Periodic index-modulated plasma waveguide

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Abstract: We demonstrate a wire-obstructed cluster flow technique for making periodically modulated plasma waveguides in hydrogen, nitrogen, and argon with sharp, stable voids as short as 50 μm with a period as small as 200 μm. These gaps persist as the plasma expands for the full lifetime of the waveguide. We demonstrate guided propagation at intensities up to 2×10^{17} W/cm^2, limited by our laser energy currently available. This technique is useful for quasi-phase matching applications where index-modulated guides are superior to diameter modulated guides.

OCIS codes: (350.5400) Plasmas; (350.3950) Mirco-optics.

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1. Introduction

Several techniques have been demonstrated for plasma waveguiding of high intensity laser pulses [1, 2]. The goal is for the guided pump pulse to efficiently couple its energy into, for example, acceleration of relativistic electrons [3, 4] or generation of coherent electromagnetic radiation at selected frequencies [5, 6] If the guiding interaction length is extended to many times the vacuum Rayleigh range, phase matching of the pump pulse to the energy coupling process becomes a dominant limitation. Perfect phase matching is only possible if the negative contribution to the index of refraction from plasma (phase velocity > c) is counterbalanced by a positive contribution. This could be accomplished using the neutral atoms in a partially ionized plasma or polarizability transients due to exploding laser-heated clusters [7], but is difficult at large intensities where highly ionized plasmas are unavoidable.

In such situations, quasi-phase matching is necessary. Recent work on quasi-phase matching techniques for high intensity laser pulses include the generation of axially modulated plasma guiding structures in cluster jets [8], and counterpropagating pulse train interference [9].

In this paper, we demonstrate a new technique for making axially modulated plasma waveguides. By modifying the flow of our cluster jet with a periodically spaced array of wires at the nozzle exit, we were able to impose gaps at regular intervals, and upon heating with a Bessel beam pulse, make plasma waveguides with sharp, stable voids as short as 50 μm with a period as small as 200 μm. The wires act as periodic obstructions to the flow of clusters, and the breaks in the channel are formed in their shadows. These breaks persist remarkably well for many nanoseconds of plasma expansion, well beyond the radial size for which they confine tight lowest order modes. This technique is especially useful in applications where index-modulated guides are superior to corrugated structures with diameter modulations. As an example, in the direct acceleration of electrons in axially modulated plasma slow wave structures [4], phase matching can be even more efficient (the dephasing time between the electron and the wave is longer) if the structure contains periodic vacuum gaps, since in those locations the wave phase velocity is c, as opposed to >c everywhere in plasma diameter modulated guides.

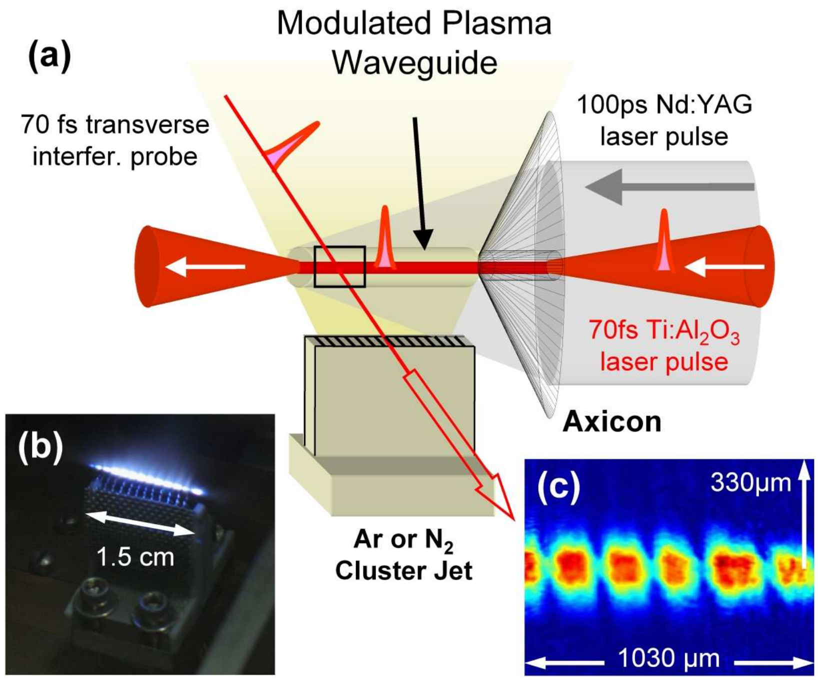

Fig. 1. Experimental geometry: Nd:YAG laser pulse (200–500 mJ, 100 ps, 1064 nm) focused by an axicon onto a elongated cluster jet (a) generates a channel to allow guiding of a (a) Ti:Sapphire laser pulse (70 mJ, 70 fs, 800 nm). A 1 mJ portion of the femtosecond pulse was directed transversely through the modulated guide for time resolved interferometric/scattering images. Image of channel with (b) 250 μm wires at a 1mm period and (c) phase image of channel with 25 μm wires at a 200 μm modulation period in argon cluster targets.

2. Experimental setup

The experimental setup is shown in Fig. 1. A 100 ps Nd:YAG laser pulse (10 Hz, 1064 nm, up to 500 mJ) is focused by an axicon to a 2.5 cm line-focus 2-3 mm above the nozzle orifice, generating a 1.5 cm long plasma channel. The cluster source in these experiments was a liquid nitrogen cooled supersonic gas jet with a 1.5 cm long by 1 mm wide nozzle exit orifice.

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Cluster formation occurs when a highly pressurized gas undergoes rapid expansion through the nozzle into vacuum. Van der Waals forces lead to the formation of aggregates at solid density of mean diameter 1-50 nm (~102 to 107 atoms), which we control using nozzle geometry, gas species, and jet temperature (115 to 295 K) and backing pressure (100 to 1000 psi) [10]. Longer channels can be obtained by decreasing the base angle of the axicon and increasing the length of the cluster jet, Waveguides were injected with 70 mJ, 70 fs, 800nm Ti:Sapphire laser pulses at f/10 through a hole in the axicon. These pulses were synchronized [11] and delayed with respect to the channel-generating Nd:YAG pulse. Channel electron density profiles were obtained by perpendicularly directing a small portion of the femtosecond pulse (~ 1 mJ) through the waveguide and imaging it through a folded wavefront interferometer onto a CCD camera, followed by phase extraction and Abel inversion.

3. Effect of wire obstructions

To understand the effect of wire obstructions on plasma waveguide generation, we initially examined the effect of a single 25 μm diameter tungsten wire aligned perpendicularly across the cluster jet flow. By varying the probe delay we observe the time evolution of the electron density in the plasma channel (Fig. 2). It is seen at the earliest delay that a ~50 μm gap appears in the plasma and this gap remains remarkably sharp and well defined until some merging of the plasma segments occurs near ~ 6ns. As the gas jet forming the clusters is supersonic, an initial concern was that wire-induced shock waves could disrupt the flow. However, the main effect of the wire is to cast a localized downstream 'shadow'. As borne out by the guiding experiments, to be discussed shortly, this shadow manifests the absence of clusters, and hence plasma. For our jet parameters [10], the mean free path for

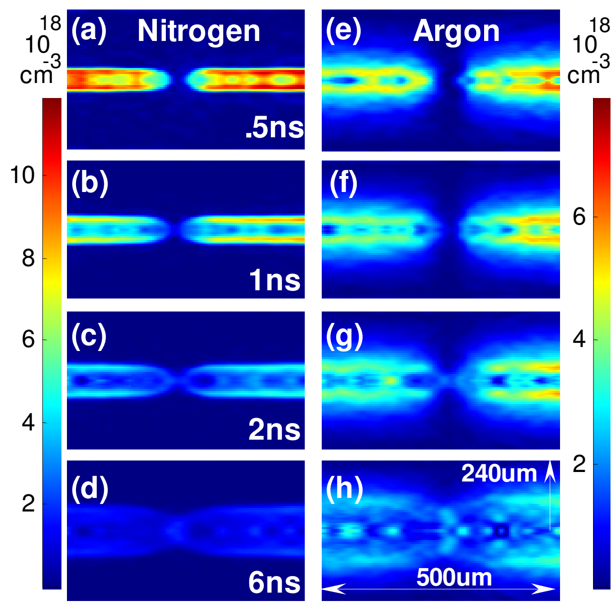

Fig. 2. Waveguide electron density profiles at indicated delays vs. radius and axial position produced in nitrogen (a-d) and argon (e-h) cluster jets at 800 psi backing pressure and -145°C (22°C), with single 25 μm diameter wire across the exit of the elongated nozzle and in contact with it. Channels were formed using a Nd:YAG pump (1064 nm, 500 mJ, 100 ps).

inter-cluster collisions is $\lambda_{cluster} = (N\sigma)^{-1}$ ~1 mm, where N ~10^{13} cm^{-3} is the density of clusters [10] and σ ~1.5x10^{-12} cm^2 is the hard sphere collisional cross section for a ~70Å cluster [10]. $\lambda_{cluster}$ is much larger than the wire diameters of this paper, so the cluster encounter with the wire is almost purely ballistic. Cluster collisions with the wire are of sufficient energy to disintegrate them, and the resulting low density accumulation of

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monomers near the wire might impede the ballistic flow of the massive clusters, although the size of this effect has not been assessed. It is seen from Fig. 2 that the nitrogen channels and gaps are significantly sharper than the argon channels/gaps. The main reason for this is more available ionization stages in argon, allowing electron density profiles to vary spatially over a larger extent.

We also tried 50, 100, and 250 µm wires, where the plasma gaps increased with wire diameter (for example, a 300 µm gap for a 250 µm wire). The sharpest gaps occurred for the smallest diameter wires. It is likely that gaps less than 50 µm can be achieved, but we found that our <25 µm wires were too fragile to mount over the nozzle in our current setup. Note that our wire-modulated cluster-generated plasma channels are highly stable and reproducible: all density profiles shown in this paper are extracted from the average phase of 200 consecutive interferograms. The shot-to-shot extracted density variation is less than 5%.

4. Multi-wire arrays for quasi-phase matching

Implementation of an array of wires is necessary to facilitate quasi-phase matching. The first array consisted of 250 µm wires with 1mm periodicity (Fig. 1(b)). An array of 25µm wires with a ~200 µm period was then used, and it was found that the resulting argon and nitrogen plasma waveguides (Figs. 3(a)-3(b)) had similar local density profiles and time evolution as with single wires. We observed a suppression of peak local plasma density where the wires in the hand-wound array were more closely spaced, possibly also reflecting the effect of monomer interference with cluster flow.

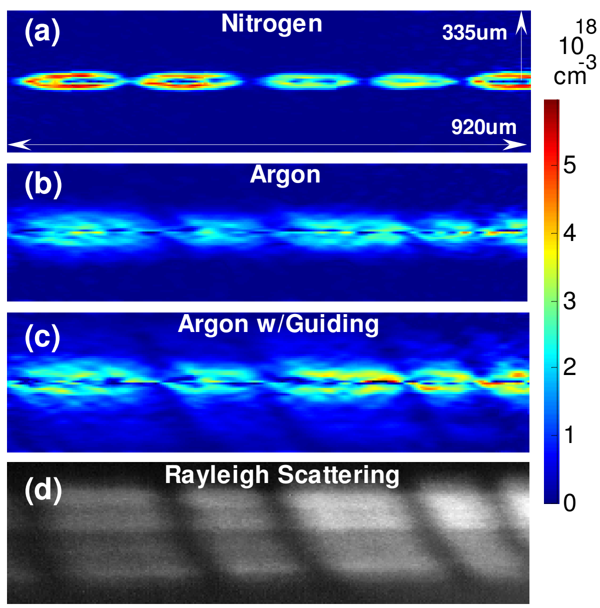

Fig. 3. Image (a) ((b)) shows the Abel-inverted electron density profile of radius vs. propagation direction of a waveguide produced in a Nitrogen (Argon) cluster jet at 800 psi backing pressure and -145°C (-80°C) with 25 um diameter obstructions at a 200 um period 2ns after channel generation. In (c) a 70 mJ, 70 fs, 800 nm Ti:Sapphire pulse has been guided down the channel, but otherwise experimental conditions are the same as (b). In (d) Rayleigh scattering from (c) was imaged by blocking the probe pulse and placing an 800 nm interference filter in the transverse imaging setup.

As any electron density in the gaps is below the sensitivity of the transverse interferometer, guiding an intense pulse down the channel allows us to determine whether the gaps contain significant unclustered gas density. We injected a 70 mJ, 70 fs, 800nm Ti:Sapphire laser pulse down our modulated argon guides 2ns after their generation. Transverse probe measurements with and without the guided pulse are shown in Figs. 3(b)

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and 3(c). As the gaps are virtually unchanged after high intensity guiding, we conclude the gas density in the gaps is below our measurement threshold. This implies a neutral gas atom density in the gaps of $<10^{16}$ cm^{-3}, corresponding to a threshold probe phase shift sensitivity at electron densities $<10^{17}$ cm^{-3}. Examination of the guided pulse scattering (Fig. 3(d)) corroborates the conclusion of negligible electron density in the gaps. Note that the slanting of the gap shadows seen in Figs. 3(c) and 3(d) is attributable to the local direction of the nozzle cluster flow near that section of the orifice.

Also seen in Figs. 3(c) and 3(d) is a 'halo' of electron density around the plasma channel that is present only after the passage of the guided femtosecond pulse. We have attributed this halo to leakage of the guided pulse from the modulated channel [8], and its scattering/absorption by un-ionized clusters at the channel periphery. However, there is no such further ionization in the peripheral regions adjacent to the gaps, further reinforcing the observation that there are no clusters in the wire shadows.

5. Summary

In conclusion, we have demonstrated a new technique for making axially modulated plasma waveguides for particle acceleration and photon generation applications that demand quasi phase matching. Unlike our earlier waveguide modulation method [8], which relies on waveguide diameter modulations, this scheme enables purely index-modulated structures.

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