Fiber delivery of femtosecond pulses from a Ti:sapphire laser

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We propose a way to deliver nanojoule-energy, 100-fs pulses at 800 nm through a few meters of standard optical fiber. Pulses from a mode-locked laser are compressed temporally, and then spectrally, to produce the desired pulses at the end of the fiber. Initial experiments agree well with calculations and demonstrate the benefits of this technique: For an energy of ~0.5 nJ, the delivered pulses are ~5 times shorter than those delivered by other techniques. The issues that must be addressed to scale the technique up to delivered pulse energies of 5 nJ are identified, and the apparatus employs only readily available components. Thus we expect it to find use in the many applications that would benefit from fiber delivery of femtosecond pulses.

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Femtosecond optical pulses have found a wide variety of applications in science and technology. The proliferation of femtosecond techniques has been particularly rapid in the past 10 years since mode-locked Ti:sapphire lasers were demonstrated and developed commercially. In many cases it would be advantageous to deliver the femtosecond pulses to the system under investigation with optical fiber. For example, multiphoton excitation of fluorescence deep in tissue or body cavities is poised to become a powerful tool in biophysics and medicine, but a means to deliver the excitation pulses is required. Initial results obtained with picosecond pulses illustrate some of the advantages of fiber delivery of excitation pulses and extraction of fluorescence.[1] Some applications, such as near-field microscopy, directly exploit the intense light at the exit of a fiber. Practical benefits of fiber delivery include the physical separation of the femtosecond laser from other instrumentation and the flexibility and convenience of pulse delivery to arbitrary locations.

The nonlinearity and normal group-velocity dispersion (GVD) of standard optical fibers at 800 nm restrict fiber delivery of 100-fs pulses to energies of ~20 pJ. This is less than 1% of the pulse energy for a standard Ti:sapphire laser and is uselessly low for many photophysical applications. A 1-nJ pulse is severely distorted after propagation through 1 m of fiber: The pulse duration increases by a factor of ~30 (which reduces the peak intensity by the same factor), and the spectrum broadens by a factor of ~4. The natural length scale associated with dispersion is L_D ($=\tau_0{}^2/\beta_2$, where τ_0 is the $1/e$ point of the intensity envelope for Gaussian pulses and β_2 is the GVD parameter). Because the temporal broadening is caused by the different spectral components' traveling at different phase velocities, it is useful to recognize that $L_D \propto 1/\Delta\omega^2$, where $\Delta\omega$ is a measure of the bandwidth of the pulse: A pulse with a larger bandwidth is affected more by dispersion. L_D for 100-fs pulses propagating through standard fiber (single-mode fiber at 800 nm) is roughly 9 cm. The nonlinear length is defined as $L_{\mathrm{NL}} = [(\omega/c)n_2 I_{\mathrm{peak}}]^{-1}$, where n_2 is the nonlinear refractive index and I_{peak} is the peak intensity of the pulse. For 100-fs pulses at 800 nm and with an energy of 1 nJ, $L_{\mathrm{NL}} \sim 1.3$ cm. Thus $L_D/L_{\mathrm{NL}} \approx 7$, and so nonlinearity initially dominates the propagation. The spectrum broadens significantly in the first few centimeters of fiber, after which GVD becomes the dominant effect. The pulse broadens, and the peak power drops proportionally. As a result, the propagation is nearly linear for all but the first few centimeters. The pulse at the output of a meter of fiber is broadened spectrally and temporally compared with the input and has an approximately linear frequency chirp.

To date, avoiding nonlinearity as much as possible has produced the best results for fiber delivery of 100-fs pulses from Ti:sapphire lasers. A large negative linear frequency chirp is imposed on the pulse (by the use of gratings or prisms), which increases the pulse duration to several picoseconds. Propagation through fiber with normal GVD restores the pulse to nearly the original duration; there is no attempt to compensate for nonlinear effects.[2] This prechirping approach works reasonably well at low energies, but even with 20-pJ pulses substantial distortion occurs in the unavoidable nonlinear propagation at the end of the fiber, where the pulse is recompressed to some extent. When a negatively chirped pulse propagates in a medium with a positive nonlinear index of refraction, self-phase modulation compresses the spectrum[3] and thus increases the pulse duration. The energy limitations of the prechirping scheme are evidenced by the experimental observation that the peak power of the delivered pulses increases less than linearly with increasing pulse energy E. The deviation is substantial: Myaing and co-workers showed that the measured two-photon fluorescence of dyes excited by such pulses increases as $E^{1.25}$ rather than as E^2.[4] Whereas the use of photonic crystal fibers offers promise of distortion-free pulse delivery,[5] such has not been demonstrated, and such fibers are not readily available.

In this Letter we describe a method for fiber delivery of energetic femtosecond-duration pulses from a Ti:sapphire laser. Pulses from the laser are compressed first in the time domain and then in the frequency domain to produce a pulse of ~100-fs duration at the output of the fiber. Numerical calculations

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agree well with experimental results obtained with this method and also show that uncompensated third-order dispersion limits the quality of the delivered pulse. Even with this limitation, the pulses are ~5 times shorter than equal-energy pulses delivered with the prechirping technique.

The concept that underlies the proposed scheme may be best understood if we assume that the goal is to deliver from the fiber a replica of the pulse from the laser. To produce a transform-limited pulse of desired duration at the output end of the fiber, the pulse needed at the input is just the phase conjugate of the pulse produced at the output when the desired pulse is launched at the input. The pulse that evolves from the desired pulse develops a broad spectrum and a nearly linear positive frequency chirp. Thus we require the same broad spectrum but a nearly linear negative chirp. An established and convenient way to generate such a pulse is to construct a pulse compressor followed by an element that imposes a negative chirp on the pulse. In practice, a single element (grating pair or prism sequence) can provide the anomalous GVD of the compressor as well as the additional anomalous GVD needed to impose the negative chirp on the pulse. The resultant chirped pulse is then transmitted through the delivery fiber. A diagram of the proposed system is shown in Fig. 1. This arrangement can be viewed as an ordinary pulse compressor followed by a spectral compressor. Its effectiveness will be determined by the deviation of the actual frequency chirp of the pulse from linearity. Such a deviation is caused by the fiber nonlinearity and will increase with increasing intensity.

We used numerical solutions to the nonlinear Schrödinger equation to help to design the pulse-delivery system and to evaluate its performance. The simulations confirm that the concept is sound: Results for a 1-nJ pulse are displayed in Fig. 1 (the pulse energy is assumed to be constant as the pulse propagates through both fibers and the dispersive delay). Deviations from a linear frequency chirp do produce some structure in the wings of the pulse. However, the root-mean-square pulse duration increases by only 7%, and the peak power decreases by 18% with respect to the input pulse. As the pulse energy increases, the deviation from linear chirp slowly degrades the output pulse. At 10 nJ, the pulse broadens by 13% and the peak power decreases by 30% compared with the input pulse. These results exceed by an order of magnitude the best that can be obtained with prechirping.

A home-built Ti:sapphire laser that generates 75-fs pulses centered at 850 nm supplied pulses for experimental evaluation of the proposed fiber delivery system. This laser is pumped by a 4-W argon laser, and its maximum pulse energy is 4 nJ. Pulses from the laser are coupled into 25 cm of fiber that is single mode for 800 nm. The dispersion of the fiber is estimated to be $\beta_2 \sim 400\ \mathrm{fs}^2/\mathrm{cm}$ and $\beta_3 \sim 300\ \mathrm{fs}^2/\mathrm{cm}$ (β_3 is the third-order dispersion parameter). A sequence of six SF10 prisms provides the necessary anomalous GVD. The prisms were initially spaced to compensate exactly for the second-order dispersion of both fibers and then experimentally adjusted to produce the optimal pulse duration. After the prisms, the light is coupled into 50 cm of fiber that is single mode for 488/514 nm (Newport SF-A). Ideally, the pulse fluence would be the same in both fibers. Because of losses the second fiber was chosen to have a small core. If the fluence is lower in the second fiber than in the first, the spectral compression will not be optimal, so net temporal compression will occur. This may be desirable and is discussed further below. The fiber lengths are not critical, and in particular the second (delivery) fiber can be much longer than 50 cm. The essential features of the propagation will be unchanged as long as the pulse experiences nearly linear propagation at the end of the first fiber and the beginning of the second fiber.

Losses in the isolating components and coupling into the fiber limited the pulse energy in the first fiber to 1.3 nJ. The pulse has a 57-nm bandwidth (as shown in Fig. 2) and a roughly 1-ps duration after the first fiber. After the prism sequence the pulse energy was 1 nJ, and 0.4 nJ of energy was delivered by the second fiber. The interferometric autocorrelation (IAC) of the delivered pulse (Fig. 2) has a FWHM of 82 fs but also exhibits secondary interference peaks superimposed upon a low, broad background. For comparison, Fig. 2 also shows the envelopes of the IACs of the input pulse and an equal-energy pulse delivered by the use of prechirping alone. The FWHM of the equal-energy pulse is 435 fs, so our scheme reduces the duration of the delivered pulse by a factor of ~5. We estimate that the FWHM pulse duration is 60–70 fs. The main portion of the pulse is estimated to contain ~60% of the pulse energy, with the remaining energy residing in a wing. Thus the peak power exceeds that obtained by prechirping by a factor of ~3. As a result of less-than-complete spectral compression, the pulses do have some excess bandwidth.

The presence of significant energy in a broad wing and the incomplete spectral compression are

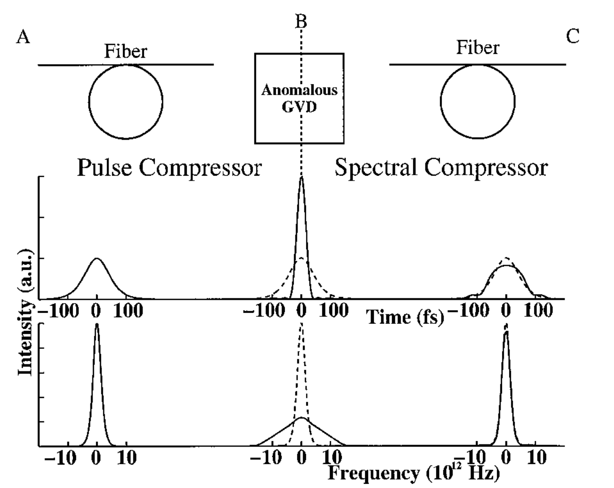

Fig. 1. Top, diagram of the delivery system: A, input; B, point halfway through the dispersive delay; and C, output. A–B acts as a pulse compressor; B–C acts as a spectral compressor. Middle and bottom, simulations of a 1-nJ pulse propagating through the delivery system. Each fiber is 1 m long. Middle, time domain; bottom, frequency domain. Dashed lines, input pulse.

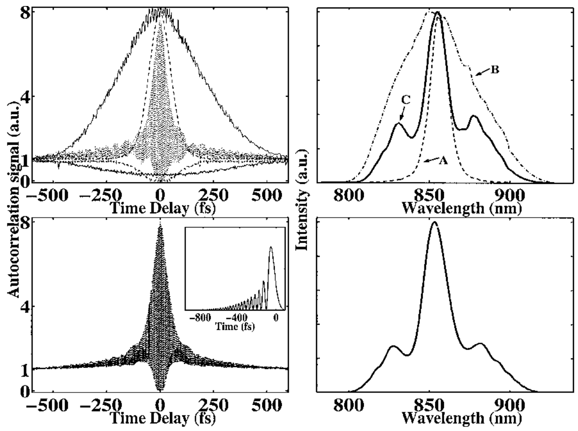

Fig. 2. Experimental (top) and calculated (bottom) pulse delivery. Top left, IAC of the output pulse, along with the envelopes of the IACs of the input (dashed curves) and the prechirped (solid curves) pulses. Top right, frequency spectra measured at the indicated points. The inset of the bottom left figure is the calculated intensity profile of the delivered pulse.

consequences of uncompensated third-order dispersion (TOD). The effects of TOD are weak: for a 1-nJ pulse, a net TOD as large as ±50% of the TOD of the fiber produces less than 1% difference in the peak power of the resultant pulse. However, the use of SF10 prisms introduces negative TOD that substantially overcompensates for the positive TOD of the fiber. The net TOD that we calculate is $\sim -4 \times 10^4\ \mathrm{fs}^3$. Numerical calculations show that the presence of TOD of this magnitude does limit the spectral compression, and it produces a substantial wing that leads the main portion of the pulse (Fig. 2). The good agreement between calculations and measurements confirms that the experiment is limited by TOD. Fortunately, it should be straightforward to reduce the TOD significantly. TOD compensation is a common issue in the generation and amplification of short pulses, and several of the designs reported for that purpose[7–9] will be applicable for this system.

As was mentioned above, the pulse-delivery system was designed to produce a near replica of the pulse generated by the mode-locked laser. This may be desirable for some applications, but in many applications the maximum possible peak power is desired. In that case, temporal pulse compression would be preferred. Ideally, pulses compressed in the first half of the apparatus would be transmitted undistorted to the end of the delivery fiber. Some spectral compression will occur in all available fibers, but net temporal compression is indeed possible, according to our calculations. With typical experimental parameters (i.e., those above) it should be possible to deliver pulses as short as ~35 fs, or a factor of 2 shorter than those produced in our experiments.

To summarize, we have proposed a scheme for fiber delivery of 100-fs pulses at 800 nm, based on temporal and spectral compression. Initial experimental results obtained with this scheme suffer from uncompensated third-order dispersion, but we still obtain much shorter pulses (and greater peak powers) than those produced by other techniques. Perhaps more significantly for applications, straightforward modifications of the experimental arrangement should significantly improve the performance. Reduction of TOD will permit the delivery of clean, nearly transform-limited pulses. The efficiency of the delivery system will be improved by the use of fiber collimators. With a Ti:sapphire laser that produces 12-nJ pulses and these modifications, we expect that fiber delivery of ~2 nJ in a 100-fs pulse will be readily achieved, and energies as high as 5 nJ, or shorter pulses, are possible. Design of such a system is in progress. If proper care is taken with the higher-order dispersion terms, this method will work with 10-fs pulses (100-fs pulses were considered in this study merely because they are readily available). This capability should facilitate many applications of femtosecond pulses.

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