

Measurements of plasma densities in laser filamentation in solids at various wavelengths spanning from near and mid infrared

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Abstract: We measure plasma densities in laser filamentation in fused silica using single-shot time-resolved interferometry when the filament driver wavelength is varied between 1.2 and 2.3 μm . The experimental results are compared with numerical simulations.

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In laser filamentation, a small laser beam size can be sustained for many times the characteristic diffraction length with minimal diffraction due to the balance of the optical Kerr effect (i.e., self-focusing) and natural diffraction/plasma defocusing [1]. However, the complex underlying physics of this exotic phenomenon is still under active investigation. Recently, it has been theoretically predicted that the plasma density during laser filamentation in air/gases decreases as the driver wavelength increases [2, 3]. Furthermore, mid-infrared optical bullet formation was theoretically predicted during filamentation in air with negligible plasma [4], whereas experimental work has reported high-density plasma ($> 10^{19} \text{ cm}^{-3}$) in air with 3.9- μm wavelength filamentation [5]. More recently, another theoretical study has investigated non-monotonic plasma-density scaling in laser filamentation in solids at various wavelengths covering mid-infrared and long-wavelength infrared [6]. Despite several theoretical studies and the critical role of plasma, systematic experimental studies of plasma in laser filamentation by varying the driver wavelength are lacking. Here we use a pump-probe technique to perform direct plasma density measurements in laser filamentation in fused silica at various wavelengths spanning from near and mid infrared, revealing the importance of driver wavelength and dispersion for plasma generation in filamentation. We also compare the experiment with numerical simulations using the nonlinear envelope equation (NEE) [7].

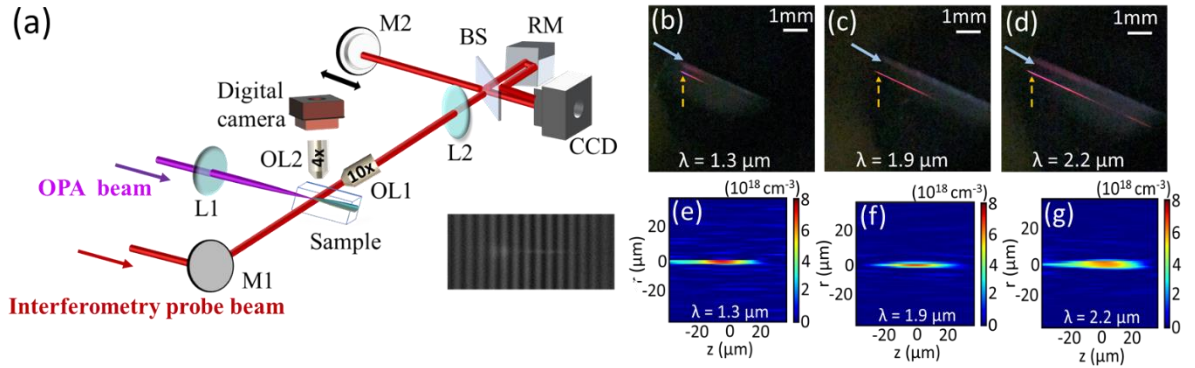


Fig. 1. (color online) The single-shot optical interferometry experimental setup is shown in (a). M1, M2: mirrors; L1: $f = 15\text{-cm}$, L2: $f = 20\text{-cm}$ lenses; OL1: 10x, OL2: 4x objective lenses; BS: beam splitter; RM: rooftop mirror; CCD: charge-coupled device camera communicating with computer. An interferogram with a shift due to plasma is shown in the inset. Top-view of the filamentation, captured by digital camera magnified by the 4x OL2 is shown in (b) for $\lambda = 1.3 \mu\text{m}$, (c) for $\lambda = 1.9 \mu\text{m}$, and (d) for $\lambda = 2.2 \mu\text{m}$. The 2-D profile of the extracted plasma densities for single shot measurements are shown in (e) for $\lambda = 1.3 \mu\text{m}$, (f) for $\lambda = 1.9 \mu\text{m}$, and (g) for $\lambda = 2.2 \mu\text{m}$. The positions at which plasma density are measured, shown with yellow dashed arrows and the direction of pump beam propagation is shown with blue arrows in (b - d).

In our experiment, the medium is fused silica and the input beam wavelength (λ) for filamentation is varied from 1.2 to 2.3 μm at interval of 0.1 μm except 1.6 μm at which the energy stability is not good. Zero group velocity dispersion (GVD) of fused silica is near 1.27 μm and thus $\lambda \geq 1.3 \mu\text{m}$ belongs to the anomalous-GVD regime. The source of variable wavelengths is an optical parametric amplifier (OPA), pumped by a linearly polarized, 1-kHz, 800-nm, 45-fs full width at half-maximum (FWHM) Ti:Sapphire laser system. The OPA beam is focused with a 15-cm focusing lens on a translation stage onto the input face of a 2-cm-long fused silica sample to generate the filament. To characterize the input beam intensity and power, we first measure the mode diameter at each wavelength at the focus and then measure the pulse duration at each wavelength using a second-harmonic generation autocorrelator, revealing FWHM pulse durations of $68 \pm 4 \text{ fs}$ for $\lambda = 1.2 - 1.7 \mu\text{m}$, $83 \pm 4 \text{ fs}$ for $\lambda = 1.8 - 2 \mu\text{m}$, 151 fs, 181 fs and 203 fs for λ

= 2.1, 2.2 and 2.3 μm , respectively. To ensure single and stable filamentation, the input power is set at ~ 7 times of critical power (P_{cr}) for $\lambda = 1.2 - 2 \mu\text{m}$, and $4P_{cr}$ for $\lambda = 2.1 - 2.3 \mu\text{m}$. For plasma density measurements, single-shot optical interferometry is performed using an 800-nm probe from the residual energy of Ti:Sapphire laser. Due to the unavailability of a fast camera, we have to decrease the pump (OPA) and probe (800 nm) pulse repetition rate from 1 kHz to 50 Hz using an optical chopper to achieve single-shot interferometry. In the experimental setup shown in Fig. 1(a), the probe beam after passing through the filament region at 90 degrees is relay-imaged using a 10x objective lens and an $f = 20\text{-cm}$ focusing lens to an interferometer, in which a rooftop mirror is used to invert the embedded perturbation of one arm relative to the other. The time delay between pump and probe is controlled by a translational stage in such a way that the maximum plasma density is measured by the probe. We also monitor filament formation by imaging the top-view of the filament onto a digital camera using a 4x objective lens. The positions in the filaments at which plasma densities are measured and which also correspond to those of maximum scattering intensities are shown by the yellow arrow in Figs. 1(b - d) for $\lambda = 1.3, 1.9$ and $2.2 \mu\text{m}$.

Phase is extracted via the Fourier technique and the Abel inversion is computed to retrieve plasma densities by assuming axial symmetry. Examples of 2-D profiles of the extracted plasma densities are shown in Figs. 1(e - g) for $\lambda = 1.3, 1.9$, and $2.2 \mu\text{m}$. Figure 2 shows the maximum plasma density (black line) vs. wavelength (averaged over 20 shots), revealing high plasma densities of $\sim 10^{19} \text{ cm}^{-3}$ near zero GVD (e.g., $1.2 \mu\text{m}$) and gradual decrease down to $\sim 5 \times 10^{18} \text{ cm}^{-3}$ at longer wavelengths. To compare with the experimental results, we perform numerical calculations based on NEE [7], for pulse propagation in fused silica under conditions similar to our experiment. The comparison between measured plasma densities (black line) and calculated plasma densities (red line) in Fig. 2 shows overall very good agreement, revealing the similar trend to the experiment though the calculated peak plasma densities are somewhat larger than the measured ones and the difference in the near-zero GVD regime is larger.

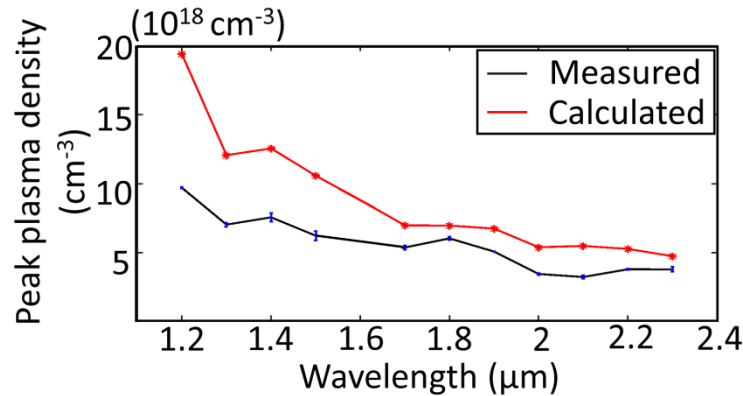


Fig. 2. (color line) Comparison between measured plasma densities (black line) and calculated plasma densities (red line) for $\lambda = 1.2 - 2.3 \mu\text{m}$ is shown. The input power is $\sim 7P_{cr}$ for $\lambda = 1.2 - 2 \mu\text{m}$, and $4P_{cr}$ for $\lambda = 2.1 - 2.3 \mu\text{m}$ for experiment and simulation both. Standard deviations in experimental measurements are shown with blue error bars.

In summary, we measure plasma densities in laser filamentation in fused silica for wavelengths spanning $1.2 - 2.3 \mu\text{m}$ using single-shot time-resolved interferometry, revealing high plasma densities of $\sim 10^{19} \text{ cm}^{-3}$ near zero GVD and decrease in plasma density approaching $< 5 \times 10^{18} \text{ cm}^{-3}$ at longer wavelengths. Our experimental results are overall in good agreement with the calculation results.

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