Programmably structured plasma waveguide for development of table-top photon and particle sources

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Programmable fabrication of longitudinal spatial structures in an optically preformed plasma waveguide in a gas jet was achieved, by using laser machining with a liquid-crystal spatial light modulator as the pattern mask. Fabrication of periodic structures with a minimal period of 200 μm and density-ramp structures with a minimal slope length of 100 μm was attained. The technique is useful for the optimization of various laser-plasma-based photon and particle sources.

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I. INTRODUCTION

Extending laser-plasma interaction length with an extended plasma waveguide is crucial to many applications, such as laser-driven electron accelerator,\textsuperscript{1-3} laser-driven betatron-radiation x-ray source,\textsuperscript{4,5} and infrared-pulse generation.\textsuperscript{6-8} For further improvement in the quality of these photon and particle sources, the capability to tailor the longitudinal density profile of plasma waveguide is essential. For instances, it has been proposed that (1) a longitudinal section of density depression can be used to increase the transverse oscillation amplitude and the energy of the electron bunch in channel betatron oscillation and thus significantly increases the flux and photon energy of the betatron radiation,\textsuperscript{9} (2) a longitudinal density down-ramp can be used to induce self-injection of an electron bunch and thus generate a stable, high-charge-number, low-energy-spread electron beam,\textsuperscript{10-13} and (3) a periodically modulated plasma channel can fulfill phase-matching condition and thus lead to efficient production of infrared pulses.\textsuperscript{6,7} Several techniques were demonstrated for making a structured plasma waveguide in a gas jet.\textsuperscript{14,15} However, change of structure in these schemes requires replacement of the diffractive optics or the wire obstructions of the gas jet, rendering optimization of applications very difficult. In this paper, we report demonstration of production of a plasma waveguide with programmable longitudinal density distribution by laser machining.\textsuperscript{16,17} The plasma waveguide was generated by using the axicon ignitor-heater scheme\textsuperscript{18} and modified with an additional transverse heater pulse passing through a liquid-crystal spatial light modulator (LCSLM) to achieve programmable control of longitudinal structure. All the above-mentioned structured plasma waveguides can be produced in this way, with a minimal slope length of 100 μm and a minimal period of 200 μm.

II. EXPERIMENTAL METHOD

In this experiment, the axicon ignitor-heater scheme\textsuperscript{18} was used for producing a plasma waveguide. In this scheme, a short intense ignitor pulse ionizes the neutral gas by multiphoton ionization to provide seed electrons. After several hundred picoseconds, a succeeding long, high-energy heater pulse heats up the plasma efficiently via inverse bremsstrahlung heating and further ionizes the gas by electron collision. Afterwards, the dense hot line-shaped plasma expands outwards and, after a delay of a few nanoseconds, the on-axis plasma
electron density is greatly reduced while the plasma electron density at the encircling outer region builds up as a result of collisional ionization by the outgoing electrons and ions. Therefore, a cylindrically symmetric plasma with an on-axis electron density lower than that at the radially outer region is produced. The main concept of this experiment is to add another laser pulse incident from the direction perpendicular to the line focus of the axicon heater pulse such that the heater fluence distribution along the axis of the plasma waveguide can be modulated, resulting in longitudinal variation of waveguide parameters.

The experiments were performed at National Central University, Taiwan, using a 100-TW-class Ti:sapphire laser system with 10-Hz pulse repetition rate. Figure 1 shows the experimental setup. Five laser beams from this system were used for this experiment. The first laser beam, with $p$-polarized (horizontally polarized), 80-mJ-energy, 35-fs-duration laser pulses, was used as the axicon ignitor beam. The second laser beam, with $s$-polarized (vertically polarized), 380-mJ-energy, 210-ps-duration laser pulses, served as the axicon heater beam. After being combined by a thin-film polarizer, the axicon ignitor and axicon heater pulses propagated collinearly and were then focused by an axicon lens of 30° base angle to a line focus of $\sim$2-cm length in full width at half maximum (FWHM). To increase the efficiency of plasma waveguide fabrication, a convex lens of 100-cm focal length with a hole of 1.5-cm diameter at the center was installed in front of the axicon to concentrate the laser energy in a length of approximately 1 cm. The temporal separation between the axicon ignitor pulse and the axicon heater pulse was 230 ps. With these two beams, longitudinally uniform plasma waveguide can be fabricated. The third laser beam, with 100-mJ-energy, 35-fs-duration laser pulses, was used as the longitudinal probe pulse to examine the guiding capability and quality of the plasma waveguide. It was focused with an off-axis parabolic mirror of 30-cm focal length onto the entrance of the plasma waveguide. The diameter of the focal spot was 10 $\mu$m FWHM. The propagation path of the longitudinal probe pulse in the gas jet overlapped with the line focus of the axicon, and a hole of 5-mm diameter at the center of the axicon allowed its passage. The delay of the longitudinal probe pulse with respect to the axicon heater pulse was 2.0 ns.

The fourth laser beam, with 210-ps-duration pulses, served as the transverse heater pulse for tailoring the longitudinal profile of the plasma waveguide. It propagated in the direction perpendicular to the axis of the plasma waveguide and was imaged horizontally from the LCSLM onto the axis of the plasma waveguide by a cylindrical lens of 20-cm focal length.
with a demagnification factor of 8. It was also focused vertically by a cylindrical lens of 30-cm focal length to produce a linewidth of 20 μm FWHM. The LCSLM (Jenoptik SLM-S320) consisted of a horizontal array of 320 strips of 10-μm-thick nematic liquid crystal layer, each of which was 97 μm in width with 3-μm dead boundary and 13 mm in height. The spatial amplitude modulation of the transverse heater pulse was achieved by the combination of the LCSLM with 45° liquid-crystal orientation and a thin-film polarizer. Within the aperture of the LCSLM, the maximum transmission was 87% and the minimum transmission was 0.2% after the thin-film polarizer. Since the diameter of the transverse heater pulse was 45 mm but the aperture of the LCSLM was 31.9 mm in width and 13 mm in height, the overall maximum energy throughput of the spatial amplitude modulator was 35%. The transverse heater pulse was \( p \)-polarized on target. An imaging system was used to measure the intensity distribution of the transverse heater on the vertical plane containing the axis of the plasma waveguide. The hydrogen gas jet was produced from a pulsed valve with a supersonic slit nozzle. The density profile had a 1.5-mm flat-top region with 200-μm boundaries.

The plasma-density distribution in the gas jet was measured with probing interferometry. The fifth laser beam, obtained from the leakage of the longitudinal probe pulse at a dielectric mirror, was split into two beams to serve as the probe pulse and the reference pulse of interferometry, respectively. The probe pulse of interferometry passed through the gas jet at an angle of 12.7° with respect to the transverse axis, with its timing set at 40 ps after the passage of the longitudinal probe pulse in the plasma waveguide. Although the probe pulse did not pass through the gas jet at the angle exactly perpendicular to the waveguide axis, the error of measurement of longitudinal plasma-density slope length is estimated to be less than 10% for all the data shown and therefore negligible for our purpose. A relayed-imaging system consisting of two wedges, a pair of lenses, an objective lens, and a 16-bit charge-coupled device (CCD) camera was used to measure the spatial profile of the longitudinal probe pulse at the exit of the plasma waveguide (the end of the gas jet).

### III. EXPERIMENTAL RESULTS

Figure 2(a) shows the preprocessed interferograms and the electron-density distributions of the plasma waveguide modified with the transverse heater pulse of delays of 0 ns and 0.2 ns with respect to the axicon heater pulse respectively and that without modification.
using the transverse heater pulse. The intensity pattern of the transverse heater pulse on
the vertical plane containing the waveguide axis for this case is shown in the topmost figure,
in which the central region of 500-μm length along the axis of the plasma waveguide is irra-
diated. Throughout this paper, the scales of interferograms, electron-density distributions,
and intensity patterns of the transverse heater pulse are all the same in each figure, and the
scale of the horizontal axis is the same as that of the vertical axis indicated in each figure.
The full on-target energy (hereafter refers to the total energy reaching the gas jet when all
the pixels of the LCSLM are set to be on) of the transverse heater pulse is 130 mJ. The atom
density of the hydrogen gas jet is 4.3×10^{19} \text{ cm}^{-3}. The radial electron-density distributions
averaged over the irradiated region for these cases are shown in Fig. 2(b). A fast Fourier
transform (FFT) based procedure\textsuperscript{19} was used to retrieve the electron-density distribution
from an interferogram. First, the original interferogram was pre-processed by (1) tracing
(curve-fitting) the fringes across the transverse plasma-gas boundaries in order to eliminate
discontinuities in fringes which may occur at the boundaries as a result of large refraction
of the probe beam and (2) applying spatial frequency filtering to remove the slowly varying
intensity modulations resulting from non-uniformity of the laser beam profile and refraction
in the plasma. Next, the phase shift was extracted with 2-dimensional FFT from the prepro-
cessed interferogram. A numerical inverse Abel transform was then applied to determine the
3-dimensional refractive-index distribution, under the assumption that the plasma waveg-
uide is of cylindrical symmetry. Using the relationship between plasma electron density and
refraction index, the plasma electron-density distribution was thus obtained. Lastly, for
each transverse cross section a parabolic fit, which was a reasonable assumption according
to Ref. 20, was applied to the central portion to eliminate the large noises associated with
the inverse Abel transform. The same procedure was applied to all the interferograms shown
in this paper. The image shown on the right-hand side of each interferogram in the figure
and the succeeding figures is the spatial profile of the longitudinal probe pulse at the exit of
the plasma waveguide plotted with the same intensity scale, in which a single small round
spot is indicative of good guiding.

Note that, for the transverse-heater delays of 0 ns and 0.2 ns with respect to the axicon
heater pulse (used for all the data presented), the vertical width of the transverse heater
pulse is significantly larger than that of the plasma filament produced by the axicon ignitor
and heater pulses at that stage (<10 μm). In addition, the Rayleigh length of the transverse
heater pulse, which determines the transverse horizontal width of the intensity distribution of
the transverse heater pulse, is much larger than the horizontal width of the plasma filament. Therefore, it is a good approximation to consider the intensity distribution of the transverse heater pulse as uniform across the transverse cross section of the plasma filament at that moment. As a result, the heating profile of the plasma filament by the transverse heater pulse is just determined by the transverse density profile of the existing plasma filament, which is of cylindrical symmetry due to the symmetry of both the axicon and the axicon ignitor and heater beams. Therefore, the succeeding evolution of the region of the plasma waveguide irradiated by the transverse heater should be also of cylindrical symmetry. This is verified by the observation that the spatial profile of the longitudinal probe pulse at the exit of the plasma waveguide, when the irradiated region is extended to the end of the waveguide, shows a single round spot, indicating that the region irradiated by the transverse heater pulse is roughly of cylindrical symmetry. The application of inverse Abel transform to the region modified by the transverse heater pulse with these short delays is thus justified.

As can be seen, there is a significant modification of the transverse electron-density profile of the plasma waveguide formed by the axicon ignitor and heater pulses when the transverse heater pulse is applied. With the transverse heater pulse on the on-axis density turns lower and the density barrier becomes larger. This is expected, since the total heater fluence contributed from both the axicon heater pulse and the transverse heater pulse are higher in the region irradiated by the transverse heater pulse. A higher heater fluence should lead to a hotter plasma filament and thus faster expansion of the on-axis plasma and more intensive collisional ionization at the radially outer region. Furthermore, at a transverse-heater delay of 0.2 ns the on-axis density is lower and the barrier is higher than that at a transverse-heater delay of 0 ns. This can be ascribed to that if the transverse heater pulse arrives after the end of the axicon heater pulse, the density of the plasma filament is higher (as a result of completion of the cascade of inverse bremsstrahlung heating and collisional ionization during the axicon heater pulse) and thus the heating produced by the transverse heater pulse becomes more effective. When the delay of the transverse heater pulse with respect to the axicon heater pulse is too large such that the vertical width of the plasma filament produced by the axicon ignitor and heater pulses is larger than the vertical width of the transverse heater pulse, it can be expected that the irradiated section of the plasma waveguide should be of elliptical transverse cross section. This is because in
this case the transverse distribution of heating by the transverse heater pulse in the vertical
direction is determined by the vertical width of the transverse heater pulse while that in
the horizontal direction is determined by the diameter of the plasma filament produced
by the axicon pulses. This inference was verified by the observation that the transverse
profile of the guided longitudinal probe pulse at the end of the gas jet was indeed elliptical
when the region irradiated was shifted to the exit end of the plasma waveguide and the
transverse-heater delay was increased significantly beyond its optimal value. Based on these
observations, it is concluded that the optimal delay of the transverse heater pulse should
be about 0.2 ns, i.e., arriving right after the end of the axicon heater pulse, in order to
have the highest energy-utilization efficiency of the transverse heater beam while keeping
the modified region of the plasma waveguide as cylindrically symmetric as the unmodified
region.

In terms of energy-guiding efficiency, all the modified plasma waveguides of various struc-
tures shown in this paper were found to have guiding efficiencies as good as that of the uni-
form, unmodified plasma waveguide. The transmission efficiencies were all about 55% with
a fluctuation of 15% (standard deviation/average). We believe beam-pointing fluctuation
of the longitudinal probe pulse is the major source of fluctuation. This indicates that the
modulations of the plasma waveguide produced in this way do not result in disruption of
the guided laser pulse, as is confirmed by the observation with the interferograms that there
is no outburst cone of plasma originating from the boundaries between irradiated regions
and non-irradiated regions. In contrast, in Ref. 14 a low throughput of 10% is reported and
ascribed to leakage out of the waveguide due to modulations.

Figure 3(a) shows the radial electron-density distributions averaged over the irradiated
region with the same intensity pattern as that in Fig. 2 for various on-target energies of
the transverse heater pulse. The delay of the transverse heater pulse with respect to the
axicon heater pulse is 0.2 ns. The atom density of the hydrogen gas jet is $4.3 \times 10^{19}$ cm$^{-3}$.
Figure 3(b) shows the on-axis electron density of the irradiated region as a function of full
on-target energy of the transverse heater pulse. The on-axis density is lower and the barrier
is higher for a larger transverse-heater energy. This verifies that the transverse heater plays
the same role as the axicon heater. As the energy of the transverse heater is increased,
the on-axis plasma becomes hotter and thus expands faster, resulting in a lower on-axis
density after the fixed time delay. The maximal full on-target transverse-heater energy in
this experiment was limited by the damage threshold and the clear aperture of the LCSLM. For some applications such as a laser-wakefield electron accelerator, a lower on-axis electron density is preferred, in order to increase the dephasing length and thus the maximal energy of the accelerated electron bunch. Therefore, a higher on-target transverse-heater energy may be needed. This limit can be overcome by replacing the LCSLM with a hard mask to sustain a much higher energy fluence, once the optimal intensity pattern of the transverse heater has been found with the LCSLM for that application. Alternatively, it can be resolved by simply using an LCSLM of larger clear aperture, if available.

Figure 4(a) shows the preprocessed interferograms and the electron-density distributions of the plasma waveguide modified with the transverse heater pulse of various intensity up-ramp lengths. The intensities of the lower plateau and upper plateau of the up-ramp are at the minimum and maximum transmissions of the LCSLM, respectively. The delay of the transverse heater pulse with respect to the axicon heater pulse is 0.2 ns, and the full on-target energy is 130 mJ. The atom density of the hydrogen gas jet is $7.7 \times 10^{19} \text{ cm}^{-3}$. Figure 4(b) shows the longitudinal on-axis electron-density distributions for various intensity up-ramp lengths of the transverse heater pulse. The results show that a longitudinal plasma-density down-ramp can be produced in the plasma waveguide, with its ramp length determined by the ramp length of the transverse-heater intensity. In the same way, a plasma-density up-ramp can be produced with an intensity down-ramp of the transverse heater. The minimal plasma-density ramp length in this experiment was about 100 \( \mu \text{m} \), at the condition of the sharpest intensity ramp (~20 \( \mu \text{m} \)). This lower limit is due to the longitudinal hydrodynamic expansion of the plasma heated additionally by the transverse heater toward the adjacent non-irradiated regions. The density bumps in the curves of Fig. 4 are an indication of this process, which did not disrupt the guiding of the longitudinal probe pulse.

Figure 5 shows the preprocessed interferograms and the electron-density distributions of the plasma waveguide modified with the transverse heater pulse of various intensity modulation periods. The delay of the transverse heater pulse with respect to the axicon heater pulse is 0.2 ns, and the full on-target energy is 130 mJ. The atom density of the hydrogen gas jet is $7.7 \times 10^{19} \text{ cm}^{-3}$. As shown, plasma waveguides periodically modulated in both on-axis density and diameter are produced, with the same modulation periods as that of the transverse-heater intensity profile. The minimal modulation period demonstrated was 200 \( \mu \text{m} \). This is about the same as the best of the results with Abel-inverted electron-density
distributions shown in Refs. 14 and 15. A smaller modulation period should be attainable at the trade-off of a reduced modulation depth, again due to the hydrodynamic expansion in the longitudinal direction.

IV. CONCLUSION

In summary, programmable fabrication of structured plasma waveguides in a gas jet was achieved by adding a transverse heater beam shaped with an LCSLM into the axicon ignitor-heater scheme for plasma-waveguide production. The programmable control via LCSLM not only greatly increases versatility and speed of optimization in plasma-structure fabrication, but also enables direct adaptive feedback optimization of the characteristics of the photon or particle beams for each specific downstream application.

REFERENCES

FIG. 1. Experimental setup. The acronyms represent LP: longitudinal probe pulse; AI: axicon ignitor pulse; AH: axicon heater pulse; TH: transverse heater pulse; TP: transverse probe pulse; R: reference pulse; OAP: off-axis parabolic mirror; CCD: charge-coupled device; CL: cylindrical lens. Diagnostic systems include (1) transverse-heater imaging system, (2) Mach-Zehnder interferometer, and (3) relayed-imaging system.
FIG. 2. (a) Preprocessed interferograms and electron-density distributions of the plasma waveguide modified with the transverse heater pulse of delays of 0 ns, (1), and 0.2 ns, (2), with respect to the axicon heater pulse and that without modification using the transverse heater pulse, (3). The full on-target energy of the transverse heater pulse is 130 mJ. The atom density of the hydrogen gas jet is $4.3 \times 10^{19}$ cm$^{-3}$. The topmost image shows the intensity pattern of the transverse heater pulse on the vertical plane containing the waveguide axis. The beam profile of the longitudinal probe pulse at the exit of the plasma waveguide for each case is shown to the right of the interferogram. (b) Radial electron-density distributions averaged over the irradiated region for various transverse-heater delays.
FIG. 3. (a) Radial electron-density distributions averaged over the irradiated region with the same intensity pattern as that in Fig. 2 for various on-target energies of the transverse heater pulse. (b) On-axis electron density of the irradiated region as a function of full on-target energy of the transverse heater pulse. The delay of the transverse heater pulse with respect to the axicon heater pulse is 0.2 ns. The atom density of the hydrogen gas jet is $4.3 \times 10^{19}$ cm$^{-3}$. 
FIG. 4. (a) Preprocessed interferograms and retrieved electron density distributions of the plasma waveguide modified with the transverse heater pulse of various intensity up-ramp lengths: (1) 20 μm, (2) 150 μm, (3) 230 μm. The intensity pattern for each case is shown on top of the interferogram. (b) Longitudinal on-axis electron-density distributions for various intensity up-ramp lengths of the transverse heater pulse. The delay of the transverse heater pulse with respect to the axicon heater pulse is 0.2 ns, and the full on-target energy is 130 mJ. The atom density of the hydrogen gas jet is $7.7 \times 10^{19}$ cm$^{-3}$. 

FIG. 5. Preprocessed interferograms and electron-density distributions of the plasma waveguide modified with the transverse-heater pulse of various intensity modulation periods: (1) 200 μm, (2) 300 μm, (3) 400 μm. The intensity pattern for each case is shown on top of the interferogram. The delay of the transverse heater pulse with respect to the axicon heater pulse is 0.2 ns, and the full on-target energy is 130 mJ. The atom density of the hydrogen gas jet is $7.7 \times 10^{19}$ cm$^{-3}$. 