Filamentation characteristics of focused fs pulses in atmosphere

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Abstract

We present the experimental investigations on the filament characteristics of sharply focused fs pulses (800 nm, 45 fs, 1 kHz) in air. Pulses with input powers in 3–12.2 P_{Cr} range were focused using three different focusing geometries f/#10, f/#15 and f/#20 corresponding to numerical apertures (NA) of 0.05, 0.033 and 0.025, respectively. The dynamics of filaments were observed via direct imaging of the entire reaction zone. The length of the filament has decreased with increasing NA from 0.025 to 0.05, while, the filament width has increased. For a given focusing geometry, the filament length and width increased with increasing power. However with higher NA, the length and width were observed to saturate at higher input powers. With the highest NA of 0.05and higher input powers used in the current study, the presence of coherently interacting multiple filaments either resulting in a fusion or exchange of power.

Keywords: fs laser pulses, propagation, multiple filamentation, external focusing, filament intensity.

1. Introduction

From the initial observation of self-channeling of high-peak power femtosecond (fs) laser pulses in air by Braun et. al. [1], propagation of intense ultra-short laser pulses in different media has been one of the most exciting fields of nonlinear optics. When the transverse power (p) of the propagating fs pulse is higher than the critical power for self-focusing (P_{Cr}) of the medium, a dynamic structure with an intense core known as filament propagates over extended distances much larger than the typical diffraction length while keeping a narrow beam size without the help of any external guiding mechanism[2]. Filamentation has found many applications to detect hazardous molecules[3] LIDAR for atmospheric applications[4], HHG[5], generation of single cycle pulses[6], Supercontinuum generation[7], THz emission[8], acoustic emission[9], laser based propulsion[10] etc. amongst many others. However measurement of intensity inside the filament has been quite a challenge and is of importance for many applications. Though most of the efforts estimating the filament intensity are based on theoretical modeling[2,11] few methods have successfully measured the filament intensity[12]. These methods rely on the spectroscopic emission from the excited states of the atoms of constituent medium. Though the filament intensity is observed to be clamped to a fixed intensity[13], recent work clearly demonstrated the presence of intensities of the order of 10^{14} W/cm^2 has opened up interesting avenues[12,14]. However the presence of multiple filaments and the interaction of the propagating filaments at higher input powers have made the measurements more challenging. In this regard, we look at the multiple filament characteristics under different external focusing conditions make a way in measuring the filament diameter accurately.

2. Experimental details

A 45 fs (at $1/e^2$ level of peak intensity) pulsed laser with central wavelength (λ=800 nm) with a repetition rate of 1 KHz was focused in air. Different Plano convex lens of focal lengths 10, 15 and 20 corresponding to numerical apertures (NA) of 0.05, 0.033 and 0.025, respectively were used to focus fs pulses. The input laser beam diameter is 10mm ($1/e^2$).The laser pulse power was varied between 0.5-1.8W corresponding to a peak power of 3-12.2 P_{Cr}. Figure 1 shows the experimental setup for capturing self-emission from propagating filaments. A Half wave plate (HWP) and Brewster Angle polarizer (BP) combination is used to vary power and Quarter Wave Plate (QWP) were placed in order to produce both Linearly Polarized (LP) and Circularly Polarized (CP) Light. The self-emission from filament was captured using a triggerable CCD camera (OPHIR SPIRICON SP620U). The images were captured under same experimental conditions for all the three different numerical apertures. CCD Camera was connected to laptop using an USB interface.

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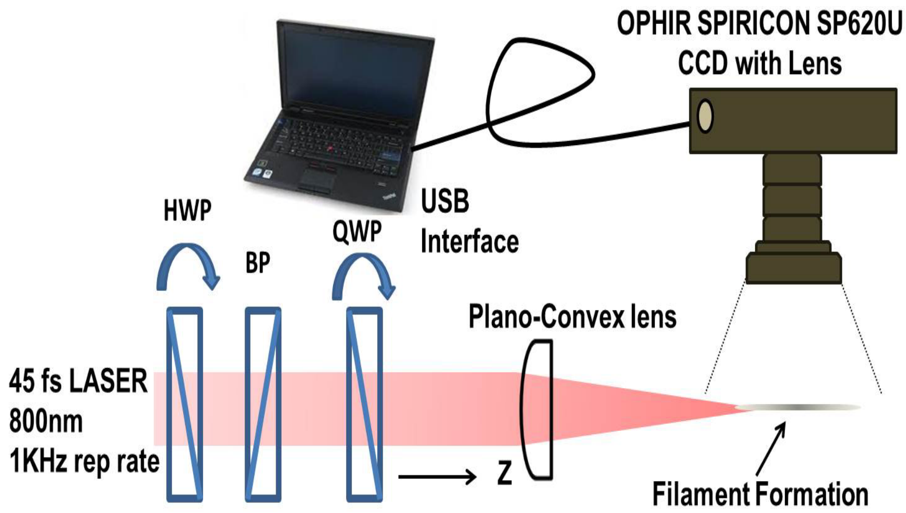

Figure 1: Set up showing filamentation formation under external focusing and capturing through CCD.

In house developed MATLAB Code was executed for extracting the length, width and intensity profile along propagation axis of laser beam [I (z) vs z] and transverse directions [I(r) vs. r] from the captured self-emission images. The presence of multiple filamentation was observed by extracting and analyzing the transverse profiles [I (r) vs. r] at different positions (z_1, z_2, z_3…) along the propagation direction. When the natural linear diffraction of the pulse is just balanced by self-focusing, the peak power equals the so-called critical power (P_{Cr}) for self-focusing. Critical power for self-focusing is given by[2]

$$P_{Cr} = \frac{3.77\lambda^2}{8\pi n_0 n_2} \tag{1}$$

where λ is the central wavelength of the pulse, n_2 value is taken as 3.2 x10^{-19} W/cm^2. The value of critical power (P_{Cr}) was taken as 3GW and used as a scaling parameter.

3. Results and discussions

Filaments were observed to propagate longer distances over few tens of Z_R, Z_R being Rayleigh length of the focused pulses in vacuum. Figure 2 shows the self-emission from the filaments produced using NA 0.05 and circularly polarized (CP) pulses at different input powers. For a given NA, polarization of pulses used, the length and intensity of self-emission increased with increasing input power. For smaller NA, filamentation occurred before the geometrical focus while the intensity at the geometrical focus was low. In such cases filament length is distance between transformed self-focusing and geometrical focus of the filament. For higher NA, the filament was more localized near the geometrical focus. A similar behaviour was observed earlier[15].

The length of the filament was observed to be longer for LP pulses. In general the filament was observed to propagate over 2-5 Z_R. However, the width was observed to spread over 2-40 ω_0; ω_0 being the spot size of the laser beam at focus in vacuum. For any given focusing geometry (NA), the length and width of the filament increased with increasing input power. The intensity of self-emission also increased with increasing power. The length of filament was observed to be longer for LP pulses compared to that observed with CP pulses. The intensity of self-emission is observed to be higher with CP pulses. These observations are in tune with the recent results reported in literature[11]. Filament Length as a function of input powers with different NA's was shown in figure 3. Comparison of filament length as a function of power for different NA's confirm that with higher NA length was almost saturated for all input powers but in lower NA length increased with increase in power.

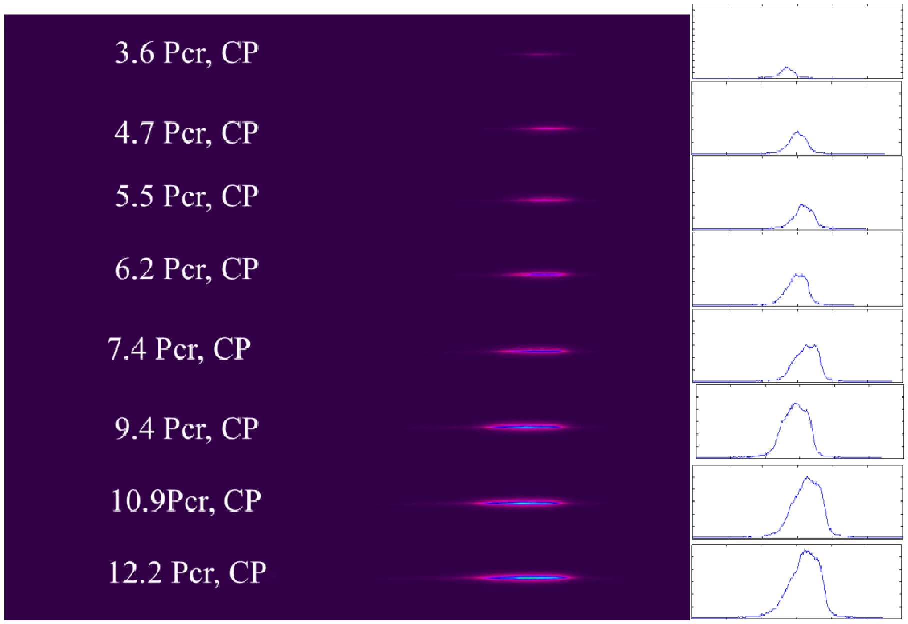

Figure 2: Filamentation images showing at different input powers with NA 0.05 for circular polarization besides showing corresponding on axis intensity profiles.

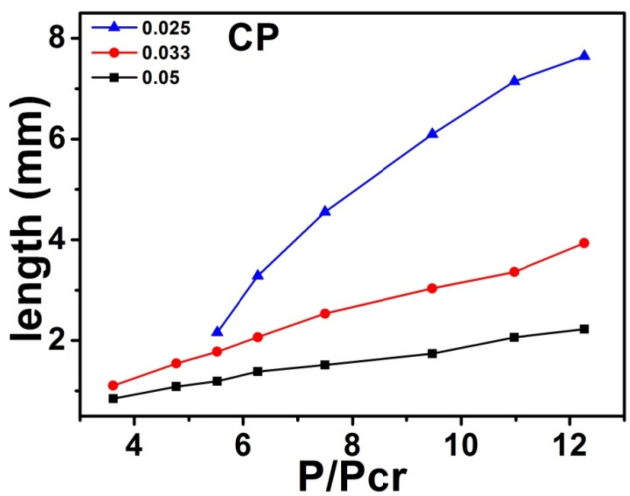

Figure 3: Filament length as function of P/PCr under different NA's for CP.

Filament width as a function of power with different NA's for CP is shown in figure 4. With increase in power the filament width increased linearly. The filament width was measured to be ~40-200 μm. with NA's of 0.025, 0.033 the presence of multiple filaments was not observed. As the NA was increased to 0.05 the width increased to 250-440 μm. This indicated presence of multiple filaments at higher NA (tighter focusing geometries) as observed by the self-emission. The filament diameter observed is in tune with the earlier measurements[11,16]. The filament width measured is used to estimate the intensity within the single filament following the methodology proposed by Shengqi et. al. [12]. From the transverse line profiles along at a fixed Z the width of the self-emission d_{sf} is measured which in turn was used to estimate the width of the plasma filament d_{laser} (laser beam diameter). The intensity for 12.2 P_{Cr}, LP under NA 0.05 is calculated to be 3.8×10^{12} W/cm^2. However the appearance of multiple filaments makes these measurements more challenging.

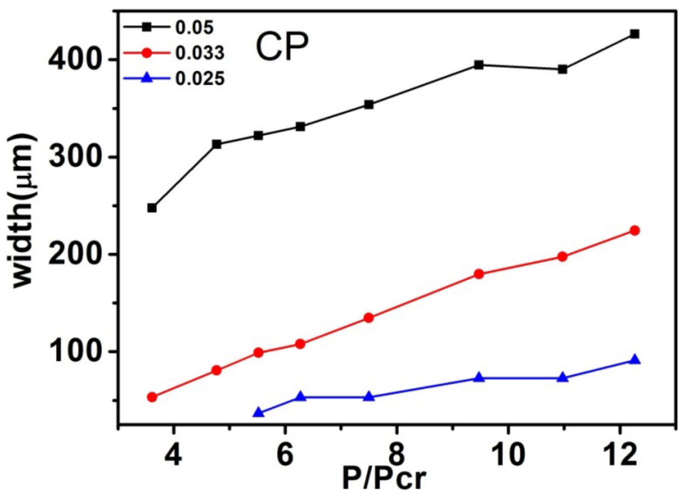

Figure 4: Filament Width as function of P/PCr under different NA's for CP.

Figure 5 shows the filament observed at tighter focusing geometry (NA of 0.05) at an input peak power of 12.2 P_{Cr}. Multiple filamentation was observed only for NA 0.05 and maximum of 3 filaments has been observed with input power in the range of 6.2-12.2 P/P_{Cr}. The self-emission profiles at three different positions along propagation direction clearly indicate the presence of multiple filaments and interaction between the propagating filaments around geometrical focus in cognizance with the phenomena observed with unfocused or loosely pre-focused fs pulses propagating in air[17]. From figure 5(b), at Z_1 position, filament was single and had a width of 69.4 µm. From figure 5(c), at Z_2 position, filament had been split into three having individual widths of 91.7 µm, 21.8 µm and 73 µm. From figure 5 (d), at Z_3 position, second and third filaments are almost in a stage of recombination and these three filaments had widths of 101.2 µm, 7.4 µm and 72.2 µm. The presence of breakup and fusion of multiple filaments along Z clearly indicates that the intensity is not constant throughout the propagation of filament at higher NA (tight focusing geometries).

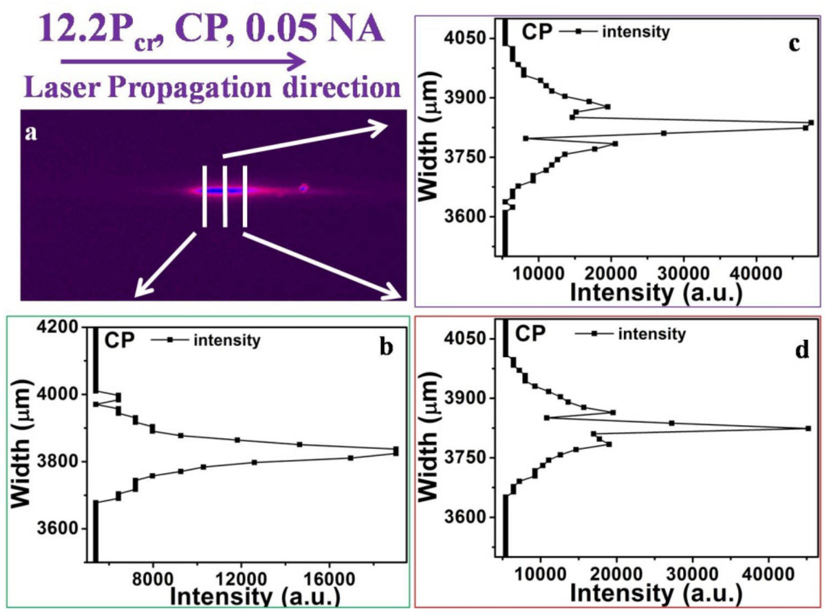

Figure 5: Filamentation image showing for 12.2 P_{Cr} for CP and line cut intensity profile at three different Z positions showing multiple filamentation.

With shorter focal lengths (higher NA) the presence of multiple filaments was observed at higher input powers only for circular polarization. Multiple filaments are well-known to grow randomly due to slightest noise in the beam intensity profile[2,18,19], modulational instability[20,21] over large range of input powers and vectorial effects[22]. Each of the multiple filament is known to take power of P_{Cr} and interact among themselves during propagation before coalescing into a single filament[2] making the measurement of filament intensity more challenging and erroneous.

4. Conclusions

Filament characteristics resulting from the propagation of kHz repetition rate fs laser pulses were studied under different external focusing conditions. The effect of polarization of the input pulses on filamentation was also studied. For a given focusing geometry, the filament length and width increased with increasing input peak power, however at higher NA, the length and width were observed to saturate. Breakup of a single filament into multiple filaments and fusion along the propagation direction was observed with higher NA of 0.05 for CP pulses. Filament intensity inside a single filament estimated from the self-emission was found to be of the order of 10^{12} W/cm^2. However the same method may not be extended to estimate the filament intensity in the presence of multiple filaments, as the effects like break up and fusion of the propagating filaments indicates varying intensity along the direction of propagation. Further work is being carried out to address the challenging scenario of filament intensity measurements in presence of multiple filaments.

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