SPM actually causes the spectrum to compress [11, 12]. In other words, power from the wings of the spectrum is nonlinearly converted to power at the central frequency, leading to a narrowing of the optical spectrum. The effect can be even more dramatic in a rare-earth doped fiber amplifier; the spectrum of 150 fs pulses at 1050 nm with a spectral width of 7.8 nm were compressed in a high power Yb-doped amplifier, to generate near transform limited picosecond pulses with a spectral width of only 0.37 nm [13].

Here, we demonstrate similar spectral compression in the erbium-doped fiber amplifier at 1550 nm. The measured output spectrum from the fiber amplifier as a function of the length of the pre-chirp SMF is shown in Fig. 4. The spectra have been offset vertically for clarity. The leads of the backward pump/signal wavelength division multiplexer (WDM) were again kept as short as possible to minimize any temporal pulse compression effects. One can clearly see that the width of the output spectrum is strongly dependent on the amount of pulse pre-chirp. It should be noted that if the input pulse were instead positively chirped, the output spectrum would be narrower in comparison to the spectrum from the unchirped pulse. However with a positively chirped pulse the spectrum would never be narrower than the spectrum of the seed pulse.

The spectral width as a function of the length of pre-chirping SMF, taken from the data in Fig. 4, is plotted in Fig. 5(a), along with the measured average power from the amplifier. The spectral width was measured at the point 10 dB down from the peak of the spectrum, to try and minimize the effect of some of the ripples seen in the spectra in Fig. 4. Simply by adjusting the length of the pre-chirping SMF, the 10 dB width of the output spectrum could be continuously varied from greater than 150 nm to less than 8 nm. With a pre-chirp fiber length of 34 m, the FWHM of the spectrum was almost ten times narrower than the spectrum of the seed pulse.

The power from the amplifier was measured to increase from 380 mW for an SMF input

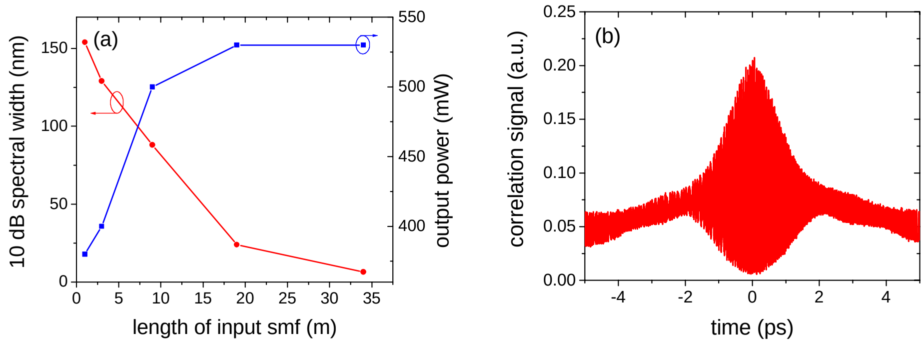

Fig. 5. (a) Amplifier output spectral width and average power as a function of pre-chirping SMF length. (b) Measured interferometric autocorrelation for a 34 m length of pre-chirping SMF.

lead length of 1 m, to 530 mW for an SMF lead length greater then 20 m, shown in Fig. 5(a). For the very broad spectra generated with nearly bandwidth limited pulses launched into the amplifier, we found that the backward pump/signal WDM clipped some of the output spectrum, particularly on the short wavelength side, causing the reduction in output power.

Additionally, the interferometric autocorrelation for a 34 m pre-chirping fiber is shown in Fig. 5(b), showing a single picosecond pulse, with a small amount of residual chirp. At this point, we have not made an attempt to fine tune the length of the input SMF to remove the rest of the residual chirp from the picosecond pulse. Simulations of the amplifier show that much of this residual chirp can be removed by further adjusting the input lead length.

These measurements show however that to produce the broadest possible spectrum at the amplifier output, a short length of pre-chirping fiber (i.e. nearly bandwidth limited launch into the amplifier fiber) is required.

2.3. Pulse compression in standard single mode fiber

Similar, lower-power erbium-doped fiber amplifier systems have shown efficient temporal compression with bulk optics [4]. Alternatively, we investigated pulse compression in a short length of standard single-mode fiber. For these experiments, the length of the pre-chirping SMF was 2 m. The length of output SMF lead that generated the optimal pulse compression was measured. The nonlinear signal from the two-photon current of a silicon photodiode was measured as a function of output lead length. Polarization controllers on the SMF input and output leads were used to optimize the two-photon signal. This signal as a function of output lead is shown in Fig. 6(a). The scatter in the data in Fig. 6(a) is because multiple settings of the polarization controller could be found that had local maxima in the two-photon signal.

Maximum pulse compression was observed for an output lead length of 45 cm. We found that, although the tolerance for choosing the optimal length of SMF was rather tight ($\approx \pm 5$ cm), day to day operation of the system was very consistent in terms of the measured correlation, as long as the length of pre-chirping fiber was not changed. The measured spectrum for this lead length is shown in Fig. 6(b). Compared to the spectrum immediately after the output pump/signal WDM, additional spectral width, as well as structure in the spectrum, was generated in the pulse compression fiber. The correlation shows that although there is a well defined pulse it sits on a broad plateau several hundred femtoseconds in width.

The pulse spectrum together with the interferometric autocorrelation are theoretically sufficient information to fully characterize a femtosecond pulse [14]. The spectrum and correlation can be used in an iterative algorithm to retrieve the intensity and phase of the femtosecond

#4483 - $15.00 US Received 1 June 2004; revised 21 June 2004; accepted 23 June 2004

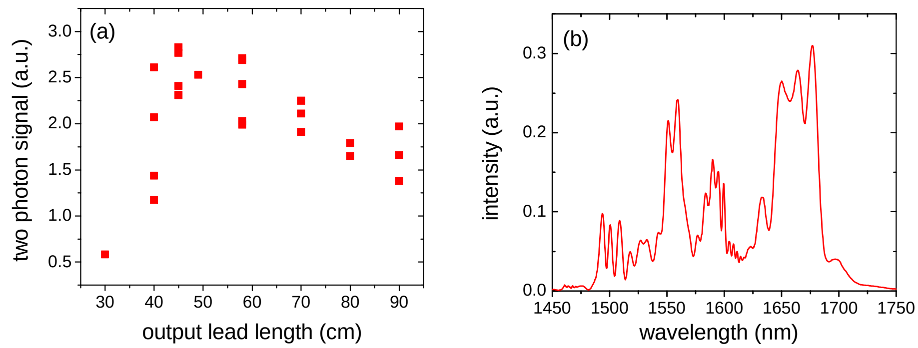

Fig. 6. (a) Pulse compression as a function of output lead length. (b) Spectrum measured at with a lead length for optimal compression. The SMF pre-chirp fiber was 2 m.

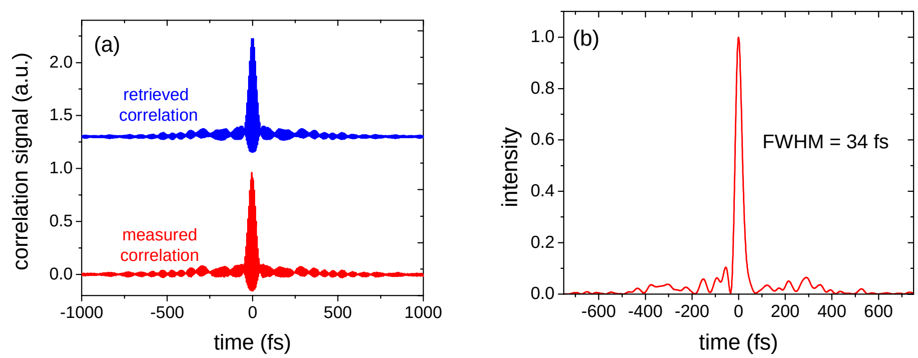

Fig. 7. (a) Measured interferometric autocorrelation for a 45 cm SMF compression fiber, plus the autocorrelation obtained from the pulse retrieval algorithm. (b) The femtosecond pulse corresponding to the retrieved correlation.

pulse. The spectrum and interferometric correlation were input into the PICASO algorithm to retrieve the pulse intensity and phase [15]. The retrieved pulse (Fig. 7(b)) consisted of a 34 fs pulse on a low pedestal. The pulse quality (the ratio of energy in the central pulse to total pulse energy) was approximately 55%, corresponding to a peak power of 140 kW. To ensure ambiguities did not affect the results of the characterization, the retrieval was performed multiple times on the data sets. While the details of the structure in the background changed from retrieval to retrieval, the peak-background ratio, the shape of the central peak, pulse quality and FWHM were consistent. Multiple retrievals gave a standard deviation in the FWHM of 0.5 fs and of 1.9% in the fraction of energy in the central pulse.

NLSE simulations of the temporal compression of the pulses in SMF were carried out. A typical simulation output of the optimally compressed pulse is shown in Fig. 8 for a 3 m prechirping fiber and an amplifier gain of 24 dB, an input average power of 2 mW and an output power from the amplifier of 500 mW. The optimal compression fiber length, determined by the point of highest peak power, was approximately 50 cm. The pulse quality was 50%, and the FWHM was 18 fs.

For these simulations, effects due to the finite gain bandwidth of the erbium fiber, and clipping due to the output WDM filter were not included. Therefore the spectrum launched into the SMF compression fiber in the model was broader by more than 100 nm than that observed experimentally. In spite of these issues, the simulations show a rough agreement with the exper-

#4483 - $15.00 US Received 1 June 2004; revised 21 June 2004; accepted 23 June 2004

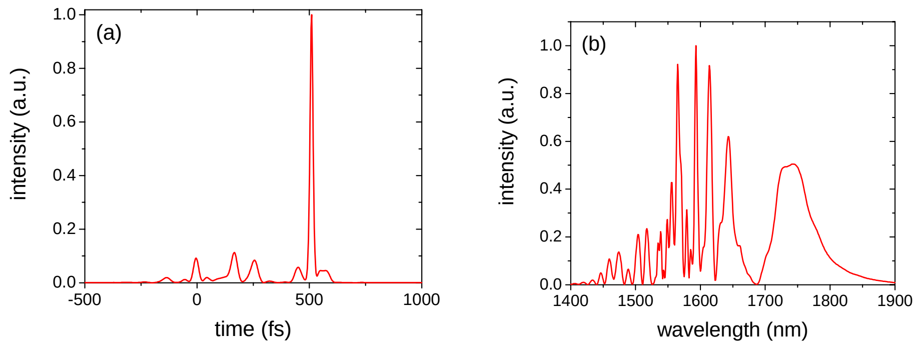

Fig. 8. (a) Intensity and (b) spectrum from the NLSE model of pulse compression in SMF after the amplifier.

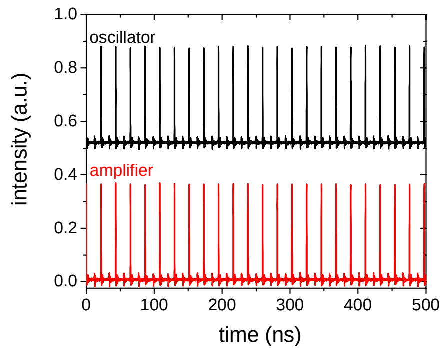

Fig. 9. Measured pulse train for both the oscillator and the amplifier.

iments in terms of pulse quality and relative height of the background pedestal. The simulations also show that the Raman self-frequency shift and SPM play a strong role in reshaping the spectrum even in such short lengths of compression fiber.

The simulations do show pulses with shorter FWHM than experimentally observed. This could be due to limitations in the optics of the autocorrelator, as well as the fact that the simulations show a broader bandwidth at the input to the compression fiber compared to the experiments. Furthermore, the simulations show that the primary pulse trails the background pedestal, compared to the results of the pulse retrieval, which show the primary pulse centered within the background pedestal. This discrepancy is most likely because the retrieval was performed on a balanced interferometric correlation, and could be resolved by using a full unbalanced, dual-correlation setup [16], or using a FROG retrieval.

Considering the large amount of amplification taking place as well as the nonlinearities present in the SMF compression fiber, it is important to carefully measure the noise properties of the pulse train after amplification. These experiments are currently underway; however, we have made initial measurements comparing the pulse train and RF spectra from the oscillator to that from the amplifier. Fig. 9 shows the pulse train measured from both the oscillator and the amplifier, and confirms that the amplification and subsequent nonlinear pulse compression do not impart large amplitude fluctuations onto the pulse train.

Measurements of the oscillator and amplifier RF spectra are presented in Fig. 10. Fig. 10(a) shows the spectra measured at the fundamental pulse repetition rate of 46.2 MHz, whereas Fig. 10(b) shows the spectra at the tenth harmonic of the pulse repetition rate. The oscillator and

Received 1 June 2004; revised 21 June 2004; accepted 23 June 2004

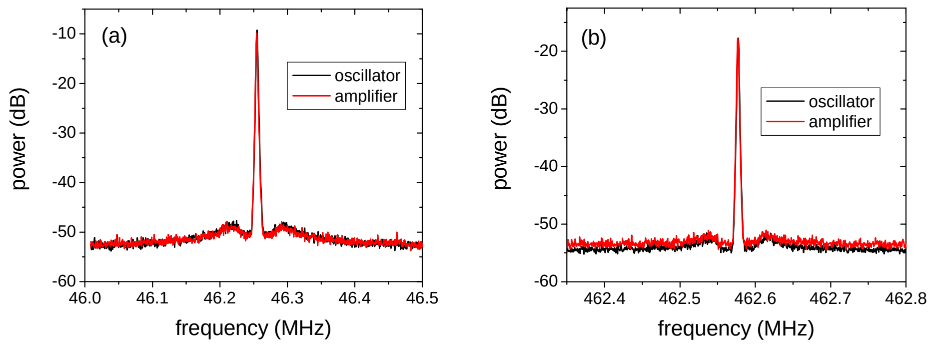

Fig. 10. RF spectrum measurements for the oscillator and amplifier (a) at the fundamental pulse repetition rate, and (b) at the tenth harmonic of the pulse repetition rate.

amplifier spectra are identical at the fundamental repetition rate, whereas at the tenth harmonic a small additional background is visible in the amplified spectrum. Further experiments are required to fully quantify the amount of noise introduced by the amplifier.

3. Supercontinuum generation in highly-nonlinear fiber

The advantage of performing the pulse compression in single-mode fibers as opposed to bulk-optics is that the output of the amplifier can then be readily fusion spliced to other fibers for experiments in nonlinear optics. Fusion splices are advantageous because they are low-loss, compact, permanently aligned, and prevent contaminants from entering the optical path.

A relatively new type of germanium doped silica fiber with low dispersion slope and a small effective area has recently been developed [17, 18]. Careful design of the index profile allows the fiber to achieve a small effective area, low dispersion and dispersion slope, while maintaining low loss. These fibers have nonlinear coefficients several times that of standard transmission fiber, and are often referred to as highly nonlinear, dispersion shifted fibers, or, more simply, HNLF. HNLF is compatible with standard telecom components, and can be easily fusion spliced with low loss to standard single mode fiber (SMF). Typical splice losses for SMF to HNLF are 0.2 dB at 1550 nm in this work, although we have demonstrated splice losses as low as 0.01 dB. Furthermore, HNLF can be low loss; for HNLF used in these experiments measured attenuation was between 0.7 and 1.1 dB/km at 1550 nm.

The HNLF dispersion was 1.19 ps/(nm km) at 1550 nm. The HNLF dispersion slope can be very low; the slope for fibers used in these experiments was 0.0092 $\mathrm{ps}/(\mathrm{nm}^2\ \mathrm{km})$ at 1550 nm. The effective area of the HNLF, Aeff,$\approx 13.9\mu\mathrm{m}^2$ at 1550 nm, and the nonlinear coefficient, $\gamma \approx 10.6\ \mathrm{W}^{-1}\mathrm{km}^{-1}$, were calculated from the measured index profile. Additionally, the HNLF in these experiments was exposed to constant UV radiation, which has been shown to broaden the continuum generated in these fibers even further [19].

A 12 cm length of HNLF, in which 8 cm had been exposed to UV radiation, was fusion spliced directly to the SMF amplifier output lead, with the amplifier output SMF lead trimmed to the optimal length for pulse compression. As the coating of the fiber is removed prior to UV exposure, the 4cm coated, unexposed section was left on in order to place in the fiber holders. In this experiment, the input SMF length was set to 8 m, in order to increase the amount of power out from the amplifier. The supercontinuum at the output of the HNLF is plotted in Figure 11. The supercontinuum spanned approximately 1.65 μm, from 850 nm to wavelengths longer than 2.6 μm. The measured average power was 400 mW. To the best of our knowledge, this supercontinuum is the highest power generated to date from an all-fiber femtosecond laser

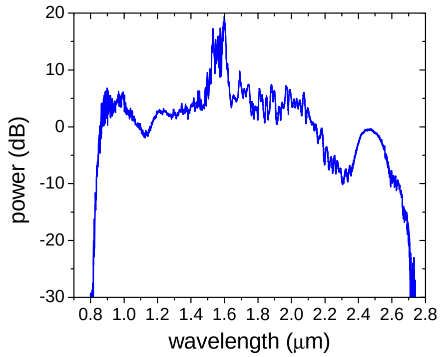

Fig. 11. Supercontinuum measured from the UV exposed HNLF.

source.

The coherence properties of the supercontinuum are very important in such applications as frequency metrology. Recent experiments have shown that the coherence of supercontinua generated in HNLF is preserved when pumped by lower power sources, and these continua showed detailed fine structure in the spectra that was stable in time [20]. Furthermore, both single shot measurements of supercontinuum generated in microstructured fibers [21] as well as simulations of HNLF supercontinua [9] show detailed structure in the spectrum. The fine structure observed in Fig. 11 was also observed to be stable in time, and is likely indicative of the supercontinuum maintaining the coherence of the original pulse train, at least to some degree. Further measurements of the coherence of the high power continuum are required.

4. Conclusions

In conclusion, we have demonstrated a single-mode, erbium amplifier producing 8.7 nJ, highly-chirped, picosecond pulses. Temporal compression in SMF generated 34 fs pulses with 140 kW peak power, which were delivered directly to the fiber tip. Furthermore HNLF was fusion spliced directly to the amplifier output, generating a supercontinuum that spanned 1.65 μm. Such a system is ideal for use in areas such as frequency metrology, or for inclusion in an endoscope for bio-medical applications.

#4483 - $15.00 US
Received 1 June 2004; revised 21 June 2004; accepted 23 June 2004