High-energy (nanojoule) femtosecond pulse delivery with record dispersion higher-order mode fiber

S. Ramachandran, M. F. Yan, J. Jasapara, P. Wisk, S. Ghalmi, E. Monberg, and F. V. Dimarcello

OFS Laboratories, 25 Schoolhouse Road, Somerset, New Jersey 08873

Received May 20, 2005; revised manuscript received August 3, 2005; accepted August 4, 2005

Delivery of high peak-power femtosecond pulses with fibers is constrained by nonlinear distortions accumulated during pulse propagation. We address this problem with a novel, to our knowledge, fiber schematic, where the pulse propagates in a small A_{eff} (18 μm^2) but highly dispersive (record value of ~ -900 ps/nm km) medium, enabled by transmission in the LP_{02} mode of a few-mode fiber. The novel fiber yields a low dispersion-to-nonlinear-length ratio (due to its large dispersion) despite its small A_{eff}, hence enabling mitigation of nonlinearities. This enables fiber delivery of distortion-free <150 fs, ~1 nJ, and 840 nm pulses—an order-of-magnitude improvement over single-mode fibers of similar A_{eff}. © 2005 Optical Society of America

OCIS codes: 320.5520, 320.7140, 170.7160, 190.5530, 060.2340.

Fiber delivery of high-power femtosecond (fs) laser pulses has a variety of applications, such as two-photon fluorescence microscopy[1] and time-resolved pump–probe experiments.[2] In the dispersion-compensated schematic used commonly, laser pulses at 800 nm (from a Ti:sapphire laser) are negatively prechirped to counteract the normal dispersion of silica fibers, hence providing a transform-limited output from the fiber. However, self-phase modulation (SPM) due to high peak powers of fs pulses causes the negatively chirped pulses to spectrally narrow and temporally broaden,[3] which substantially reduces the efficiencies of two-photon processes to be enabled by them.

Standard silica fibers that are single mode at 800 nm have a very small effective area, which leads to very high peak-power densities. Thus 100-fs pulses of energies >0.1 nJ are severely distorted due to SPM in SMF. A majority of approaches explored to circumvent this involve working with large A_{eff} fibers—either conventional[4] or microstructured[5] fibers. In both cases, extra care is needed to ensure single-mode propagation, and it is unclear if the advantage of low bend losses or mode coupling at tight bends provided by small A_{eff} fibers is retained. Alternatively, air-guided photonic bandgap fibers have shown great promise,[6] though manufacturability, susceptibility to bends and PMD, and termination issues need to be addressed.

In this Letter we propose and demonstrate an alternative means to deliver high-power fs laser pulses with a fiber—instead of increasing the A_{eff} to decrease nonlinearities, we use a highly dispersive fiber (with what is to our knowledge a record dispersion value of −896 ps/nm km) to decrease the ratio of the dispersion to the nonlinear length of the fiber medium, and thus mitigate the influence of nonlinearities. This record dispersion value is achieved in the LP_{02} mode of a specially designed few-mode fiber, exploiting the property of higher-order modes (HOMs) of a fiber to be highly dispersive with moderate A_{eff}.[7,8] Pulse widths <150 fs with almost order-of-magnitude higher energies compared to SMF are obtained, even for light residing in a mode with only 18 μm^2 A_{eff}. Hence this technique retains all the other advantages of pulse propagation in SMF, namely, operation in one pure mode, ability to navigate sharp bends, and ease of termination (with splices, lenses, etc.).

Our approach hinges on the fact that nonlinear distortion is governed not just by A_{eff} but by the ratio of the dispersion length L_D (length over which a pulse is substantially compressed and hence possesses high peak powers) to the nonlinear length L_{NL} (length over which the SPM-induced phase shift is significant) in a fiber[9]:

$$L_D = \left(-\frac{2\pi c}{\lambda^2}\right)\left(\frac{\tau^2}{D}\right),$$

$$L_{\text{NL}} = \frac{A_{\text{eff}}\lambda}{2\pi n_2 P_{\text{peak}}}, \tag{1}$$

where τ is the undistorted, transform-limited pulse width, D is the dispersion of the fiber waveguide, c is the speed of light, λ is the central wavelength of the pulse, n_2 is the nonlinear response of the fiber material, P_{peak} is the peak power of the pulse in the fiber, and A_{eff} is its effective area. For a chirped pulse entering the fiber, the pulse compresses, and hence the peak powers become substantial only for lengths of the order of L_D, and if L_{NL} is substantially longer than that, pulse distortion is minimal. In other words, for the condition $L_D/L_{\text{NL}} \ll 1$, the pulse will not travel a large enough distance with high peak power to experience significant nonlinear pulse distortion, hence facilitating high-energy pulse transmission. Large A_{eff} fibers previously proposed as alternatives for SMF work on the principle of increasing L_{NL} by increasing A_{eff}. Here we achieve a low L_D/L_{NL} ratio by the use of a highly dispersive fiber that decreases L_D instead. Note that the above discussion ignores

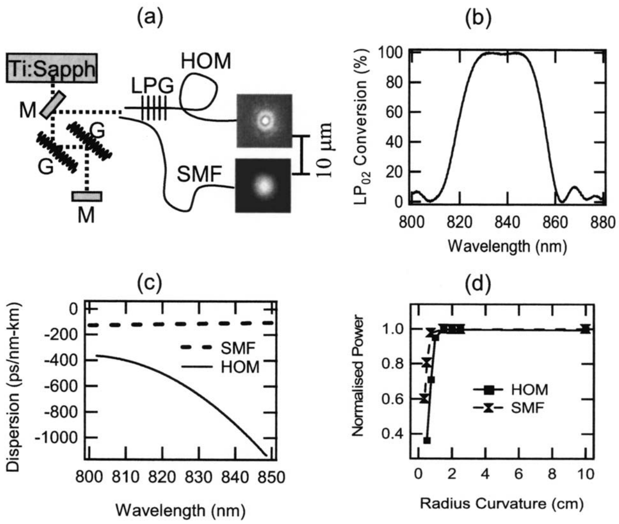

Fig. 1. (a) Schematic of the experiment and the device structure. Output modal images indicate similar modal areas for HOM and SMF. M, mirror; G, bulk grating. HOM fiber preceded by LPG, whose conversion efficiency is shown in (b). (c) HOM dispersion is ~8.5 times higher than SMF. (d) Both the SMF and the HOM have negligible bend loss for radii ⩾1 cm, due to small A_{eff}.

the physical length of the fiber. This is because the prechirped input pulses will compress, and hence attain high enough peak powers for nonlinearities to matter, only over a length scale of L_D at the fiber exit. Hence physical fiber lengths substantially larger than that, as will be shown to be the case in these experiments, will not influence the level of nonlinearities accumulated.

The setup is shown in Fig. 1(a). The commercial Ti:sapphire laser was operated at 840 nm, delivering 90 fs (FWHM) sech pulses at a repetition rate of 80 MHz. This light was passed through a pair of bulk gratings to negatively chirp the pulses by the required amount to compensate for the dispersion of the fiber. Also shown in this schematic are the experimentally recorded near-field images at the outputs of the HOM and SMF, respectively. The image shows that the spatial extent of the two outputs are similar ($A_{\text{eff}}=14\ \mu\text{m}^2$ for SMF and $18\ \mu\text{m}^2$ for HOM). Figure 1(b) shows the conversion efficiency of the long-period grating (LPG), which spatially transforms the incoming light into the desired LP_{02} mode. Peak conversion efficiencies of 99.7%, and more than 98.8% conversion over a 16.5-nm bandwidth, easily covering the 10 nm bandwidth of the pulse, are achieved.[10] Given a grating background loss of 2%, negligible fiber propagation loss, and the high conversion efficiency, the HOM schematic enables a system with ~2% loss and >97% modal purity.[11] Figure 1(c) shows the dispersion of the SMF and HOM, respectively, measured by spectral interferometry.[12] The highly dispersive nature of HOMs enables realizing a fiber with dispersion as high as −896 ps/nm km at 840 nm for the LP_{02} mode ($D_{LP_{02}} \sim 8.5\times$ higher than SMF). Given the data in Fig. 1(c) and A_{eff} calculations from the images in Fig. 1(a), we estimate from Eq. (1) that the L_D/L_{NL} ratio for the HOM fiber is 10.85 times smaller than that for SMF at any given power level. Hence, conversely, we expect that the pulse energy threshold for the onset of nonlinearities will be 10–11 times higher in HOMs compared to SMF. Figure 1(d) compares the bend loss behavior of SMF and HOMs and illustrates the significant attribute of this novel scheme—losses are negligible for bend radii as small as 1 cm (transmission = 97% for SMF and 95% for HOM at $r=1$ cm).

Intensity autocorrelations and spectra of the pulses were measured for different power levels at the output of the fiber. The dispersion of the bulk-grating pair was matched with that of the fibers by adjusting the bulk grating separation to obtain the narrowest autocorrelation trace at a power level of 2 mW. The low power level ensures that nonlinear effects were negligible as the optimal dispersion map was realized. While 1.95 m of HOM fiber yielded the narrowest pulses (93±6 fs) for a grating separation of 107 mm, the corresponding optimal grating separation distance for 16.85 m of SMF was 104 mm (shortest recorded width for SMF ~97±6 fs). Hence the ratio of the second-order dispersion between the two fibers is 8.4, similar to the ratio deduced from the dispersion values plotted in Fig. 1(c). From the above data we estimate that L_D is 8.7 mm for HOM and 7.3 cm for SMF. Both these values are substantially shorter than the fiber physical lengths, and hence nonlinear distortions would depend primarily on the L_D/L_{NL} ratio. Thus the use of dissimilar lengths of SMF and HOM (necessitated by limitations in tuning the bulk grating pair) does not impact the comparison of the nonlinear distortions caused in these fibers.

Figure 2(a) shows spectra obtained at the output of the SMF and HOM fibers, respectively, at different fiber-output-power levels. At low power levels (4 mW), the spectra out of both the HOM fiber and SMF look similar and featureless. The absence of interference ripples in the HOM spectrum indicates negligible energy in any mode other than the desired LP_{02} mode, as is expected from the highly efficient mode transformer (LPG) used. As the power at the fiber output increases, the spectrum out of the SMF becomes significantly more distorted than that out of the HOM, indicating higher levels of SPM in SMF. Figure 2(b) shows the FWHM of the spectra shown in

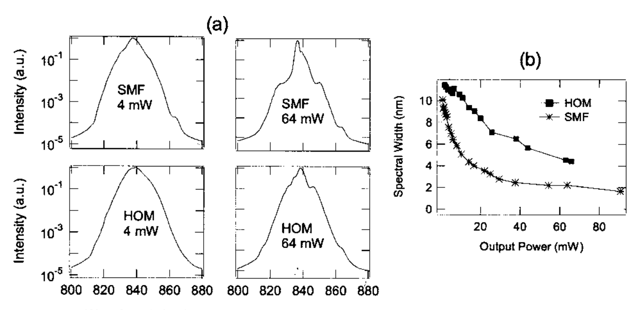

Fig. 2. (a) Spectra of the HOM and the SMF at selected output power levels (spectral resolution = 0.1 nm). No ripples in the low-power HOM spectrum indicates high modal purity. (b) Spectral width versus power. SPM-induced spectral narrowing more pronounced in SMF.

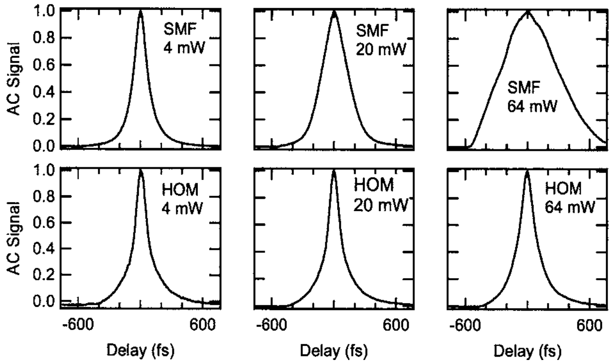

Fig. 3. Intensity autocorrelation at selected output power levels. High power: HOM broadens slightly but maintains shape; SMF significantly broadens and distorts.

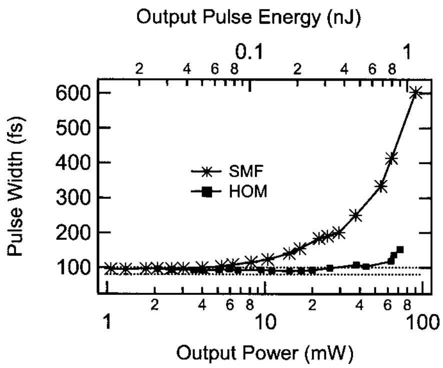

Fig. 4. Pulse width versus output power or pulse energy. SPM onset in SMF at 0.075 nJ; in HOM at 0.8 nJ. The power handling capability of the HOM is 10.67 times higher than that of the SMF. Transmitted up to 0.9 nJ for pulse widths <150 fs with the HOM.

Fig. 2(a), as a function of power at the fiber output. Spectral compression, as is expected due to SPM on a negatively chirped pulse, is clearly visible in both cases, but the SMF spectrum compresses significantly faster than that of the HOM.

Figure 3 shows the traces of intensity autocorrelations at selected power levels for the two fibers. Again, at low power levels, both fibers yield outputs that are roughly 90 fs wide. As the power is increased, the pulse out of the HOM broadens somewhat ($\tau \sim 118$ fs for 64 mW HOM) but maintains approximately the same pulse shape. In contrast, higher powers not only broaden the pulse out of the SMF, the pulse shape also severely distorts, indicating the presence of significant nonlinear effects.

A more quantitative comparison of the performance of SMF and the HOM fiber is obtained via the data shown in Fig. 4 (plot of the pulse width versus fiber output power and (or) pulse energy). The onset of nonlinearities in either case is evident from increases in pulse widths beyond the reference (horizontal dotted lines depict the reference along with its measurement uncertainty). In the case of SMF, the onset is at ~6 mW (pulse energy ~0.075 nJ) while SPM effects become barely measurable in the HOM fiber only at 64 mW (0.8 nJ). Even so, the pulse width at 72 mW (0.9 nJ) is less than 150 fs. Hence it is clear that the HOM fiber of similar $A_{\rm eff}$ can transmit an undistorted pulse of energy that is ~10.67 times higher than the tolerance limit of SMF. This is similar to our estimates based on the device characteristics and Eq. (1), which indicated that the $L_D/L_{\rm NL}$ ratio for the HOM fiber is approximately 10.85 × lower than that of the SMF.

In summary, we demonstrate a novel, to our knowledge, device for fiber delivery of high-power fs pulses and show an order-of-magnitude improvement over SMF in terms of the maximum pulse energy that can transmitted without nonlinear distortions. We exploit the highly dispersive nature of HOM fibers to realize a fiber with what we believe to be a record dispersion value of −900 ps/nm km. Due to the extreme dispersion values of this LP_{02} mode, substantial pulse compression (and high peak power) occurs over a length smaller than that required for significant nonlinear distortions to accumulate. Hence we achieve up to 0.9 nJ pulse energies with pulse widths <150 fs. Unlike conventional demonstrations of higher-power fs-pulse delivery, this device maintains the small $A_{\rm eff}$ advantages of SMF, such as low bend losses, high modal purity, and ease of termination. The device throughput losses are less than 2%, and the fabrication procedure is based on a conventional, low-cost, fiber-manufacturing platform. Moreover, the enhanced dispersion-engineering capabilities of HOMs can facilitate fibers with much higher dispersion values for similar or larger $A_{\rm eff}$, making this novel technological platform attractive for any application requiring delivery or compression of high-power fs pulses.

The authors thank G. Chen, O. Mitrofanov, and R. Rapaport for access to and help with the experimental setup. S. Ramachandran's e-mail address is sidr@ieee.org.

References

1. G. Alexandrakis, E. B. Brown, R. T. Tong, T. D. McKee, R. B. Campbell, Y. Boucher, and R. K. Jain, Nat. Med. (N.Y.) **10**, 203 (2004).
2. S. Smith, N. C. R. Holme, B. Orr, R. Kopelman, and T. B. Norris, Ultramicroscopy **71**, 213 (1998).
3. M. Myaing, J. Urayama, A. Braun, and T. Norris, Opt. Express **7**, 210 (2000).
4. F. Helmchen, D. W. Tank, and W. Denk, Appl. Opt. **41**, 2930 (2002).
5. D. Ouzounov, K. Moll, M. Foster, W. Zipfel, W. W. Webb, and A. L. Gaeta, Opt. Lett. **27**, 1513 (2002).
6. W. Goebel, A. Nimmerjahn, and F. Helmchen, Opt. Lett. **29**, 1285 (2004).
7. S. Ramachandran, B. Mikkelsen, L. C. Cowsar, M. F. Yan, G. Raybon, L. Boivin, M. Fishteyn, W. A. Reed, P. Wisk, D. Brownlow, R. G. Huff, and L. Gruner-Nielsen, IEEE Photon. Technol. Lett. **13**, 632 (2001).
8. S. Ramachandran, J. Lightwave Technol. (to be published November 2005).
9. G. P. Agrawal, *Nonlinear Fiber Optics* (Academic, 2001), Chaps. 3 and 4.
10. S. Ramachandran, Z. Wang, and M. F. Yan, Opt. Lett. **27**, 698 (2002).
11. S. Ramachandran, J. W. Nicholson, S. Ghalmi, and M. F. Yan, IEEE Photonics Technol. Lett. **15**, 1171 (2003).
12. D. Menashe, M. Tur, and Y. Danziger, Electron. Lett. **37**, 1439 (2001).