Ultrashort pulse compression and delivery in a hollow-core photonic crystal fiber at 540 nm wavelength

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We have fabricated a bandgap-guiding hollow-core photonic crystal fiber (PCF) capable of transmitting and compressing ultrashort pulses in the green spectral region around 532 nm. When propagating subpicosecond pulses through 1 m of this fiber, we have observed soliton-effect temporal compression by up to a factor of 3 to around 100 fs. This reduces the wavelength at which soliton effects have been observed in hollow-core PCF by over 200 nm. We have used the pulses delivered at the output of the fiber to machine micrometer-scale features in copper. © 2010 Optical Society of America

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The transmission of high-power ultrashort pulses of light through meter-scale lengths of optical fiber is of interest for a range of materials-processing and imaging applications. However, in index-guiding structures, such as conventional fibers or solid-core photonic crystal fiber (PCF), the mode is confined predominantly to a volume filled with silica. Hence, high-intensity fields are subject to rapid nonlinear spectral broadening by the silica and the pulses are subsequently torn apart by dispersion. On the other hand, the nonlinearity of hollow-core PCF (HC-PCF), in which the optical mode mainly propagates in an air-filled core [1,2], is orders of magnitude less than that of index-guiding structures, allowing high-power pulses to propagate without catastrophic distortion [3]. Furthermore, in bandgap-guiding HC-PCF, a balance of the positive chirp typically imparted by nonlinearity-induced self-phase modulation with the anomalous dispersion present across most of the photonic bandgap allows the formation of temporal solitons. In this regime, if the fiber loss is sufficiently low, intense pulses can be transmitted almost without distortion [4–6].

Typically, the transmission window of state-of-the-art bandgap-guiding HC-PCF has a width that is less than 20% of its central wavelength; this central wavelength is proportional to the period of the cladding structure. To date, the minimum wavelength at which ultrashort pulse propagation and delivery in HC-PCF has been demonstrated has been limited to Ti:sapphire wavelengths around 800 nm by the difficulty of fabricating smaller photonic crystal structures suitable for guiding shorter wavelengths [5,7]. However, applications demand shorter wavelengths: in multiphoton imaging techniques, one can achieve greater resolution at shorter wavelengths, and, in materials-processing applications, it may be desirable to use short-wavelength femtosecond pulses to machine new materials while preserving the flexibility of fiber-based delivery.

The difficulty in fabricating HC-PCFs with smaller dimensions arises because of surface tension, which acts to close the holes in the photonic crystal structure during the fiber draw. As the hole diameter, and, therefore, the guided wavelength, is reduced, the pressure that must be exerted in order to keep a hole open increases rapidly. Hence surface tension exacerbates any accidental differences in hole size in the cladding when the preform is drawn to fiber. As the structure becomes smaller, it is ever more difficult to balance surface tension and pressure throughout the cladding, leading to deformation and loss of guidance in the fiber. This limits the minimum scale of the cladding structure that one can fabricate and, thus, the shortest wavelength that can be guided. Furthermore, in order to propagate and compress femtosecond pulses, the relative dispersion slope of the fiber (the ratio of third-order dispersion to group-velocity dispersion) must be low, requiring a highly periodic cladding structure [6,8].

Nevertheless, we have successfully fabricated a series of HC-PCFs that guide light with wavelengths between 500 and 700 nm. These fibers consist of a core (formed by removing seven capillaries from the center of the structure) with a diameter ranging from 4.4 to 5.9 μm, surrounded by a photonic crystal cladding with a hole spacing (pitch) of 1.4 to 2.1 μm [9]. The experiments reported in this Letter were conducted using a green-guiding HC-PCF with a pitch of 1.45 μm and a core diameter of 5.6 μm [10]. The peak transmission wavelength of this fiber was 557 nm (where the attenuation was 0.87 ± 0.03 dB/m), and the spectral width over which the loss was within 0.5 dB/m of its minimum value was 50 nm (532–583 nm). The fiber dispersion was measured in a white-light interferometer, and the zero-dispersion wavelength was found to occur at 532.5 nm. The attenuation and dispersion data are displayed in Fig. 1(a) along with a scanning electron micrograph of the cleaved fiber end face.

The apparatus is shown in Fig. 1(b). The green pump pulses for the following experiments were derived from a mode-locked, amplified fiber laser (Fianium Ltd.) emitting 10 W at 1064 nm with a repetition rate of 20 MHz. The pulses from the laser were highly chirped due to self-phase modulation in the amplification stage. Propagation through 15 m of 1064 nm guiding seven-cell HC-PCF

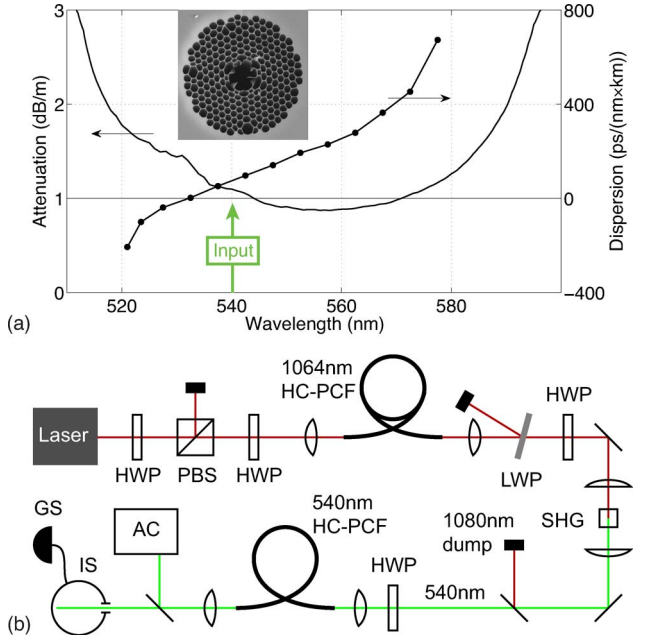

Fig. 1. (Color online) (a) Measured attenuation and dispersion of the green-guiding HC-PCF. Inset, electron micrograph of the cleaved end face. The damage around the hollow core was caused during the fiber end face preparation. (b) Apparatus. See text for details.

(1064 nm HC-PCF) removed this chirp by a combination of linear compression followed by soliton formation, as described in [11]. A fraction of each pulse traveled as a dispersive wave and was removed with a long-wave-pass filter (LWP, cutoff at ~1070 nm) after the 1064 nm HC-PCF. This yielded almost transform-limited pulses with a central wavelength of 1078 nm, a FWHM bandwidth of 5.4 nm, and a pulse energy of 100 nJ. These pulses were frequency doubled in a 3-mm-long noncritically phase-matched lithium triborate (LBO) crystal (SHG). The conversion efficiency into the green was over 50%, yielding 55 nJ pulses at 540 nm with a bandwidth of 2.7 nm and a FWHM duration of 300 fs—approximately twice the transform limit. The power of the 540 nm beam was varied up to the maximum of 1.1 W by rotating the polarization of the 1080 nm pump pulses with a half-wave plate (HWP) before the SHG. The polarization of the 540 nm beam remained unchanged, as it was defined by the axes of the LBO crystal. The residual 1080 nm light was removed with a dichroic mirror.

The 540 nm pulses were coupled into a 3.00 m length of green-guiding HC-PCF (540 nm HC-PCF). The slight ellipticity of the core of this fiber gave it a significant birefringence as well as a large difference in loss between light polarized on each axis at 540 nm. Therefore, a HWP was placed before the fiber to allow the input polarization to be orientated on the axis that gave the minimum loss. The total transmission of this polarization through 3.00 m of fiber (including coupling loss) was 33%, suggesting a coupling efficiency of approximately 65%. This remained constant throughout the experiment, as the input face of the fiber was not recleaved. The dispersion length of the pump pulses in the HC-PCF was approximately 3 m.

The average power and spectrum of the pulses emerging from the HC-PCF were recorded at average input powers ranging from 100 mW to 1 W in steps of 50 mW. The input coupling was checked and optimized at each power level. Spectra were recorded using an integrating sphere [IS in Fig. 1(b)] and an Ocean Optics HR4000 spectrometer (GS). The pulse duration was also measured at each power level by recording an intensity autocorrelation with an APE PulseCheck commercial autocorrelator (AC) and assuming a deconvolution factor of 1.5. The output end of the fiber was mounted on a rotation platform, allowing the input polarization to the autocorrelator to be set to the correct angle. The maximum fiber length (3.00 m) and minimum input power (100 mW) were set by this instrument as it was not possible to obtain a reliable signal with less than 30 mW reaching the autocorrelator. To avoid damaging the input face of the HC-PCF, the input power was limited to 1 W; hence, the same input cleave could be used to record a compete data set for different lengths of fiber by cleaving sections off the output end of the HC-PCF. The measure-

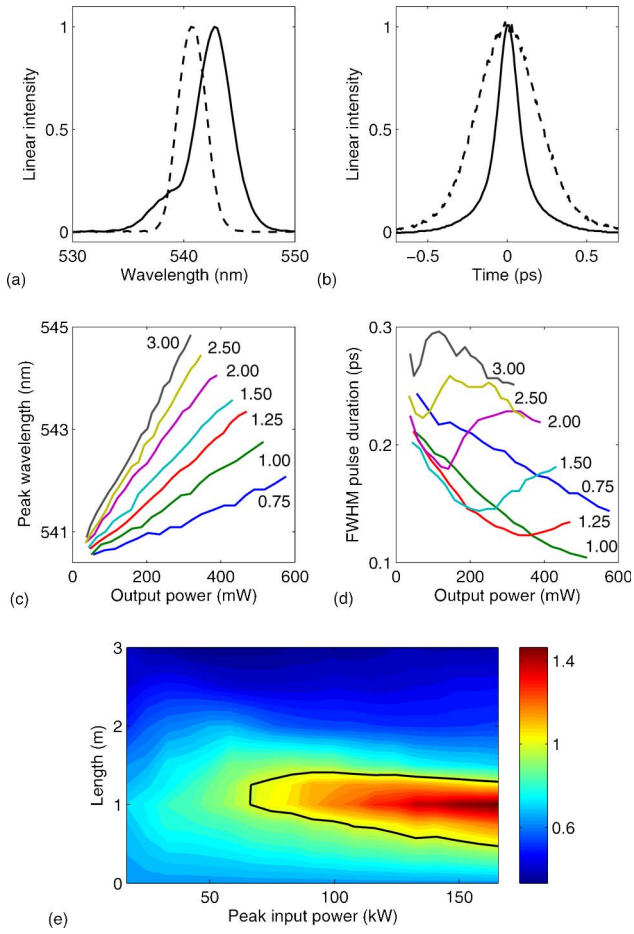

Fig. 2. (Color online) Examples of (a) spectra and (b) normalized autocorrelation traces for input (dashed) and output (solid) pulses with a 540 nm HC-PCF length of 1 m and input power of 1 W. (c) Peak wavelength and (d) FWHM pulse duration at the 540 nm HC-PCF output as functions of average output power for each fiber length, labeled in meters. (e) Peak output power (normalized to the peak input power) as a function of peak input power and HC-PCF length. Black contour is plotted at unity; power at zero length is scaled by the coupling efficiency.

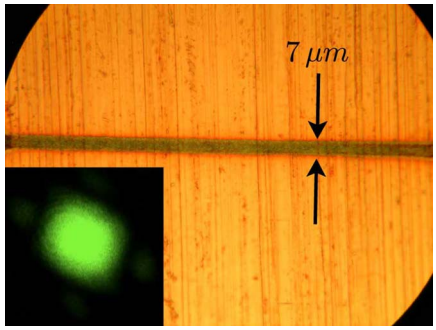

Fig. 3. (Color online) Optical micrograph of a copper surface after micromachining with 540 nm pulses transmitted through 1 m of HC-PCF. Inset, output spatial mode from the HC-PCF in the far field.

ments were performed for fiber lengths of 3.00, 2.50, 2.00, 1.50, 1.25, 1.00, and 0.75 m.

The results are shown in Fig. 2. Figure 2(c) demonstrates that the frequency shift due to intrapulse Raman scattering was approximately linearly dependent on input power and increased with fiber length. Note that, in this fiber, loss cannot be ignored and the dispersion is relatively high; hence, the simple rules of soliton self-frequency shift do not apply. Figure 2(d) shows the FWHM pulse duration after each length of HC-PCF as a function of output power. For all lengths, at low power the nonlinear length was greater than the longest fiber length and the pulse duration was predominantly reduced through linear compensation of the input pulse chirp by anomalous dispersion; the minimum output pulse duration for 100 mW input power was 202 fs, obtained with a fiber length of 1.50 m. However, for HC-PCF lengths greater than 1.50 m, the overall compression ratio was small at all power levels. As the power was increased, although the nonlinear length became shorter than the length of the fiber and soliton effects occurred due to increased self-phase modulation, the overall performance was compromised by the high total loss.

Shorter lengths of fiber showed much more favorable behavior. As well as transmitting more average power due to the lower total loss, the compression ratio achievable was much greater as the pulses reached the output of the fiber at the optimum point of their solitonic evolution. This is reflected in Fig. 2(e). For a length of 1 m and an input power of 1 W (corresponding to an output power of over 500 mW) the pulses attained their minimum duration of just over 100 fs as they left the fiber. At this point the time–bandwidth product was 0.4.

To demonstrate the potential of these pulses for materials processing, we have used them to inscribe a copper surface. The light leaving a 1 m length of HC-PCF was collimated and subsequently focused onto a flat sheet of copper using a 40× magnification aspheric lens. The copper was translated perpendicular to the beam to ablate a trench, shown in Fig. 3. The minimum feature size in this sample was around 7 μm, though the high quality of the output mode from the HC-PCF suggests that, with more careful focusing, one could obtain submicrometer feature sizes.

In conclusion, we have presented a HC-PCF suitable for high-power ultrashort pulse transmission at 540 nm. We have achieved compression by up to a factor of 3, delivering pulses of around 100 fs duration at the output of 1 m of HC-PCF and demonstrated the use of these pulses for machining copper.

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