Guiding of intense femtosecond pulses in preformed plasma channels

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Received June 18, 1997

We report guiding of sub-100-fs pulses at intensities up to 5×10^{15} W/cm^2 over a distance of 1 cm in a preformed plasma channel. The width of the guided pulse was shortened, which we attribute to ionization-induced refraction at the channel entrance. A pulse energy throughput of 30% in the lowest-order was measured.

The development of intense femtosecond laser technology[1] has stimulated interest in compact plasma particle accelerators, x-ray lasers, and other devices based on the interaction between a high-intensity laser pulse and a plasma.[2] The effectiveness of such devices depends on the laser–plasma interaction length, which is often limited by the diffractive divergence of the laser. An attractive way to overcome this limitation is to use preformed plasma waveguides or channels.[3] These channels allow controllable, diffraction-free propagation of a laser pulse in plasma.

In this Letter we present the results of experiments on coupling and guiding of an intense sub-100-fs pulse in a preformed plasma channel. Our experimental setup used two synchronized 10-Hz laser systems, one for channel generation and one for pulse injection.

The plasma channel was produced through hydrodynamic relaxation of a hot laser-produced spark in an ambient gas. The time scales for the hydrodynamic evolution of the plasma channel produced in ~100-Torr background gases are in the range 0.1–1 ns, where the fastest time of ~0.1 ns is the growth time of the shock wave that forms the channel boundary and the longer time of ~1 ns is the scale of overall radial expansion.[4] These time scales suggest that synchronization of the channel-generation laser (a mode-locked 100-ps Nd:YAG system) and the pulse-injection laser (sub-100-fs Ti:sapphire chirped-pulse-amplification system) to an accuracy of ~100 ps is sufficient. Synchronization was achieved with a feedback loop that tuned the cavity length of the Ti:sapphire oscillator by a piezo-driven mirror, matching the phase of the oscillator's optical pulse train with the phase of the reference rf signal from the mode locker of the Nd:YAG oscillator. We verified the synchronization by sum-frequency mixing of the output beams of the Nd:YAG and Ti:sapphire oscillators in a 1-mm KDP crystal. The FWHM of the cross-correlation curve (Fig. 1) is 109 ps, indicating that the residual jitter is less than the Nd:YAG pulse width.

For the experiments reported here a pulse (1.064 μm, 100 ps, up to 500 mJ) from the Nd:YAG regenerative–power-amplifier system produced a 1-cm-long plasma channel at the focus of a 35° base angle axicon, with intensities at the focus of $\sim 5 \times 10^{13}$ W/cm^2. A pulse (0.78 μm, 90 fs, up to 10 mJ) from the Ti:sapphire system was focused into the plasma channel at an adjustable delay with $f/18$ optics. We kept the energy of the Ti:sapphire laser pulse at ~10 mJ to reduce nonlinear phase distortions owing to self-phase modulation in the windows of the experimental chamber and the focusing optics. We adjusted the timing between the two pulses by passing the rf reference signal from the Nd:YAG mode locker through a variable transmission line delay. A lens was set at the output of the channel for recollimation of the Ti:sapphire beam. This lens was followed by a beam splitter, allowing simultaneous frequency-resolved optical gating (FROG) measurements and imaging of the Ti:sapphire pulses emerging from the channel. We used the image at the channel exit to monitor coupling efficiency during the experiment by integrating the image intensity for the guided mode and dividing it by the integral for the vacuum beam profile.

For the case of a 1-cm-long channel formed in a mixture of 300-Torr He and 50-Torr N$_2$O and a maximum injected pulse energy of 6 mJ, coupling efficiency into the lowest-order mode was measured to be 30%, and the near-Gaussian mode size measured at the channel exit was 25 μm FWHM, resulting in a guided intensity of 5×10^{15} W/cm^2. The N$_2$O component aids waveguide generation by field ionizing early in the Nd:YAG pulse at $\sim 10^{13}$ W/cm^2 and providing seed electrons

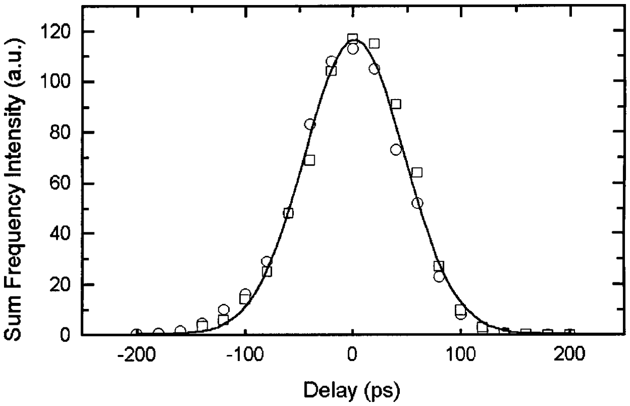

Fig. 1. Cross-correlation function of the Nd:YAG and Ti:sapphire oscillators. The width of the curve is 109 ps (FWHM).

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for the uniform avalanche breakdown of He. The injection of the femtosecond pulse into the channel was accompanied by rapid field ionization of neutral gas in advance of the entrance region, as evidenced by the lengthening of the spark at the channel entrance. At delays of less than 2–3 ns the characteristic beam pattern at the channel exit consisted of a central guided mode surrounded by blueshifted light outside the channel, indicating time-dependent ionization-induced defocusing at the channel entrance. At delays longer than ~5 ns the blueshifted component appeared in the spectrum of the now spatially multimode guided beam, suggesting trapping of defocused light. Without the channel the output beam consisted mainly of the blueshifted scattered light. Spatially dependent blueshifting attributed to laser-induced ionization and defocusing was measured previously in short-pulse–gas interaction experiments.[5]

To study the effect of injection and guiding on the envelope and phase of the intense 90-fs FWHM pulse, we used a FROG diagnostic in the polarization-gating configuration.[6] A sliding mirror and an aperture enabled us to sample different portions of the beam with the FROG. The FROG trace and its retrieved pulse phase and amplitude for the evacuated chamber are shown in Fig. 2(a). The phase indicates a small amount of self-phase modulation owing to the chamber windows and focusing optics, and the pulse is ~100 fs FWHM. Figure 2(b) shows the output of the plasma channel for 2-ns delay, and it can be seen that the pulse is shortened to ~70 fs; the negative-going phase shift indicates ionization during the pulse. FROG measurements of the portion of the beam outside the guided mode give complex traces with slightly longer pulse duration (≥100 fs) than that of the input pulse.

To investigate the origin of the pulse shortening and phase shift shown in Fig. 2(b), we performed experiments with a gas backfill and an ~50-Torr He gas jet of ~1-mm width. For the gas backfill case, in which the interaction region extends before and after the focus, the duration of the on-axis trace is typically shortened by 30%, and the off-axis traces are complex, with envelopes slightly longer than those of the input pulse. Use of the gas jet limited the interaction length for ionization of neutrals to a size similar to that of the region in front of the channel entrance. Figure 2(c) is a FROG trace for the evacuated chamber, for a slightly larger beam diameter than in Fig. 2(a). As in Fig. 2(a), the pulse is broadened (to ~105 fs), with evidence of a small amount of phase modulation in the windows and focusing optics. The on-axis FROG trace from the gas jet shows pulse shortening [Fig. 2(d)], accompanied by a negative-going phase shift, implying ionization during the interaction. The amount of phase shift is similar to that in Fig. 2(b), suggesting that little ionization was induced in the channel by the guided pulse. Off-axis traces are complicated in envelope and phase and again show overall pulse lengthening.

We performed a calculation of short-pulse (6 mJ; 100 fs; spot size, 10 μm) propagation through a 1.5-mm FWHM helium gas jet to understand further the shortening. The basic model is described in Ref. 7 and includes $\chi^{(3)}$ effects and field ionization. The vacuum laser focus was located 0.5 mm into the jet. Shown in Fig. 3 is the on-axis laser intensity envelope in the far field for a range of gas pressures. As can be seen, at lower pressures, the on-axis portion of the pulse is shortened, whereas at higher pressure much of the energy in the pulse is scattered off axis. Detailed analysis of the time and space dependence of the pulse shows that the shortening is due to refraction of the head of the pulse by plasma created by field ionization of neutral atoms and singly charged He ions, which leads to an apparent shortening of the on-axis portion of the beam, whereas the off-axis portions of the beam are blueshifted and not shortened in general.

The coupling of an intense femtosecond pulse into a plasma waveguide produced in a gas backfill (380/20 Torr Ar/N_2O) and the ionization generated during this process are strikingly illustrated by Fig. 4. Here a folded wave-front interferogram[8] of the tapered channel end (of a 1-cm channel) with the Ti:sapphire pulse entering from right to left is shown. The higher atomic number fill gas at higher pressure was chosen to allow better visualization of the ionization track left by the femtosecond pulse.

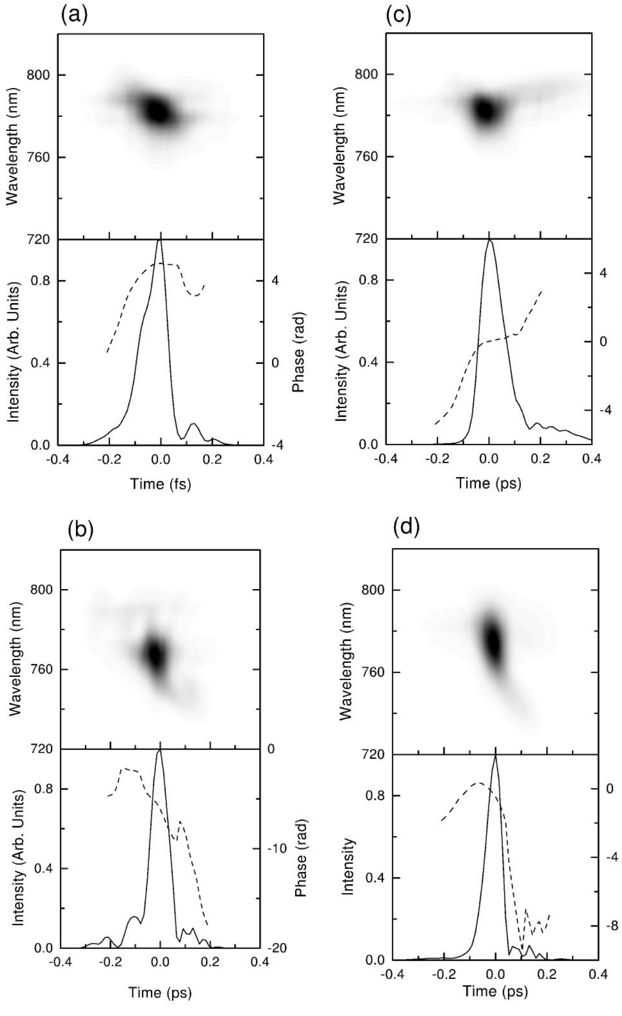

Fig. 2. FROG traces and retrieved intensity and phase for (a) input of the plasma channel (evacuated chamber), (b) output of the plasma channel, (c) input of the gas jet (evacuated chamber), and (d) on-axis output of the gas jet.

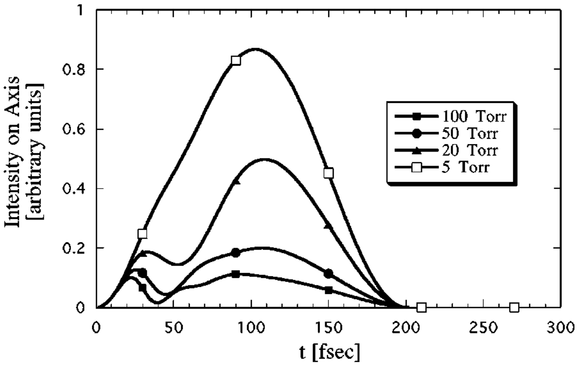

Fig. 3. Far-field on-axis laser intensity versus time for a range of gas jet pressures.

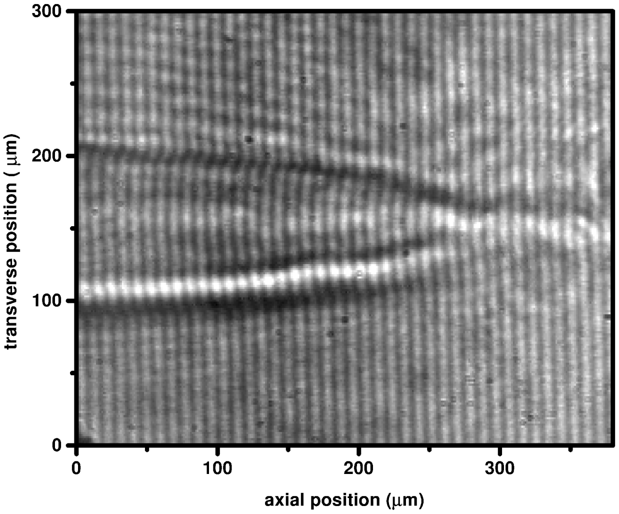

Fig. 4. Interferometric image showing the effect on electron density of the coupling of a 100-fs, 10-mJ Ti:sapphire pulse focused at $f/12$ (vacuum intensity, $\sim 10^{17}$ W/cm^2) into the end of a channel formed in a 20/380-Torr N_2O/Ar gas mixture. The delay between the channel-forming pulse and the injected Ti:sapphire pulse is 4 ns, and the interferometry probe delay with respect to the Ti:sapphire pulse is 700 ps. The Ti:sapphire pulse path can be followed from right to left as the bright region resulting from refraction of the probe owing to excess ionization produced by the guided pulse.

In conclusion, we have demonstrated guiding of sub-100-fs laser pulses at an intensity of 5×10^{15} W/cm^2 over a distance of ~1 cm in a preformed plasma channel. A 30% energy throughput in the lowest-order mode was achieved. Pulse shortening was observed for the guided beam and was attributed to ionization-induced refraction of the injected beam before it entered the plasma channel.

We acknowledge the support of the National Science Foundation (PHY-9515509) and the U.S. Air Force Office of Scientific Research (AFOSR-F49620-96-10095).

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