Propagation of femtosecond pulses in large-mode-area, higher-order-mode fiber

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Abstract

We demonstrate propagation of 14-nJ femtosecond pulses through a large-mode-area, higher order mode fiber with an effective area of 2100 μm^2. The pulses propagate stably in the LP_{07} mode of the fiber through lengths as long as 12 m. The strongly chirped pulses exiting the amplifier fiber are de-chirped by the high-order-mode fiber, resulting in pulses with a peak power of 61 kW after propagation in 5 m of the positive dispersion fiber. A small amount of self phase modulation is observed in the compressed pulses, and is described well by a nonlinear-Schrödinger equation model that takes into account the measured effective area and dispersion of the HOM fiber.

OCIS codes: (320.7090) Ultrafast lasers ; (140.3510) Lasers, Fiber;

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Mode-locked fiber lasers have attracted much interest recently as reliable, low noise sources of femtosecond pulses. Amplified fiber laser systems can generate ultra-short pulses that now compete in performance with bulk-optic, solid-state femtosecond laser sources. The inherently flexible nature of such lasers, along with the prospect of obtaining transform-limited pulses at the tip of a fiber are make them attractive light sources for a variety of applications such as frequency metrology[1,2], bio-optics[3,4], and nonlinear optics[5,6]. However, the advantageous features of fiber-based lasers, namely mode-confinement and long propagation lengths also limit the attainable peak powers, because nonlinearity and dispersion serve to distort ultra-short, high-peak-power pulses. For many applications such as frequency metrology or bio-medical imaging, pulses on the order of 100 fs with energies around 1 to 10 nJ are required, and conventional single-mode fibers (SMF) cannot handle the high peak power.

Pulse propagation in optical fibers can be described using two characteristic lengths, the dispersion length, L_D, and the nonlinear length, L_{NL}[7]. When the dispersion length is much shorter than the nonlinear length, pulse propagation is primarily linear, and governed by the fiber dispersion, so the pulse stretches or compresses in time as it propagates, depending on the sign of the initial pulse chirp. Alternatively, if the nonlinear length is much shorter than the dispersion length, then the pulse can build up a significant nonlinear phase while the temporal profile is unaffected by dispersion. The ratio of the dispersion length to the nonlinear length is given by $L_D / L_{NL} = \gamma E_p T_o / \beta_2$, where γ is the nonlinear coefficient of the fiber, E_p is the pulse energy, T_0 is the pulse width, and β_2 is the group velocity dispersion. For distortion-free pulse propagation, a small L_D/L_{NL} value (preferably < 1) is required.

One approach to decreasing this ratio is to increase the effective area of the fiber. However, simply scaling the fiber dimensions up to large sizes is problematic for A_{eff}'s beyond 800 μm^2 due to loss and modal coupling[8]. Photonic crystal fibers have been shown to help the situation somewhat, by enhancing the bend-induced loss of higher order modes[9] but the largest A_{eff} demonstrated with this approach is still 1400 μm^2, and the fibers are significantly more bend-sensitive than SMF. Rod type fibers[10] can have A_{eff} as large as 4500 μm^2, but these fibers must be held straight, are limited to lengths of a few tens of cms and require careful optimization of the launch conditions with bulk optics, negating several advantages of all-fiber devices.

Recently a novel approach to very large effective area fibers based on propagation in a few-moded fiber was demonstrated[11]. The fiber consisted of an SMF-like inner core surrounded by an inner cladding region with a diameter of 86 μm and a protective down-doped trench. Coupling into the higher order modes was achieved with a broadband long-period grating (LPG) that ensured only the desired high-order mode was launched with very high fidelity (peak coupling > 99% over 94 nm bandwidth). Depending on the higher order mode excited, effective areas from 2100 μm^2 to 3200 μm^2 were demonstrated, and propagated stably through lengths as long as 50 m. Furthermore, the fiber could be coiled to a bend radius as small as 4.5 cm, and was splice compatible to SMF. For further details regarding the fiber see Ref. 11. In this Letter we demonstrate femtosecond pulse propagation in long lengths of this fiber and show a small amount of SPM broadening consistent with the fiber effective area.

A calculation of the ratio for L_D/L_{NL} as a function of the effective area of a fiber for two representative values of dispersion is shown in Fig. 1 for a 100-fs, 10-nJ pulse. For SMF, L_D/L_{NL} for such pulses is nearly 100, and even for traditional LMA fibers, the ratio is approximately 10. However for the LMA-HOM fiber, this ratio is approximately 1, owing to their larger dispersion and record-high values of A_{eff}.

Additional details of the modal properties of the LMA-HOM fiber in relation to pulse propagation are shown in Fig. 2. The dispersion of different LP_{0m} modes as a function of wavelength (Fig. 2a) was calculated from the measured index profile of the fiber, showing a variety of dispersion and dispersion slope values can be achieved by selectively exciting the desired HOM. More specifically, in Fig. 2b, the dispersion and A_{eff} at 1550 nm are plotted as a function of mode number. For systems in which the primary nonlinearity is independent of dispersion (e.g. Raman or Brillouin scattering due to long (ns) pulses one would use the largest A_{eff} mode that can propagate stably. On the other hand, for femtosecond-pulse propagation, the interplay between dispersion and Aeff plays an important role, and hence the ratio of L_D/L_{NL} must be considered. Figure 2c shows that the L_D/L_{NL} ratio is nearly independent of mode number for a given fiber waveguide. However, an additional consideration for short pulses with broad bandwidth is the contribution of the higher-order dispersive characteristics of the medium. A succinct way to characterize this contribution is with the quantity, relative-dispersion slope (RDS), defined as the ration of dispersion-slope to dispersion. For optimal performance of short-pulse systems, the RDS of various components (fibers) must be matched. Figure 2d plots the RDS vs. mode number for HOM fibers, showing that while L_D/L_{NL} is constant vs mode number, a range of values of RDS are achievable, allowing a degree of flexibility in designing fs-pulsed systems.

The experimental setup for pulse propagation is shown in Fig. 3a. A passively modelocked, figure-eight, Er-doped fiber laser was used as a seed source. This laser produced a 46 MHz pulse train with 0.8 mW average power. The 29 m long erbium-doped-fiber amplifier was forward and backward pumped with a total power of 1.06 W at 1480 nm. The negative dispersion of the erbium fiber provided amplification as well as pulse stretching and spectral broadening in a wave-breaking-free regime. The pulses exiting the amplifier had an average power of 655 mW, corresponding to approximately 14 nJ of pulse energy. An auto-correlation of the strongly chirped pulses immediately after the backward pump/signal WDM is shown in Fig. 3b. The negative dispersion of the Er amplifier, as well as the nonlinear phase accumulated from SPM imply that the pulses require a positive dispersion fiber for re-compression.

The LMA-HOM fiber was then spliced to the amplifier output WDM. During these experiments, the HOM fiber was coiled to a bend radius of 7 cm. A broad-bandwidth LPG provided conversion from the SMF like fundamental mode of the fiber to the LP_{07} mode, which had an A_{eff} of 2100 μm^2, and a dispersion of +35 ps/nm-km. The longest length of HOM fiber used was 12 m. The HOM fiber was cut back until the peak correlation was observed, at a 5 m length of HOM fiber. The correlation, shown in Fig. 3c, corresponded to a 152 fs pulse with a peak power of 61 kW, taking into account the pedestal on the correlation, which was most likely due to uncompensated third order phase. Note that optimizing the RDS of HOM fibers is feasible (see Fig. 2c), and hence we expect that our current limitation can be addressed by judicious choice of mode order in future experiments utilizing LMA-HOM fibers.

The L_D/L_{NL} value for this fiber is approximately one, as calculated from the measured A_{eff} and dispersion of the LP_{07} mode (see Figs. 1 and 2c). Therefore we expect some amount of SPM and spectral re-shaping while the pulses propagate in the HOM. The spectra measured at different points after the amplifier are shown in Fig. 4. The spectrum immediately after the amplifier, before the LPG, is shown as a black line in both Fig. 4a and 4b. The spectrum measured after 5 m of propagation in the HOM, the point corresponding to maximum pulse compression, and after 12 m are plotted in Fig. 4a and 4b, respectively, as dashed lines. There is a small amount of spectral re-shaping apparent in the spectrum at the point of maximum pulse compression (Fig. 4a), however as pulses propagate further in the HOM and begin to stretch again, the spectrum reshapes to be nearly identical to the input spectrum (Fig. 4b). For comparison purposes the HOM fiber was removed and the pulses were propagated through 10 m of SMF. In this case the pulses were severely distorted due to nonlinearities in the SMF (dotted curve, Fig. 4b).

The details of the propagation of the pulses in the HOM fiber were modeled using a nonlinear Schrödinger equation simulation. The measured input spectrum, along with an assumed linear chirp, was used as the initial condition for the simulation. The fiber was modeled using the measured A_{eff} and dispersion. The simulated spectra (dot-dash lines in Fig. 4a and 4b) show good agreement with the measured spectra and confirm that the level of SPM in the HOM for the compressed pulses, in addition to the return to the input spectral shape after 12 m propagation, is explained well by the modal effective area,.

In summary, we have demonstrated propagation and compression of 14 nJ pulses to 61 kW peak powers using the LP_{07} mode of a higher-order-mode fiber with an effective area of 2100 μm^2. The fiber was coiled to a bend radius of 7 cm during the propagation experiments, although bend radii down to 4.5 cm have been demonstrated. The pulses were propagated through a total length of 12 m of fiber, and compressed after a 5 m length. The peak power of the pulses was sufficient to observe a small amount of SPM at the point of compression that was consistent with a nonlinear Schrödinger equation calculation. Such a fiber is ideal for applications in pulse delivery and compression for experiments in frequency metrology, bio-medical optics, and nonlinear optics.

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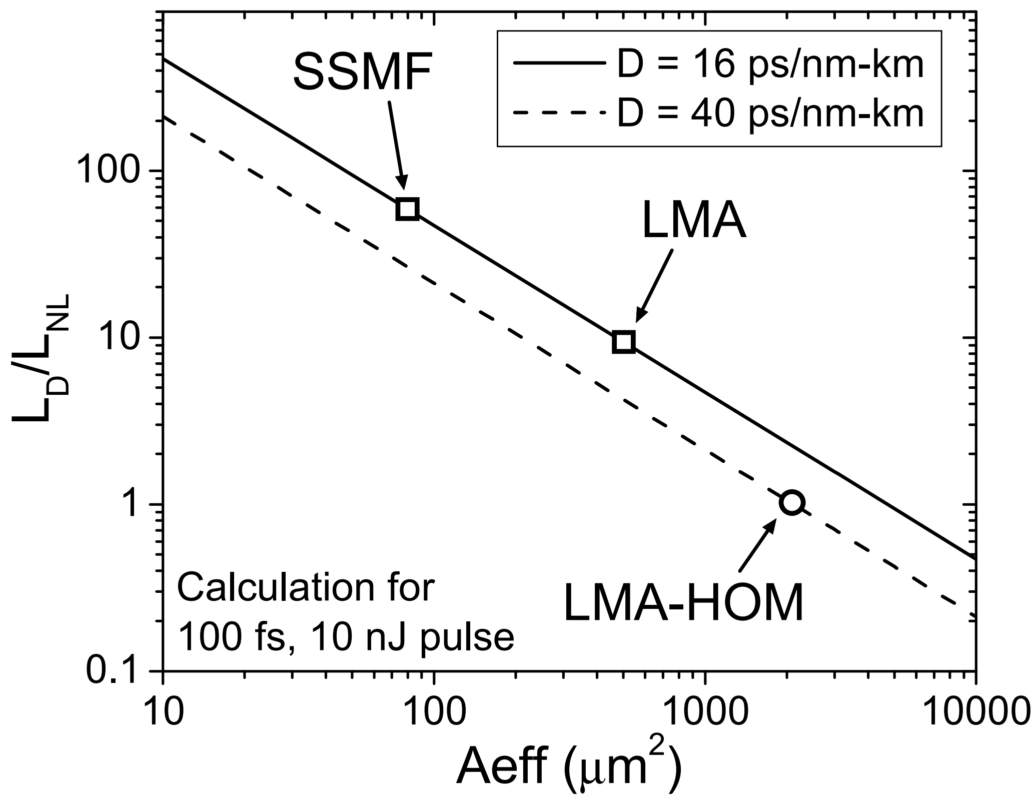

Figure 1 : Calculation of the ratio of the dispersion length to the nonlinear length as a function of effective area for a 100 fs, 10 nJ pulse. Points corresponding to standard single mode fiber, conventional large mode area fiber, and the LMA-HOM fiber are indicated.

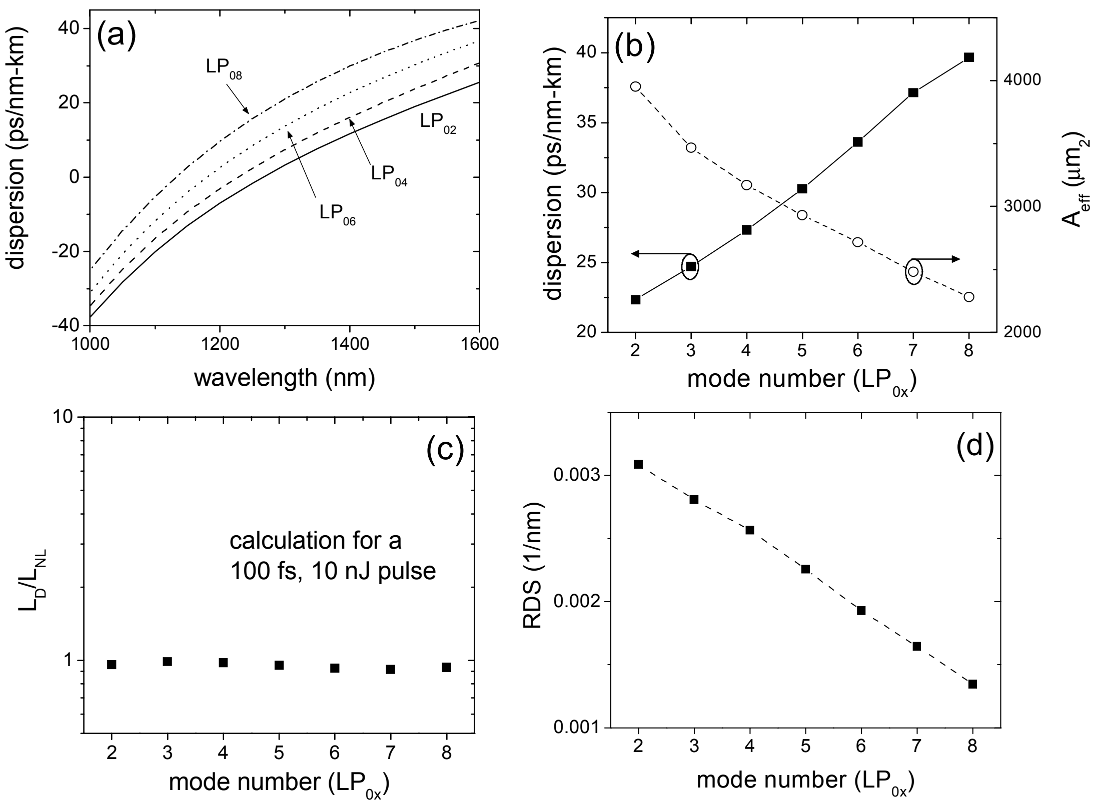

Figure 2 : Properties of the higher order modes. (a) Dispersion of several different higher-order-modes calculated from the measured index profile. (b) Dispersion and A_{eff} as a function of mode number at 1550 nm. (c) L_D/L_{NL} as a function of mode number for a 100 fs, 10 nJ pulse. (d) Relative Dispersion Slope (RDS) as a function of mode number at 1550 nm.

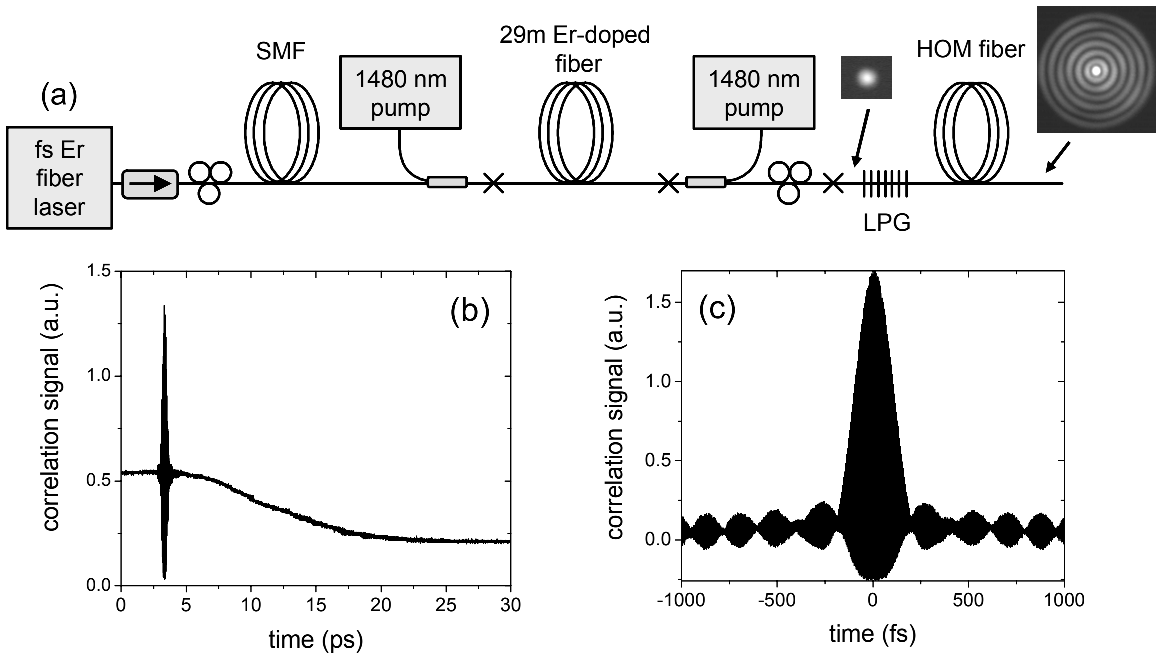

Figure 3 : (a) Schematic of the experimental setup. Mode images are shown for the fundamental and LP_{07} mode of the HOM fiber. (b) Measured correlation before launch into the LPG. (c) Compressed pulse after 5 m propagation in the HOM fiber.

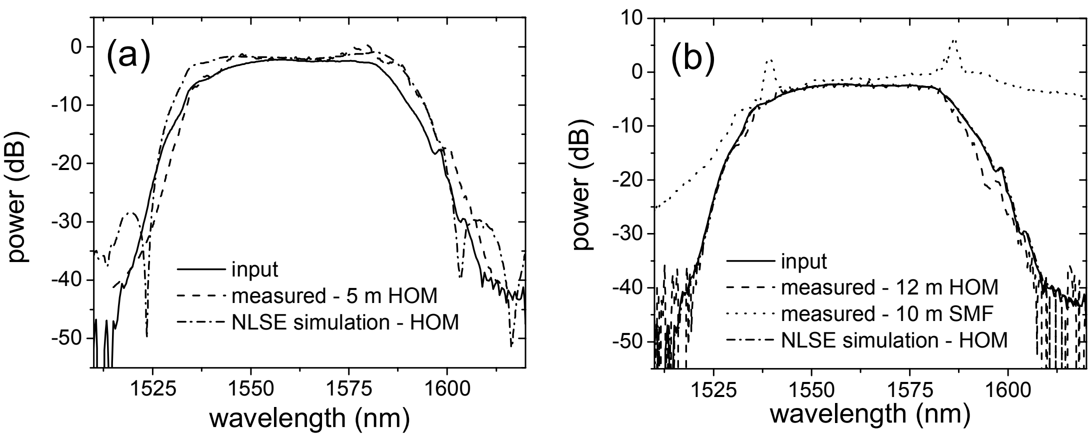

Figure 4 : Pulse spectra after (a) 5m and (b) 12m propagation in the HOM. Solid line: input reference spectra; dashed line: measured spectra; dot-dash line: calculated from an NLSE model. For comparison the spectrum measured after 10 m of SMF is shown in (b) as a dotted line.