Nonlinear femtosecond pulse compression at high average power levels by use of a large-mode-area holey fiber

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Received March 10, 2003

We demonstrate that nonlinear fiber compression is possible at unprecedented average power levels by use of a large-mode-area holey (microstructured) fiber and a passively mode-locked thin disk Yb:YAG laser operating at 1030 nm. We broaden the optical spectrum of the 810-fs pump pulses by nonlinear propagation in the fiber and remove the resultant chirp with a dispersive prism pair to achieve 18 W of average power in 33-fs pulses with a peak power of 12 MW and a repetition rate of 34 MHz. The output beam is nearly diffraction limited and is linearly polarized.

OCIS codes: 320.5520, 190.4370.

In the past few years, substantial progress has been achieved in the generation and application of femtosecond laser pulses. A main direction of research was the development of high-average-power passively mode-locked lasers with picosecond or femtosecond pulse durations. Whereas some years ago the output power of such lasers was restricted to a few watts, we recently demonstrated that passively mode-locked thin disk lasers can be scaled to tens of watts in subpicosecond pulses. We obtained 60 W of power in 810-fs pulses[1] directly from a mode-locked laser (without an amplifier), and the shortest pulse duration achieved from a high-power (>10-W) laser was 240 fs with 22 W of average power.[2] In both cases, passive mode locking was achieved with a semiconductor saturable-absorber mirror.[3,4] Fiber-based systems that use chirped-pulse amplification can also reach multiwatt average powers in the femtosecond regime,[5] generating as much as 10.2 W in 80-fs pulses[6] and 60 W (or even 76 W, not yet published) in 350-fs pulses.[7] Although the available average powers in few-hundred femtosecond pulses are continually increasing, generating similar powers in the sub-100-fs regime appears to be a challenge: For bulk lasers, amplification bandwidth, laser cross sections, and thermal properties of available laser crystals set the limits, whereas fiber amplifier systems suffer mainly from excessive nonlinear effects and bandwidth limitations.

A well-known technique for generating pulses with durations less than 100 fs is nonlinear compression in a fiber.[8,9] First, the nonlinearity of the fiber is used to broaden the optical spectrum, and the resultant chirp is subsequently removed by a dispersive element. This method, however, has to our knowledge never been applied to generate pulse trains with average powers of more than a few watts. In this Letter we demonstrate a way in which the method of fiber compression can be extended for use at much higher power levels.

For standard single-mode fibers, optical damage at the input end limits the launched average power to a few watts, particularly for femtosecond pulses with correspondingly high peak powers. Therefore it is necessary to use fibers with larger effective mode areas but that still provide robust single-transverse-mode propagation. The use of recently developed holey (microstructured) fibers represents one way to achieve this goal.[10] These fibers are made from a single material (usually silica) and contain an array of air holes distributed across the fiber's cross section. In our experiment we used a holey fiber with a mode radius of 8 μm and an effective mode area of 200 μm^2. A scanning electron microscope image of the fiber is shown in Fig. 1. The hole spacing is $\approx$11 μm, and the hole diameter is $\approx$2.7 μm. The dispersion of the fiber is mainly determined by the material dispersion of fused silica; the zero-dispersion wavelength is $\approx$1.3 μm.

The experimental setup is shown in Fig. 2. We used 810-fs pump pulses from a passively mode-locked thin disk Yb:YAG laser similar to the one described in Ref. 1 but operating with $\approx$45 W of average output power. The laser output passed $\lambda/2$ plate #1 for adjustment of the power level, a Faraday isolator, $\lambda/2$ plate #2 to control the input polarization, and a focusing lens with 35-mm focal length. We measured 38 W of average power incident upon the 17-cm-long fiber and 23 W at the fiber output, indicating a launch efficiency of 60%. We removed the fiber's polymer jacket to prevent damage by absorption of light launched into the

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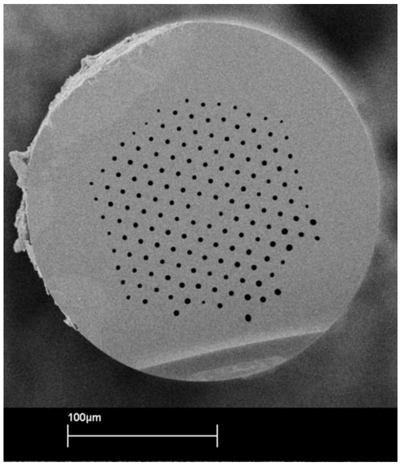

Fig. 1. Scanning electron microscope image of the large-mode-area microstructured fiber. The effective mode area is $\approx 200\ \mu m^2$, the hole spacing is $\approx 11\ \mu m$, and the hole diameter is $\approx 2.7\ \mu m$.

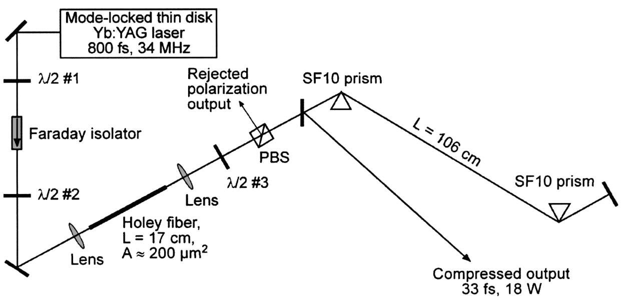

Fig. 2. Experimental setup (not to scale): L, length; A, area.

cladding. Stable operation over hours was possible despite the high incident peak intensity of $1.2\ TW/cm^2$, although a few times we observed damage of the input fiber end, which may have been due to dust particles.

The output of the fiber was collimated with another lens and sent through $\lambda/2$ plate #3 (Fig. 2). The orientations of $\lambda/2$ plates #2 and #3 were optimized for maximum power after the polarizing beam splitter (PBS), which defines a linear polarization state. The pulses were linearly compressed with a pair of Brewster-angled SF10 prisms. The beam traveling in the backward direction through the prism pair was slightly offset in the vertical direction such that it could be extracted with a mirror. A prism separation of 106 cm has been found to lead to optimum compression (with $\approx$4-mm insertion of both prisms).[11] The estimated double-pass dispersion of the prism pair was $\approx -9000\ fs^2$.

For optimum adjustment of the $\lambda/2$ plates we obtained 19 W of power after the polarizer, whereas 4 W was measured in the unused polarization state. This rejected power could not be further reduced, apparently because of nonlinear polarization rotation in the fiber. At the compressor output we obtained 18 W of average power. The optical spectrum of the output (Fig. 3) spans the range 970–1090 nm.

We characterized the compressed pulses by using a pulse retrieval technique called phase and intensity from correlation and spectrum only (PICASO).[12] As input data for this retrieval algorithm we used the measured spectrum (Fig. 3) and noncollinear autocorrelation (solid curve in Fig. 4) of the compressed pulses plus another autocorrelation of the pulses taken with a different setting of the prism compressor, i.e., with a defined change in dispersion. The retrieval algorithm optimizes the spectral phase for optimum agreement with the experimental data. The retrieved pulse (Fig. 5) has a FWHM duration of 33 fs, with the central pulse carrying 78% of the pulse energy, and a peak power of 12 MW. The calculated autocorrelation of the retrieved pulse (dashed curve in Fig. 4) shows excellent agreement with the experimental data.

The calculated Fourier-limited FWHM pulse duration for the measured spectrum would be 23 fs, i.e., significantly shorter than the retrieved 33 fs. We suspect that the noncollinear superposition of beams in the autocorrelator leads to some increase of the autocorrelation widths by a few femtoseconds. We

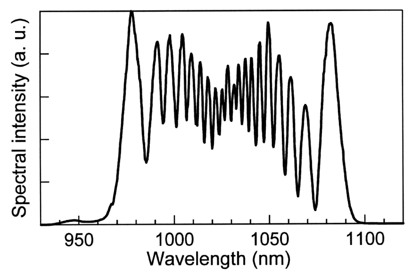

Fig. 3. Measured optical spectrum of the output with highest average power (18 W).

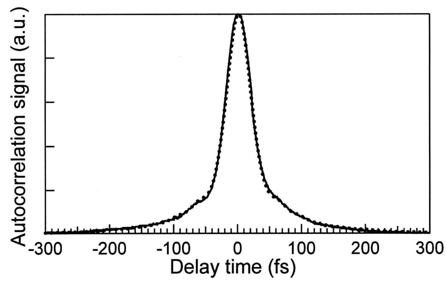

Fig. 4. Measured autocorrelation (solid curve) and retrieved autocorrelation (dashed curve) obtained by use of the PICASO algorithm for the output with highest average power (18 W).

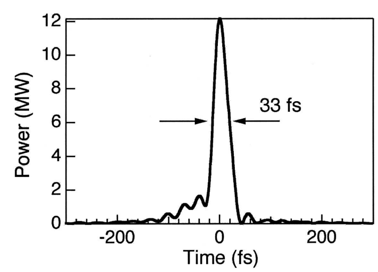

Fig. 5. Pulse retrieved by use of the PICASO algorithm for the output with highest average power (18 W; see the experimental data in Figs. 3 and 4).

estimated the influence of this effect on the PICASO result and found that under these conditions PICASO simply retrieves pulses with correspondingly increased duration, whereas the temporal structure is not strongly affected. From this we conclude that the actual pulse duration might be a few femtoseconds shorter than the retrieved pulse, which would bring the pulses closer to the transform limit, whereas the temporal shape shown in Fig. 5 is correct.

The output beam is linearly polarized and close to diffraction limited, with measured M^2 values of 1.2 and 1.3 in the horizontal and vertical directions, respectively.

In conclusion, we have generated 33-fs pulses with an unprecedented average power of 18 W and a peak power as high as 12 MW. We did so by combining a passively mode-locked thin disk Yb:YAG laser with a large-mode-area holey fiber for nonlinear compression. The required negative dispersion was small enough to be generated with a prism pair, which had much lower losses than a grating pair and thus permitted good power efficiency of 47% from the incident beam at the fiber input end to the compressed output. Further increases of the compressed power should be possible by application of a higher pump power to a fiber with an even larger mode area. With focusing to a beam diameter below 5.5 μm, our laser source would already generate peak intensities above 10^{14} W/cm^2. Therefore we envisage applications in strong-field physics, particularly high-harmonic generation[13,14] and femtosecond laser plasma generated x rays.[15] So far, such interactions have been driven only with amplified sources operating with kilohertz repetition rates, whereas the use of multimegahertz pulse trains with sufficiently high peak power could strongly increase the signal-to-noise ratios of measurements, e.g., in microscopy and ultrafast spectroscopy applications.

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References

1. E. Innerhofer, T. Südmeyer, F. Brunner, R. Häring, A. Aschwanden, R. Paschotta, U. Keller, C. Hönninger, and M. Kumkar, Opt. Lett. **28,** 367 (2003).
2. F. Brunner, T. Südmeyer, E. Innerhofer, R. Paschotta, F. Morier-Genoud, J. Gao, K. Contag, A. Giesen, V. E. Kisel, V. G. Shcherbitsky, N. V. Kuleshov, and U. Keller, Opt. Lett. **27,** 1162 (2002).
3. U. Keller, D. A. B. Miller, G. D. Boyd, T. H. Chiu, J. F. Ferguson, and M. T. Asom, Opt. Lett. **17,** 505 (1992).
4. U. Keller, K. J. Weingarten, F. X. Kärtner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au, IEEE J. Sel. Top. Quantum Electron. **2,** 435 (1996).
5. A. Galvanauskas, G. C. Cho, A. Hariharan, M. E. Fermann, and D. Harter, Opt. Lett. **26,** 935 (2001).
6. J. Limpert, T. Schreiber, T. Clausnitzer, K. Zöllner, H. J. Fuchs, E. B. Kley, H. Zellmer, and A. Tünnermann, Opt. Express **10,** 628 (2002), http://www.opticsexpress.org.
7. J. Limpert, T. Clausnitzer, T. Schreiber, A. Liem, H. Zellmer, H. J. Fuchs, E. B. Kley, and A. Tünnermann, in *Advanced Solid-State Photonics*, J. J. Zayhowski, ed., Vol. 83 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2003), p. 378.
8. D. Grischkowsky and A. C. Balant, Appl. Phys. Lett. **41,** 1 (1982).
9. C. V. Shank, R. L. Fork, R. Yen, R. H. Stolen, and W. J. Tomlinson, Appl. Phys. Lett. **40,** 761 (1982).
10. J. C. Knight, T. A. Birks, R. F. Cregan, P. St. J. Russell, and J.-P. de Sandro, Electron. Lett. **34,** 1347 (1998).
11. R. L. Fork, O. E. Martinez, and J. P. Gordon, Opt. Lett. **9,** 150 (1984).
12. J. W. Nicholson, J. Jasapara, W. Rudolph, F. G. Omenetto, and A. J. Taylor, Opt. Lett. **24,** 1774 (1999).
13. M. Ferray, A. l'Huillier, X. F. Li, L. A. Lompré, G. Mainfray, and C. Manus, J. Phys. B **21,** L31 (1988).
14. P. Salières and M. Lewenstein, Meas. Sci. Technol. **12,** 1818 (2001).
15. M. M. Murnane, H. C. Kapteyn, M. D. Rosen, and R. W. Falcone, Science **251,** 531 (1991).