Practical all-fiber source of high-power, 120-fs pulses at 1 μm

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Received December 13, 2002

Amplification of femtosecond pulses at 1.03 μm in a standard Yb-doped single-mode fiber is reported. A pulse energy of 8 nJ and an average power of 400 mW are obtained, limited by available pump power. To our knowledge these are the highest pulse energy and average power obtained from an integrated, single-mode fiber amplifier. After dechirping, 120-fs, 6-nJ pulses are obtained. A practical fiber-based source with performance comparable with that of a bulk solid-state laser is thus demonstrated, and scaling to substantially higher powers will be possible. © 2003 Optical Society of America

OCIS codes: 060.7140, 060.4370, 060.2320, 140.3510, 320.7090, 320.7140.

There is rapidly growing, application-driven interest in ultrafast lasers. The development of efficient, compact, highly stable femtosecond lasers and amplifiers promises to have a major effect on the use of ultrafast optics outside the laser research laboratory. Fiber lasers offer a number of practical advantages over bulk solid-state lasers, including compact size, better stability, and freedom from misalignment. However, maximum pulse energies are ~1 nJ, limited by the inherent fiber nonlinearity. This is in contrast to the 5–10-nJ pulse energies available from bulk solid-state lasers and demanded by many applications. Thus amplification is necessary in order to generate pulses with energies that can equal and surpass those of bulk solid-state lasers.

There is great interest in practical short-pulse sources at wavelengths from 1.0 to 1.3 μm. In particular, biological applications such as optical coherence tomography, multiphoton microscopy, and laser-assisted eye surgery benefit from tissue transparency in this wavelength range. Besides bulk solid-state lasers, a source of 8-nJ femtosecond pulses based on amplification in Yb-doped fiber has been demonstrated.[1] The performance is good, but the setup is complicated: Pulses are generated with a fiber oscillator at 1.5 μm, Raman shifted to 2.1 μm, converted to 1 μm through second-harmonic generation, and finally amplified in a double-clad fiber pumped by a multimode diode laser.

Yb-doped fiber is an attractive gain medium for high-energy femtosecond pulse generation owing to its high efficiency and broad emission spectrum at 1 μm. Furthermore, amplification in the presence of normal dispersion avoids pulse breakup induced by soliton effects at high energies.[2] This feature has been exploited in parabolic amplification, which permits accumulation of large nonlinear phase shifts.[3,4] Practical all-fiber chirped-pulse amplifiers at 1.5 μm have attracted much attention, but pulses shorter than 400 fs could not be obtained, and the maximum pulse energy after dechirping was limited[5] to ~3 nJ. Currently, there is much excitement surrounding fiber amplifiers with tens of watts of average power or as high as millijoule pulse energies.[6,7] These amplifiers utilize multimode fibers and double-clad geometry for pumping with multimode diodes. The double-clad pumping technique requires the use of longer fibers, which increases the strength of the nonlinear effects. Multimode fibers are typically used to offset the nonlinear effects. These techniques represent a significant deviation from the simplicity of standard single-mode fibers (SMFs) and thus offset some of the advantages of fiber. The fiber equivalent of bulk solid-state lasers made from only readily available components could have broad effects.

Two relevant, enabling advances have recently occurred. The first is the development of high-energy Yb fiber lasers. The first reliable and compact femtosecond Yb fiber lasers were limited[8] to ~60 pJ. Ideally, an amplifier should be fiber coupled to the oscillator for simplicity and freedom from misalignment. To prevent instabilities and ensure high-quality seed pulses, only a small fraction (<10%) of the pulse energy can be diverted into the amplifier. Recently, we demonstrated an Yb fiber laser[9] with pulse energy in excess of 1 nJ, which can be used to reliably seed an amplifier with a small fraction of its pulse energy. The second advance is the development of pump lasers: 980-nm diode lasers that deliver more than 500 mW in single-mode fibers have become commercially available. The use of single-mode diodes permits the construction of an all-fiber amplifier.

Here we explore the limitations of a femtosecond pulse source that uses a standard SMF only. A simple and compact source delivering 6-nJ, 120-fs pulses at 1.03 μm with a repetition rate of 50 MHz is demonstrated through the use of a short gain fiber. These are the highest pulse energy and average power obtained through amplification in a standard SMF to our knowledge. Overall we obtained close to an order of magnitude increase in peak power, as well as an approximately threefold increase in average power compared with previous all-fiber devices.[5] The setup consists of an Yb fiber amplifier seeded by a fiber oscillator. The use of a SMF and pump diodes permits a high level of integration and excellent stability. Except for wavelength tunability, this approach matches and will eventually surpass the performance of a standard Ti:sapphire laser.

The experimental setup is shown in Fig. 1. A stretched-pulsed Yb fiber oscillator seeds the amplifier

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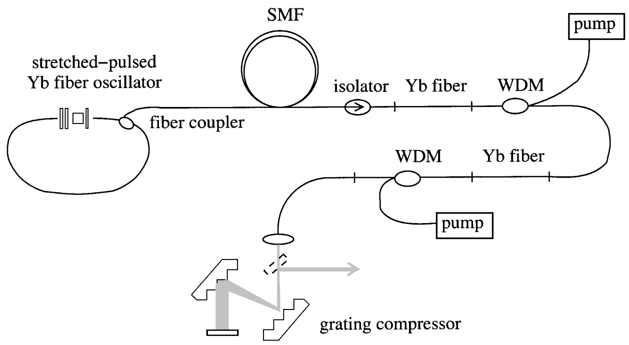

Fig. 1. Experimental setup.

with 100-fs pulses. Ideally, the seed pulses should be clean and unstructured for the highest-quality amplification. Therefore the oscillator was designed to operate at low anomalous dispersion ($-0.02\ \mathrm{ps}^2$). The pulses are directed into the amplifier via an ~7% fiber coupler placed after the gain fiber in the oscillator. The coupled energy is ~0.1 nJ. The pulses are then dispersively stretched to ~15 ps in a 20-m-long SMF to minimize nonlinear effects[10] and are amplified in a highly doped Yb fiber (23,600 parts in 10^6 doping, numerical aperture of 0.12, core diameter of 6 μm). The Yb fiber consists of two ~20-cm-long segments and is pumped by two 980-nm diode lasers providing 1 W of total power through wavelength-division-multiplexed (WDM) couplers. The pulse energy after amplification is 8 nJ, corresponding to 400 mW of average power. A single segment of Yb fiber can be used if a 1-W diode laser is available or if the pump light from the two diode lasers can be efficiently combined.

The experimental results are compared with numerical simulations. Propagation in each fiber segment is modeled with an extended nonlinear Schrödinger equation that accounts for group-velocity dispersion, third-order dispersion, Kerr nonlinearity with a Raman contribution, and gain in the Yb fiber. The gain saturates with total energy and has a parabolic frequency dependence with a bandwidth of 40 nm. These simulations indicate that consideration of Kerr nonlinearity, group-velocity dispersion, and gain saturation are sufficient for a qualitative understanding of the amplification process. Raman scattering was found to be negligible. Quantitative agreement can be obtained with the inclusion of gain bandwidth and an effective frequency filter imposed by the WDM couplers. The results of the simulations are summarized in Fig. 2. Amplification is simulated for various pulse energies corresponding to stretching in 10 and 20 m of SMF. Peak power is maximized with optimal dechirping (linear losses are ignored). As the pulse energy increases, broader spectra are obtained, which produce pulses with smaller FWHM duration. This is balanced by distortion of the pulse shape; a larger fraction of the energy resides in the wings of the pulse. As a result, an approximately linear dependence of peak power on pulse energy is obtained. The need for a minimum length of SMF to avoid distortion is evident; a squarelike spectrum develops at 8 nJ with 10 m of SMF, whereas clean pulses are obtained with 20 m of SMF. The experimental spectra for 8-nJ pulse energy agree well with the results of the simulations (Fig. 2). The simulations also demonstrate that pulse energies at least an order of magnitude higher can be accommodated by stretching the seed pulses in a longer segment of SMF. The pulse shape is not degraded despite larger uncompensated third-order dispersion (mostly from the grating compressor), gain narrowing, and Raman scattering.

The spectra of the seed and amplified pulses are presented in Fig. 3(a), along with the results of numerical simulations. The amplified pulses are subsequently dechirped in a grating compressor. After dechirping, the pulse energy is reduced to ~6 nJ owing to loss at the gratings. Interferometric autocorrelation of the dechirped pulses is shown in Fig. 3(b). The calculated pulse duration is 125 fs, assuming a sech^2 pulse shape. The intensity and phase profiles were inferred by the use of a pulse-retrieval algorithm based on fitting the measured interferometric autocorrelation and spectrum.[11] The corresponding pulse width is 115 fs, which is close to that of the constant-phase

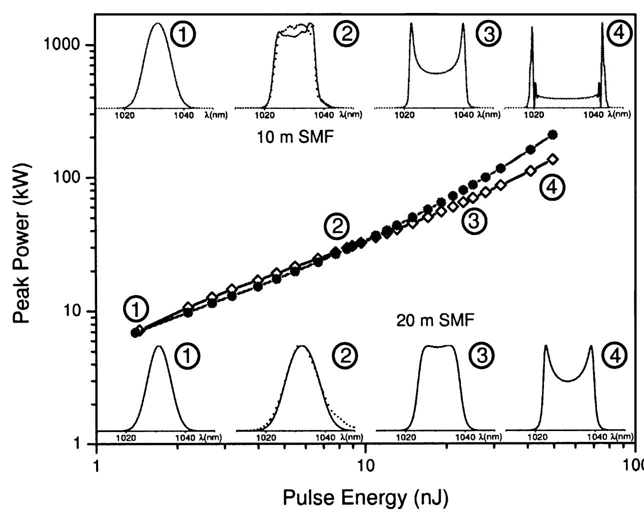

Fig. 2. Peak power of amplified and dechirped pulses as a function of pulse energy with stretching in 10 m (filled symbols) and 20 m (open symbols) of SMF. Insets: Calculated pulse spectra (1), (2), (3), and (4) are for pulse energies of 1.4, 8, 25, and 50 nJ, respectively. Note the agreement of calculated spectra with experimental results for 8-nJ pulse energy.

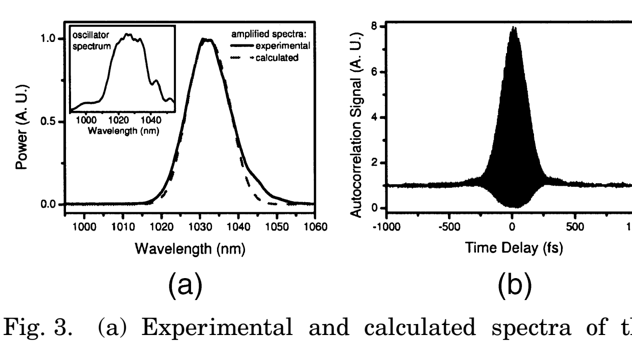

Fig. 3. (a) Experimental and calculated spectra of the amplified pulses. Inset: Spectrum of the pulses from the oscillator. (b) Interferometric autocorrelation of the dechirped pulses.

transform of the pulse spectrum. The benefits of normal dispersion are evident; in the presence of anomalous dispersion the stretched pulses (~0.6-kW peak power) would be significantly reshaped as a nonlinear phase shift in excess of π accumulated toward the end of the gain fiber and in the 1-m-long SMF of the WDM coupler.

Since the amplifier is completely integrated, the overall stability is identical to that of the oscillator. The grating compressor is decoupled from the nonlinear dynamics and does not degrade the stability. Uninterrupted operation can be maintained for at least several weeks. In comparison with a bulk solid-state laser, the setup is less expensive, more stable, and easier to duplicate, since only standard components are used. Performance comparable with that reported in Ref. 1 is obtained in a much simpler device. The current setup occupies a volume of $<0.05\ m^3$ and could be made smaller.

In conclusion, we have demonstrated amplification of femtosecond pulses from an Yb fiber laser as high as 8 nJ (400 mW of average power) in a single-mode Yb fiber diode pumped through fiber couplers. After dechirping, 120-fs, 6-nJ pulses were delivered. We obtained performance similar to that of a bulk solid-state laser by use of a scheme that employs SMFs and diodes only. Equally significantly, this approach can be scaled to higher energies as more-powerful pump diodes become available. Energies of 20 nJ at a 50-MHz repetition rate can reasonably be expected in the next few years. An all-fiber Yb laser would allow a further level of integration. Recently, 100-fs, 1-nJ pulses have been obtained from an Yb fiber laser that employs a photonic-crystal fiber for dispersion control.[12] With this approach an all-fiber laser can ultimately be constructed of polarization-maintaining fiber and serve as the basis of environmentally stable pulse generation.

This work was supported by the National Institutes of Health under grant RR10075 and by Clark-MXR, Inc. The authors thank Coherent, Inc., for providing the high-power laser diodes. J. Buckley acknowledges the support of the National Physical Science Consortium through a graduate research fellowship. F. Ö. Ilday's e-mail address is ilday@ccmr.cornell.edu.

References

1. M. E. Fermann, A. Galvanauskas, M. L. Stock, K. K. Wong, and D. Harter, Opt. Lett. **24,** 1428 (1999).
2. D. Anderson, M. Desaix, M. Karlsson, M. Lisak, and M. L. Quiroga-Teixerio, J. Opt. Soc. Am. B **10,** 1185 (1993).
3. M. E. Fermann, V. I. Kruglov, B. C. Thornsen, J. M. Dudley, and J. D. Harvey, Phys. Rev. Lett. **84,** 6010 (2000).
4. J. Limpert, T. Schreiber, T. Clausnitzer, K. Zöllner, H.-J. Fuchs, E.-B. Kley, H. Zeller, and A. Tünnermann, Opt. Express **10,** 628 (2002), http://www.opticsexpress.org.
5. A. Galvanauskas, M. E. Fermann, and D. Harter, Opt. Lett. **19,** 1201 (1994).
6. J. Limpert, A. Liem, T. Gabler, H. Zellmer, A. Tünnermann, S. Unger, S. Jetschke, and H. R. Müller, Opt. Lett. **26,** 1849 (2001).
7. A. Galvanauskas, IEEE J. Sel. Top. Quantum Electron. **7,** 504 (2001).
8. L. Lefort, J. H. V. Price, D. J. Richardson, G. J. Spühler, R. Paschotta, U. Keller, A. R. Fry, and J. Weston, Opt. Lett. **27,** 291 (2002).
9. H. Lim, F. Ö. Ilday, and F. W. Wise, Opt. Lett. **28,** 660 (2003).
10. D. Strickland and G. Mourou, Opt. Commun. **56,** 219 (1985).
11. J. W. Nicholson, J. Jasapara, W. Rudolph, F. G. Omenetto, and A. J. Taylor, Opt. Lett. **24,** 1774 (1999).
12. H. Lim, F. Ö. Ilday, and F. W. Wise, Opt. Express **10,** 1497 (2002), http://www.opticsexpress.org.