Effect of lens tilt on SCE and filamentation characteristics of femtosecond pulses in air

S. Sreeja[a,b], T. Shuvan Prashant[a,c], Ch. Leela[a], V. Rakesh Kumar[a], Surya P. Tewari[a], S. Venugopal Rao[a#], P. Prem Kiran[a*]

[a]Advanced Centre of Research in High Energy Materials **(ACRHEM),** University of Hyderabad, Hyderabad 500046, India.
[b]International School of Photonics, Cochin University of Science and Technology, Cochin 682022, India.
[c] Currently at 2 Science Drive 3, Department of Physics, National University of Singapore, Singapore -117542.

Abstract

We present the evolution of SCE associated with filaments due to the tilt of focusing lens under tight focusing geometries. Transform limited femtosecond (fs) pulses (800 nm, 45 fs, 1 kHz repetition rate) were focused in ambient air using three different focusing geometries f/#6, f/#7.5, and f/#12 corresponding to numerical apertures (NA) of 0.08, 0.06, and 0.04, respectively. The focusing lens was tilted from zero up to 20 degrees. The filaments decayed into two shorter parts through tilting of the lens and the separation between shorter filaments increased with increasing lens tilt, in tune with earlier reports [Kamali et al., Opt. Commun. 282, 950-954 (2009)]. The separation between the filaments matched well with the predicted distances due to astigmatism induced in loose focusing geometries. However the deviation increased as we moved to the tighter focusing geometries. The SCE spectrum demonstrated an anomalous behaviour. The SCE spectrum was suppressed at larger tilt angles of 12 – 20°. However at lower tilt angles, up to 8°, the SCE was observed to be same to that measured without any tilt of the focusing lens. This behaviour is predominant with tighter focusing geometries of f/#6 and f/#7.5, wherein the SCE was observed to be higher at 4° and 8° in comparison with that observed at an angle of 0°. Systematic study of the focusing lens tilt on anomalous SCE spectra and filament characteristics in the tight focusing geometry are presented.

Keywords: femtosecond laser filamentation, Supercontinuum emission, atmosphere propagation, tight focusing geometry, focusing lens aberration, astigmatism

1. Introduction

Intense ultra-short laser pulses are well suited for long range propagation in many transparent media. This long range filamentary propagation is due to the dynamic balance between nonlinear self focusing of an intense optical pulse and laser plasma induced defocusing[1]. These long propagating filaments in air have received significant attention over the last decade due to impending applications in the fields of remote sensing [2,3], lightning guiding [4–6], supercontinuum generation (SCG) [7-9], pulse compression[10] and THz generation.[11] During the propagation of filament the pulse undergoes temporal and spectral changes due to the linear and nonlinear effects within medium such as self-phase modulation and Raman scattering amongst others[1,12,13]. Filamentation of a fs pulse comes into play when a high intense laser pulse having transverse power (P) greater than critical power for self-focusing (P_{Cr}), propagates through air,. For very low powers, generally, a single filament is observed. As the power of the beam increases unavoidable spatial irregularity across the wave front would be induced either due to imperfection of the beam quality or due to propagation through a non-homogeneous medium in the real environment and the pulse exhibits pulse splitting, multiple collapse, and repeated filamentation over large distances. This results in the breaking up of single filament into many, termed as multiple filamentation[14-16]. Understanding and controlling multiple filaments[17-19] during the long range propagation of high power fs pulses has been a major challenge for various applications[20].

Authors for correspondence: *premsp@uohyd.ernet.in, #svrsp@uohyd.ernet.in

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Lens tilting has been used for the suppression of number of filaments in managing multiple filaments over long distances [17, 20]. It has been demonstrated that it is possible to control the number, pattern, and spatial stability of filaments by changing the tilt angle of the focusing lens[19]. Moreover, the effect of spherical aberration on femtosecond filamentation has been reported[21], where a single filament was observed to split into two along the propagation direction. However, to date attention has been mainly focused on the effect of lens tilting on the filament properties under a long focusing geometry. In this letter, we present the systematic study of the focusing lens tilting on filamentation characteristics and Supercontinuum emission (SCE) for both tight and loose focusing geometries.

2. Experiment

Figure 1 shows the typical experimental schematic used for the study. Transform limited linearly polarized pulses with duration of 45 fs, 800 nm, with a repetition rate of 1 kHz (Coherent; Legend-USP) were focused into air. The amplifier was seeded with ~15 fs pulses from an oscillator (MICRA, Coherent, 1W average power, 80 MHz repetition rate, and 800 nm). The pulse characteristics were measured using 'Silhouette' (Coherent, USA) based on the Multiphoton Intrapulse Interference Phase Scan (MIIPS) technique. The input diameter ($1/e^2$) before the focusing element was 10±0.1mm. BK-7 lenses of focal length 60 mm, 75 mm, and 120 mm were used to attain the focal geometries of f/#6, f/#7.5 and f/#12.. The corresponding numerical apertures (NA) were 0.04, 0.06 and 0.08. The focusing lens was placed on a rotation stage with a precision of 1/60 degree and was tilted from 0 up to 20 degrees. The self-emission from the filament was captured using a calibrated digital camera. A set of neutral density filters (NDFs) were used in front of the camera to avoid the saturation of image. An attenuator, combination of a half wave plate (HWP) and a Brewster polarizer (BP) was used to vary the input pulse energy into the medium. Inside the filament, because of self phase modulation and self steepening, the 800 nm laser pulse self-transforms into a chirped white light laser (Super continuum). The SCE associated with filaments was scattered and collected using a fibre optic coupled spectrometer (USB 4000, Ocean Optics Spectrometer). A set of calibrated NDFs were placed in front of the spectrometer to avoid saturation of the CCD pixels.

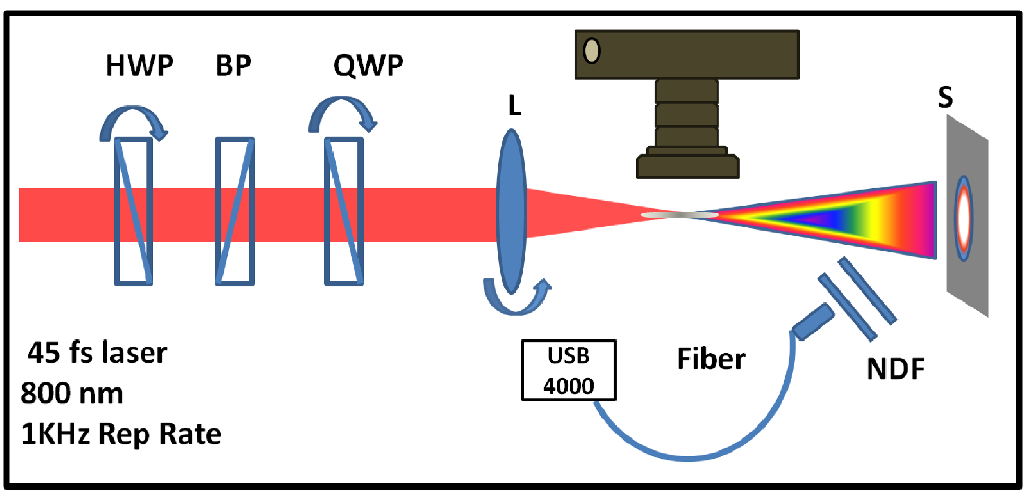

Figure 1: Experimental schematic showing filament formation at the geometrical focus captured through CCD and SCE collected through optical fibre after passing through a set of ND filters.

3. Results and Discussions

The critical power for self focusing was calculated using the equation $P_{Cr} = 3.77\lambda^2/8\pi n_0 n_2$ where λ is the central wavelength, n_0 and n_2 are the linear and nonlinear refractive indices, respectively. The P_{Cr} for air was calculated to be 3

GW for air and is used as the scale parameter. The self-emission from the filaments was recorded for different tilt angles from 0 to 20° for all the three focusing geometries. Figure 2 shows the evolution of the filaments with the tilt of focusing lens in f/#12 geometry. In all these focusing geometries (f/#6, f/#7.5, f/#12) only one filament was observed when the lens was tilted from 0° up to 8°. At a tilt angle of 8°, the single filament was observed to break up into two shorter filaments along the propagation direction, with the filament towards the focusing lens having weak intensity looking almost like a comet. Beyond a rotation of 8°, the separation between the filaments was observed to increase continuously with increasing tilt of the lens. For all the angles greater than 8°, the intensity of the filament towards the focusing lens is smaller compared to that of the farther filament. This is attributed to the astigmatism coming into play because of the lens tilt[21].

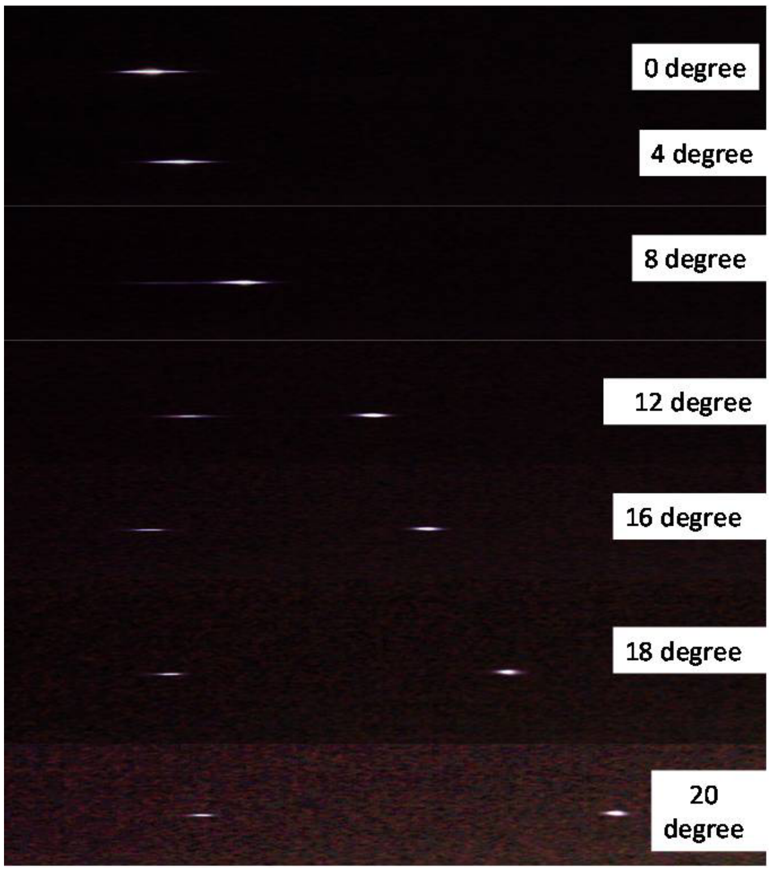

Figure 2: Filaments for different tilt angles under f/12 focusing geometry.

The separation between the filaments can be estimated from the formula[21,22]

$$X = f \sin\Phi \tan\Phi \qquad (1)$$

where f and Φ are the focal length and the tilting angle of the lens. Figure 3 shows measured separation between the filaments and the calculated separation using equation 1. Both these match very well for longer focusing geometries of f/#12 in our measurements compatible with the earlier reports[21]. However at tighter focusing geometry of f/#6, the mismatch between the estimated and observed separation has increased as we moved to larger tilt angles. At any given lens tilt, the separation between the filaments increased linearly with decreasing NA. At a tilt of 16° the separation between the filaments is ~ 0.4 cm and 0.94 cm for f/#12 (NA ~ 0.04) and f/#6 (NA ~ 0.08) geometry respectively. The separation scaled almost linearly for the NA used in the measurements.

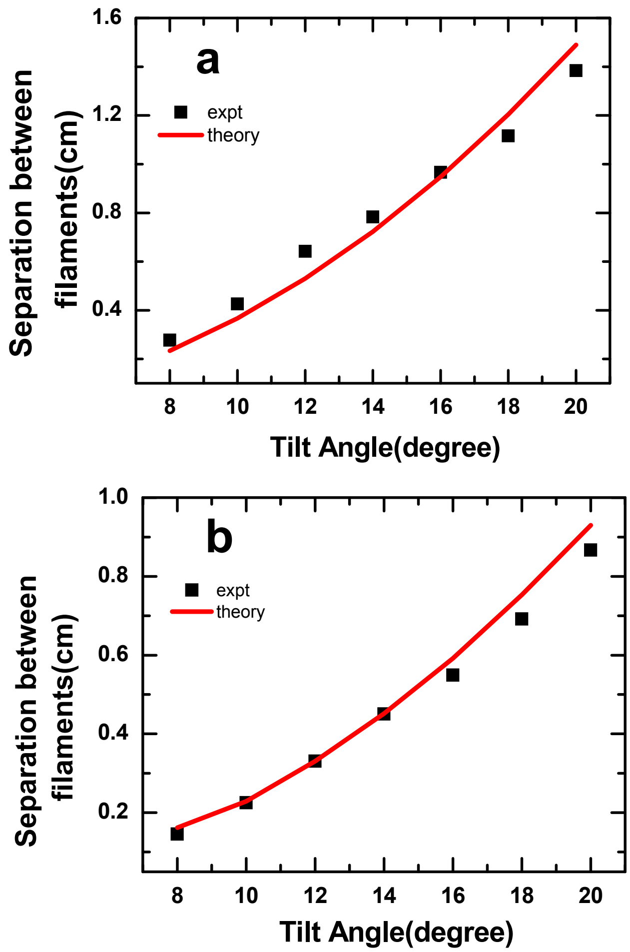

Figure 3: Comparison of experimentally measured separation between the filaments with that of estimated value for different tilt angles under (a) f/#12 (b) f/#7.5 focusing geometries.

The SCE associated with the filaments illustrated interesting behaviour with increasing tilt of the lens. For longer focal lengths of 12 cm, the SCE intensity decreased monotonically with increasing tilt angle and the data is shown in Fig 4(a). The reduction in the SCE (white light continuum) can be attributed to the distinct separation and shortening of the filaments, which is clearly depicted in Fig 2. However, as we moved on to shorter focal lengths (or higher NA), the SCE intensity increased, up to 8° tilt, in the blue region of the spectrum over 550 – 650 nm. The shorter the focal length the intense was the SCE in the blue spectral region. Above the tilt of 8° the spectrum decreased monotonically with increasing tilt angles. Under tight focusing geometry, though the two filaments were observed, they had a certain region of overlap ensuring localization of the pulse energy over a continuous distance along the propagation direction.

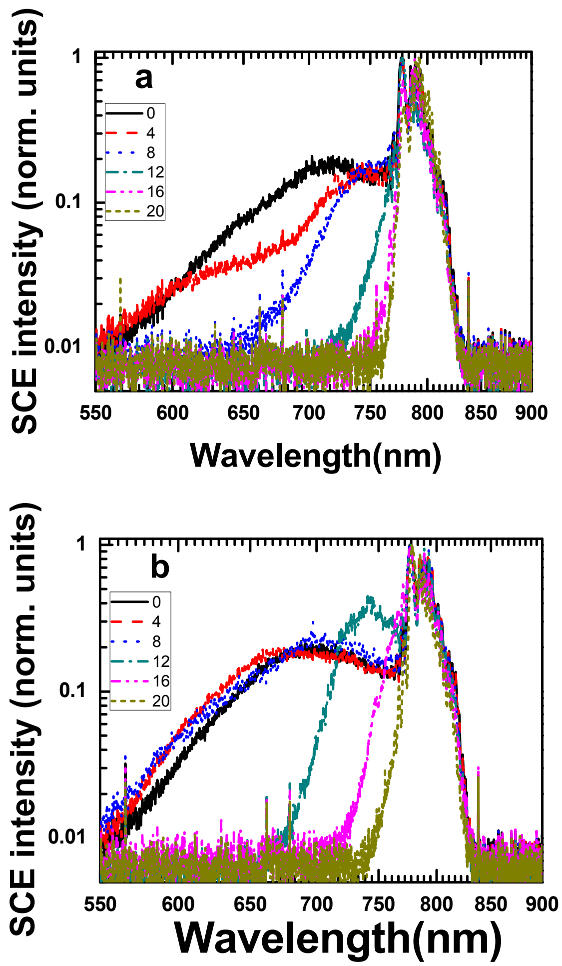

Figure 4: SCE spectra for different tilt angles under (a) f/12 and (b) f/6 focusing geometries.

4. Conclusion

The dominant phenomenon of multiple filamentation under tighter focusing geometry was controlled by tilting the lens, leading to a brighter SCE in the blue region. Tilting of the lens ensures the presence of a single filament propagating over a long distance, leading to an intense SCE. The observed phenomenon was found to be dominant for tighter focusing geometries compared to that of looser focusing geometries. To conclude, a careful design of the astigmatism, a geometrical aberration, can be utilized in making brighter SCE sources under tight focusing conditions, by exploiting the phenomenon of filamentation without conventional intensity clamping[23,24].

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