Control of Filamentation for Enhancing Remote Detection with Laser Induced Breakdown Spectroscopy

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ABSTRACT

We report on the use of a novel phase element to control the far-field intensity pattern generated by a high-peak-power, femtosecond laser. The pre-determined intensity pattern results in a well defined location of the filaments formed by the propagation of these beams through the atmosphere. This enhancement of the localization and repeatability of the intensity distribution can be extremely beneficial for laser induced breakdown spectroscopy (LIBS) of remote regions of interest.

Keywords: Filamentation, Vortex Phase Elements, Chirped Pulse Amplification, Laser Induced Breakdown Spectroscopy

1. INTRODUCTION

The propagation and development of intense plasma filaments in gaseous media from femtosecond laser pulses has been a topic of considerable interest since their discovery by Mourou and co-workers[1]. Specific applications, for example but not limited to LIBS and femtosecond machining, call for precise control of the beam profile and subsequent location of the generated filament(s)[2]. Diffractive optical elements, specifically a vortex phase plate provide a simple and robust solution for shaping the beam intensity profile in a manner which can improve the repeatability of the filament location and transverse pattern for these and other applications[3-5].

2. EXPERIMENTAL SETUP

In this experiment, a hybrid chirped-pulse amplification system consisting of a sub-35 fs Tsunami as an oscillator and an amplifier based on the Spectra-Physics TNA/Spitfire design. The system is pumped at 1 kHz by an Evolution 30 and at 10 Hz by a QuantaRay Pro290, also from Spectra-Physics. The system is capable of delivering 2.4 mJ and 30 fs at 1 kHz and < 30 mJ and 30 fs at 10 Hz in a 0.5 cm ($FWHM_I$) beam. Laser performance is enhanced by arbitrary pulse shaping with a Dazzler from Fastlite. Both 10 Hz and 1 kHz beams were used to generate single and multiple filaments in air. These filaments were formed at a distance of 4 m from the laser output by varying the compressor spacing to reach the required multi-photon ionization conditions within the available laboratory space. Due to the lower peak power of the 1 kHz beam, it is also loosely focused through a 4 m focal length lens to achieve these intensity conditions. Spectral detection of the emission lines from the filament induced plasma was made with a fiber optic detection system in combination with a Czerny-Turner spectrometer (Acton SP2500i) with a 600 grooves/mm blazed grating. The linear dispersion of the spectrograph is 3.1 nm/mm with a resolution of 0.19 nm. Light was delivered to the spectrograph via a fiber situated perpendicular to the beam path at a distance of 10 cm. One single element vortex optic of m = 3 was used, in addition to two novel elements for investigation of far-field distribution patterns.

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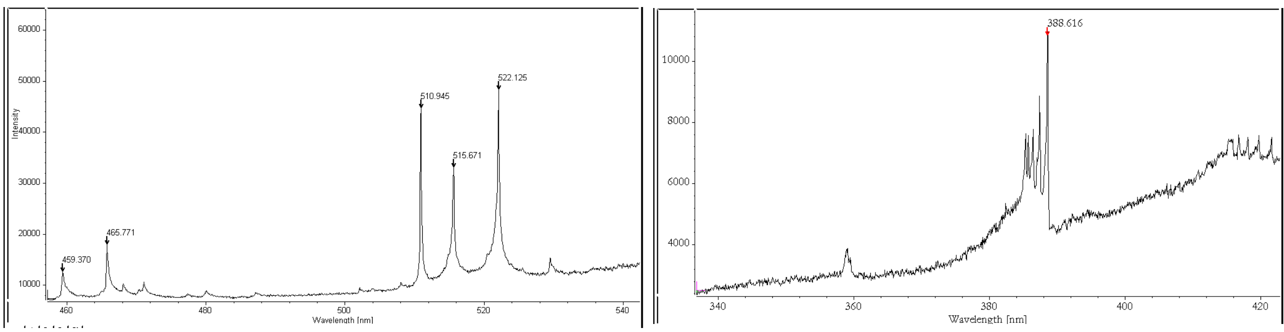
3. RESULTS

Typical 1 kHz LIBS spectra for Cu and polystyrene are shown in Figure 1. The copper spectrum is integrated over 2 s and the polystyrene sample was integrated for 20 s. The intensity in the filament is on the order of 4×10^{14} W/cm^2, and the spot size was measured to be 100 µm, both consistent with previously determined values for the intensity and size[4]. For spectral measurements, only one filament was allowed to impinge the target.



Copper

Polystyrene

Figure 1. LIBS spectra obtained with a single filament at 1 kHz. .

A vortex phase element, shown in Figure 2, was used to manipulate the far-field intensity profile in such a manner as to coerce filament formation at specific locations in the transverse beam profile. This optic alters the phase of the incident beam by an $e^{im\theta}$ term, m being the topological charge of the optic, and results in the rotation of the electric field through propagation. Solutions to the 3D NLSE (Non-linear Schrödinger equation) under the influence of a phase element show that the field distribution is highly insensitive to radial and azimuthal instabilities. Additionally, the center of the vortex phase element is a region containing all possible phases, resulting in zero intensity. The net result is a far-field intensity distribution, Figure 1, which maintains its donut shape despite diffraction and produces filamentation with greater stability, even in the presence of normal atmospheric turbulence.

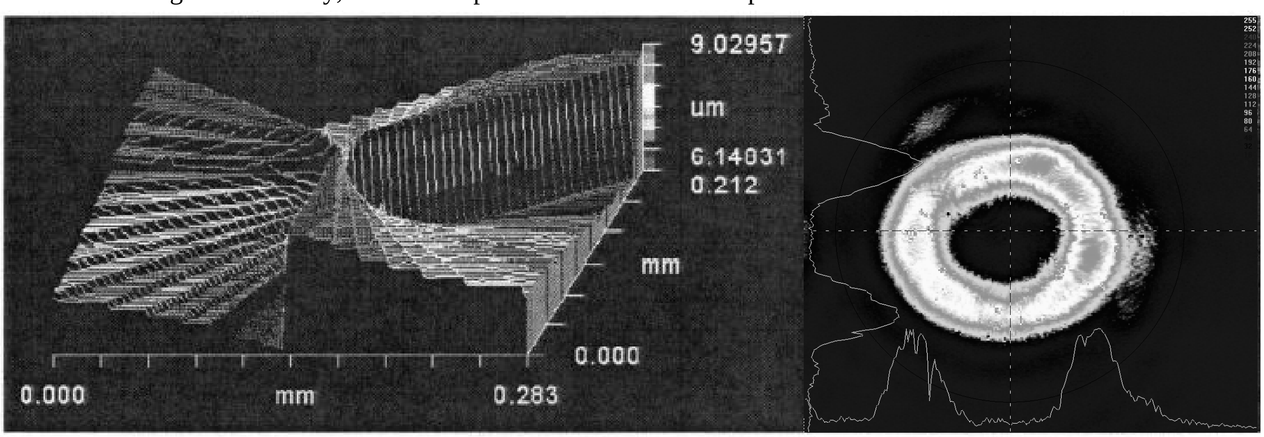
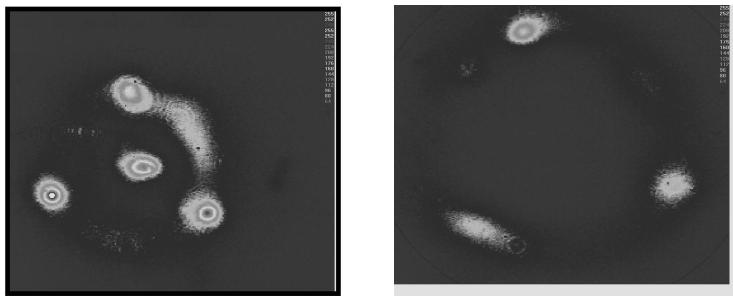


Figure 2. Zygo interferometric plot of a 16 level phase element for a topological charge of 3 and a far field beam profile image showing the formation of the distinct donut pattern.

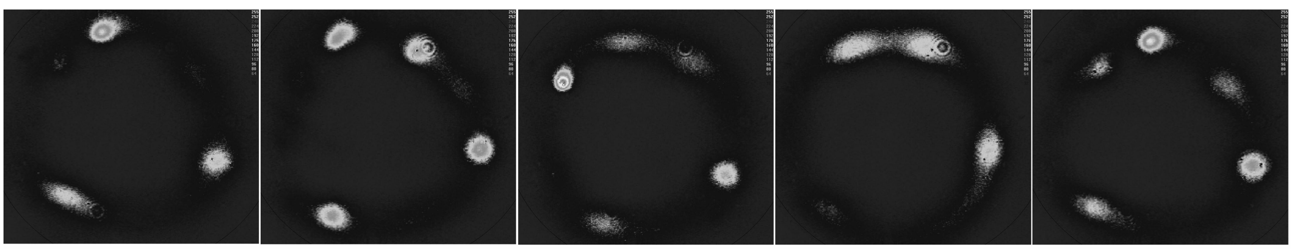
Controlled filamentation was initially demonstrated by placing the single vortex optic in the 10 Hz beam path and measuring the effect on the filament distribution. Initially, five filaments were present, due to the beam power being $\approx 50\ P_{crit}$. Insertion of the vortex optic caused the intensity pattern to form as in Figure 2, with 3 well defined filaments. These results are shown in Figure 3. These filaments were observed to propagate in over distances of several meters and the intensity distribution retained the annular ring form, with a small amount of light generated via supercontinuum diffracting into the hole. This diffraction is independent of the intensity distribution imposed by the vortex optic.



No Vortex   Vortex

Figure 3. Impact of the vortex lens on 10 Hz beam filament distribution.

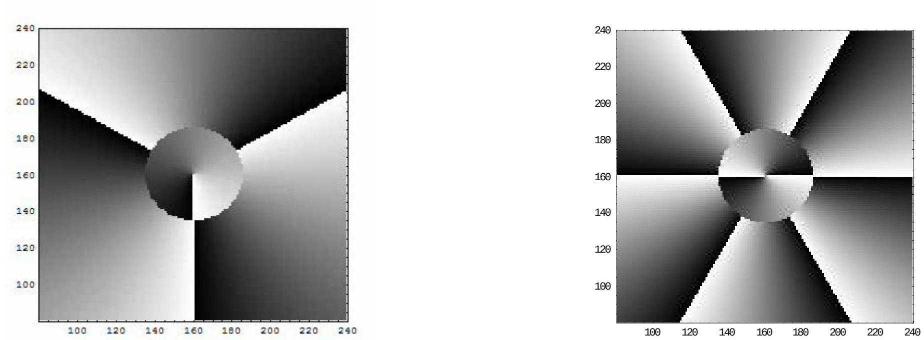
The rotational properties of the vortex were measured by mounting the optic in a rotation stage and observing the effect of the rotation on the filament pattern. Additionally, the beam profile was measured at different propagation distances and it was determined that the filament pattern rotated at a rate of 10°/m. The results of the rotation measurements are demonstrated graphically in Figure 4.



0°   30°   60°   90°   120°

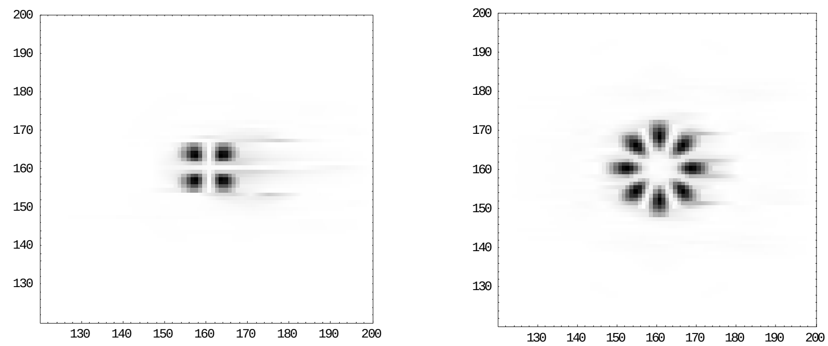
Figure 4. Effect on filamentation due to rotating m = 3 vortex optic through 120°

The effects of higher order vortexes were investigated with 2 novel vortex distributions. These distributions were chosen based on the results of modeling 2 element patterns. Each element consists of an inner vortex ring of one topological charge and an outer ring of a different topological charge. The rings were sized according to the input beam diameter. Additionally, the rings were chosen to rotate the phase in different directions. Figure 5 shows a computer generated mapping of the phase distribution from a (1, -3) and a (2, -6) vortex optic. Figure 6 shows the theoretical far-field intensity patterns generated from a Gaussian beam input.



(1, -3) Vortex Optic (2, -6) Vortex Optic

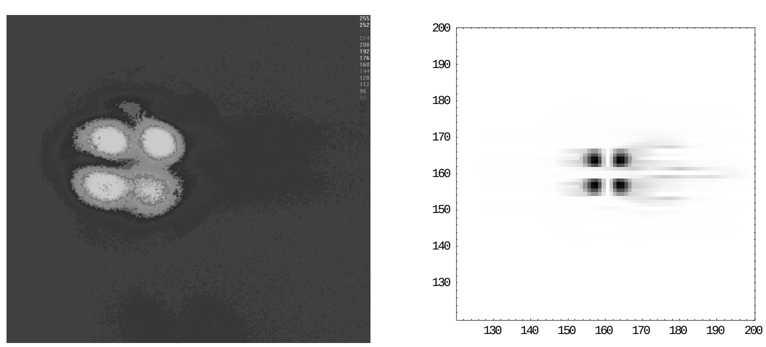
Figure 5. Higher order vortex optic phase distributions



(1, -3) Vortex Optic (2, -6) Vortex Optic

Figure 6. Theoretical far-field intensity distributions for higher order vortex optics

Each optic was placed in the beam and the effect on filamentation was investigated. Adjusting the 10 Hz beam for best beam quality, a peak power of 500 GW was achieved. The results for the (1,-3) optic are shown in Figure 7. The beam profile was taken at a distance of 10 m from the laser output after passing through the vortex optic and clearly shows the formation of 4 distinct filaments showing excellent agreement with the theoretical intensity pattern generated from solutions to the linear Schrödinger equation. This power is too low to induce filamentation in air for the (2,-6) vortex optic, so the intensity distribution was investigated by allowing filamentation to occur in a thick piece of BK7 glass. The higher value of n_2 for BK7 versus that of gaseous media such as air made it possible to produce the theoretical intensity distribution.



Experimental Theoretical

Figure 7. Filament pattern generated from the 10 Hz beam passing through the (1,-3) vortex optic

3. CONCLUSION

We show that the onset of filamentation of high peak power femtosecond laser pulses can be controlled with improved stability and repeatability by the use of a vortex phase plate element. Manipulation of the intensity distribution for various applications has also been demonstrated through rotation and the use of higher order vortex optics. The intensity distributions caused by the addition of these vortex optics should lead to highly repeatable spatial and temporal distributions of the filament and improved signal obtained in remote LIBS by the formation of multiple filaments.

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