Enhanced absorption and plasmon excitation in the bulk of fused silica with femtosecond Bessel beams

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Abstract: We image femtosecond Bessel beam propagation in fused silica under ablation conditions, and observe unexpectedly high absorption. We identify plasmon excitation and plasma channel field enhancement as the likely mechanism for this increased absorption.

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1. Introduction

Numerous applications require high-speed processing of glass, and femtosecond laser machining is now a key processing technology for transparent materials. Being able to control the propagation of femtosecond laser pulses as they propagate *inside* a material enables control of the energy deposition mechanism. In this regard, the use of femtosecond Bessel beams has been shown to be highly advantageous, allowing ultra-high aspect ratio drilling in glass with only a single pulse [1]. In contrast to Gaussian beam focusing, Bessel beams propagate in a quasi-invariant manner over extremely long distances (several tens of µm to mm), and this invariant propagation is assumed to be maintained even at ablation-level intensities when the beam generates a nanometer-scale plasma column. However, the invariant propagation of Bessel beams during material ablation has not actually been confirmed experimentally.

In this work, we report an experimental study where we directly image the propagation of Bessel beams at ablation-level intensities, allowing us to explicitly confirm their propagation-invariant behavior [2]. Our results also allow *quantitative comparison* with numerical simulations but surprisingly, our results show that current propagation models of femtosecond beams in plasma cannot completely capture all the physics. In particular, our experiments show extremely high beam absorption (by the plasma) which is not predicted by state-of-the-art filamentation simulation models [3]. However, a model of longitudinally-invariant propagation in the plasma using Maxwell's equations reveals the existence of a previously-unreported transverse plasmonic resonance. We identify this novel effect as the underlying mechanism that causes the enhanced absorption observed experimentally.

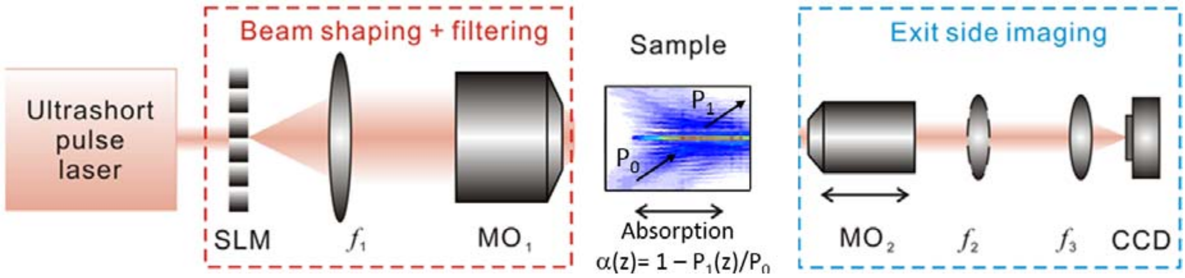

Figure 1. Experimental setup for femtosecond Bessel beam shaping and imaging of propagation in fused silica. Beam scanning allows us to reconstruct in three dimensions the fluence distribution inside the sample. Far-field scanning is possible by inserting lens f_2 in the setup. MO: microscope objective. Absorption measurements of the incident beam along the plasma column were deduced from the measured power distribution as indicated.

2. Experimental setup

Our experimental setup for filamentation imaging in the bulk is described in detail in reference [2]. Femtosecond (~120 fs) Bessel beams are generated with a Spatial Light Modulator (SLM). They are generated within a fused silica sample where we accurately control the position of the beam within the sample. With a high-numerical aperture (NA = 0.8) imaging system, we record the fluence distribution on the exit side of the sample. Our setup is calibrated to allow absolute fluence measurements (in J/cm^2). The progressive translation of the beam in the sample across the exit side surface, allows reconstruction of the fluence distribution in three dimensions.

3. Results and comparison with nonlinear Schrödinger model

Figure 2 shows experimental results of fluence distributions for (a) propagation in the linear regime and (b) at a pulse energy of 0.7 µJ under conditions of material ablation. The Bessel beam cone angle used was 25°(in air) and this energy corresponds to the threshold for single-shot nanochannel drilling [1]. We see from Fig. 2(b) that the beam propagation is essentially unaffected by the plasma generation, nor by self-focusing effects, since the radial beam structure and subsidiary lobe positions remain constant along propagation, and near identical to the linear regime. Note that we confirmed the invariance of the measured fluence distribution for a wide range of energies up to ~3 µJ, well above the ablation threshold.

Figure 2 (c,d) compares experimental results with computed fluence distributions from numerical simulations based on a coupled nonlinear Schrödinger-plasma equation [3]. Simulations, however, were unable to reproduce the propagation invariance seen in experiment using standard parameters for fused silica over a wide range. Fig. 2(c) shows typical simulation results with a (Drude model) collision times of τ = 1 fs [3] and the discrepancy with experiment in Fig. 2(b) is evident. Reducing the collision time to τ=15 fs does yield simulations that agree with experiment (Fig 2(d)), but such a collision time is unphysical. On the other hand, since the collision time in simulations effectively describes the balance between absorption and defocusing, these results suggest the presence of an unidentified significant absorption mechanism. In fact, experimental measurements of beam absorption in the plasma (see Fig. 1) exceeded values of α = 0.7, never reached by any of the models of plasma we used.

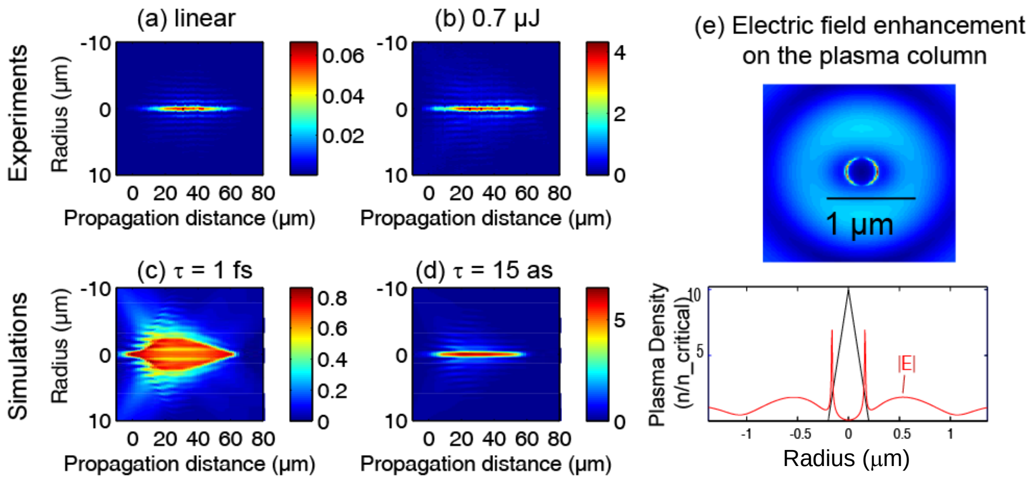

Figure 2. Comparison between experimental fluence maps (a-b) and simulations with nonlinear Schrödinger model (c-d). The unit of fluence used in the colormaps is J/cm^2. (e) Modelling results: Top - transverse distribution of linearly polarized electric field. Bottom – line profile of field is shown in red for conditions of a linear plasma density distribution (black).

4. Plasmon excitation model

To understand the origin of this unexpected absorption, we have modelled (using Maxwell's equations) the electromagnetic field in the vicinity of a nanometric plasma column (black line in Fig 2(e), with 200 nm diameter at critical density). The red line in Fig. 2(e) shows electric field enhancement by one order of magnitude on the side of the plasma channel in the vicinity of the critical density region. This enhancement arises from the creation of (bulk) plasmons and leads physically to resonance absorption (as observed in planar plasmas under oblique incidence [4]) which effectively suppresses plasma defocusing and yields invariant propagation.

5. Conclusion

Our experimental characterization of Bessel beam propagation has allowed us to identify a fundamental limitation in existing filamentation models that do not reproduce optically-invariant propagation at ablation-level intensities. Numerical simulations suggest the presence of an additional absorption mechanism arising from plasmon resonance. We anticipate these results will stimulate further research to manipulate plasmas in the bulk of materials.

[1] M. K. Bhuyan *et al*. Applied Physics Letters, **97**, 081102 (2010)
[2] C. Xie *et al*. Scientific Reports, **5**, 8914 (2015)
[3] L. Sudrie *et al*. Phys. Rev.Lett., **89**, 1 (2002)
[4] W. L. Kruer, "The Physics of Laser Plasma Interactions", Westview Press (2003)