Self-Focusing of Ultraintense Femtosecond Optical Vortices in Air

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Our experiments show that the critical power for self-focusing collapse of femtosecond vortex beams in air is significantly higher than that of a flattop beam and grows approximately linearly with the vortex order. With less than 10% of initial transverse intensity modulation of the beam profiles, the dominant mode of self-focusing collapse is the azimuthal breakup of the vortex rings into individual filaments, the number of which grows with the input beam power. The generated bottlelike distributions of plasma filaments rotate on propagation in the direction determined by the sense of vorticity.

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Studies on the propagation of ultraintense laser beams in transparent gaseous media are motivated by exciting potential applications ranging from remote detection of atmospheric pollutants to channeling various forms of electricity including microwaves and lightning strikes [1,2]. The high value of the self-focusing power threshold in gases, which is of the order of several GW, necessitates the use of ultrashort optical pulses with the duration in the subpicosecond range. If the peak power of these pulses is many times the critical power, transverse modulation instability breaks the initially smooth beam profile into individual filaments. Their placement within the beam can, to some degree, be controlled through the introduction of amplitude and phase distortions into the input beam profile [3].

Beam shaping as an effective tool for control over femtosecond laser filamentation in gases has been extensively investigated in the past. Optical vortices [4], with their doughnut-shaped intensity distributions, are particularly interesting in this context. From the application standpoint, optical vortices can be potentially applied to the generation of extended bottlelike distributions of plasma filaments in air which can be useful in channeling microwave radiation [5,6]. From the fundamental science perspective, the interest in the studies of self-focusing dynamics of optical vortices stems from the fact that these beams carry orbital angular momentum and allow for the elucidation of mechanical properties of light. Furthermore, since the transverse intensity distribution in the case of a vortex beam is a quasi-one-dimensional object (a ring), the problem of transverse modulation instability in this case is reduced to one transverse dimension, thus making its approximate analytical treatment feasible.

Numerous analytical and computational studies on self-focusing of optical vortices have been conducted in the past. Analytical investigations were restricted to the continuous-wave (cw) case and conducted in the framework of the standard $(2+1)$-dimensional nonlinear Schrödinger equation (NLS). The critical power for self-focusing collapse of vortex rings as a whole, as a function of the vortex order, has been derived by using a specific ringlike self-similar ansatz into the NLS, under the assumption that the ring fragmentation into individual filaments does not happen [7]. Later, the abovementioned estimate for the critical power was improved by using a different form of self-similar ringlike ansatz [8], still completely disregarding the possibility of the fragmentation of the ring. The approximate formula for the critical power for self-similar collapse of an optical vortex of order m, derived in [8], is particularly simple: $P_{\rm crit}(m) \approx 2\sqrt{3}mP_{\rm crit}(0)$, where $P_{\rm crit}(0)$ is the critical power for a Gaussian beam in the same medium. This result suggests that the critical power for self-focusing of optical vortices may be many times that for the ordinary Gaussian beam. That observation led to the suggestion that the use of vortex beams may help transmit laser pulses with very high peak power over long distances, as the absence of the beam collapse translates into the reduction of the multiphoton absorption losses.

Another interesting problem in the context of pattern formation in nonlinear dynamic systems is that of the number of hot spots or filaments that the vortex ring will break up into, as a result of azimuthal modulation instability. Azimuthal fragmentation of a vortex ring in a self-focusing medium has been analytically investigated through the ansatz that assumes that the ring propagates while maintaining its overall shape and diameter, and it is weakly amplitude modulated along its circumference [9]. For the case of the pure classical NLS, i.e., the basic form of the equation without any terms accounting for the arrest of the self-focusing collapse, the analysis has shown that an optical vortex of order m is expected to break up into $(2m+1)$ individual filaments, if its total power equals the critical power for self-similar collapse of that vortex order. That result has been later generalized onto the case of optical vortices with arbitrary power [10].

Experimentally, the propagation of vortex beams of orders 1 and 2 has been studied in a condensed medium (water) [10]. The generation of a femtosecond vortex beam of order 1 with peak power high enough for the observation of nonlinear propagation effects has also been reported [11].

In this Letter, we report an experimental study on the propagation and self-focusing of ultraintense femtosecond vortex beams of various orders in air. We point out that most of the analytical results mentioned above are not directly applicable to our study, as those are obtained for the cw case. Still, it is of interest to investigate whether various analytical results obtained for the cw case apply, even qualitatively, to the case of femtosecond optical vortices with a finite level of distortions of their doughnut-shaped intensity profiles.

Our results show that with less than 10% of initial transverse intensity modulation, the self-focusing threshold for femtosecond vortex beams is significantly higher compared to that of a Gaussian beam. The critical power for self-focusing grows approximately linearly with the vortex order. The dominant mode of self-focusing collapse is found to be the azimuthal breakup of vortex rings into individual filaments, the number of which, for a particular vortex order, grows with the input power of the beam. The generated filament pattern rotates on propagation in the direction determined by the sense of vorticity.

The laser source used in our experiments is a commercial Ti:sapphire chirped pulse amplification system operating at 10 Hz pulse repetition frequency and generating transform-limited optical pulses of 38 fs duration, at 800 nm center wavelength. The pulse energy attainable from the system is 30 mJ, in an 18 mm diameter beam. Vortex beams of orders 3, 4, 6, 8, and 10 are generated by passing the beam through appropriate phase masks, followed by weak focusing of the beam with a spherical mirror telescope. Both mirrors of the telescope are operated at a near-normal incidence, to minimize aberrations. The effective focal length of the telescope is 3 m, and, prior to the focusing, the beam is passed through an iris with a clear aperture of 10 mm. The phase masks used to generate vortex beams are fabricated on 1 mm thick fused silica substrates. The mask used to generate the vortex beam of order m imposes a modulation in the form of $\exp(im\phi)$, modulo 2π, onto the flat phase front of the incident beam. ϕ above is the azimuthal angle. Phase distributions across the surfaces of the masks are characterized using a Wyko NT9800 optical profiling system and found to be within 5% of the design phase profiles. The vortices are formed in the vicinity of the focal plane of the optical system. Photographs of the transverse beam patterns in the weak (linear) intensity regime, for three selected vortex orders, are shown in Fig. 1. For all generated vortex orders, the peak-to-peak intensity variations, along the circumferences of the vortex rings, are within 10% of the maximum intensity levels. These variations are static and do not change from one laser shot to another as

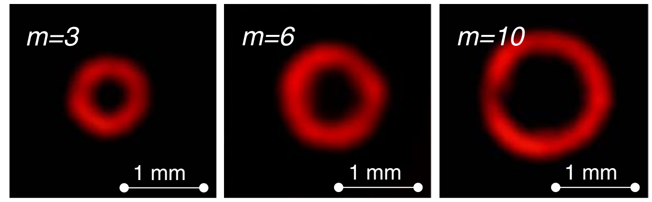

FIG. 1 (color online). Intensity beam patterns for low-power vortex beams of three selected orders, photographed near the focal plane of the optical system.

they result from the imperfections of the phase-mask fabrication process.

In order to quantify the critical power for self-focusing of a particular femtosecond vortex beam, we gradually increase the beam power and detect the onset of plasma generation at the focal plane of the weakly focusing telescope. The density of plasma is measured, on an arbitrary unit scale, using the capacitive plasma probe schematically shown in the inset of Fig. 2 and described in detail elsewhere [12]. In the present experiments, the probe has 1 cm $\times$ 1 cm square electrodes that are parallel to each other, separated by a distance of 1 cm and charged to several hundred volts. Somewhat arbitrarily, we select a threshold for the signal returned by the probe and assume that exceeding that same threshold by the probe signal is indicative of the onset of self-focusing for all vortex orders.

The results of plasma-density measurements are shown in Fig. 2, for selected vortex orders, as well as for the unmodulated flattop beam. The signal threshold used for the identification of the onset of self-focusing is marked by the horizontal dashed line. For the input flattop beam, the critical power measured that way is about 6 GW, which is close to that reported for femtosecond pulses at 800 nm wavelength in air [13].

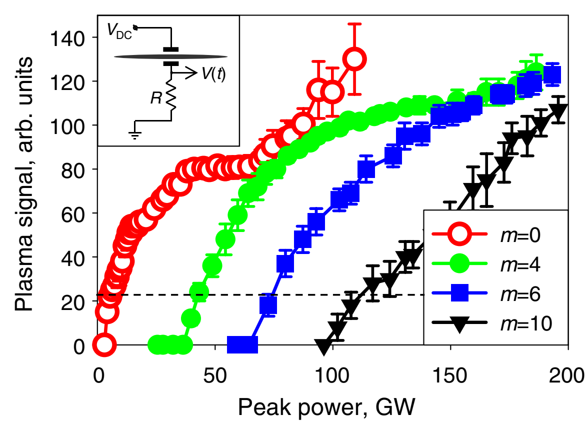

FIG. 2 (color online). Plasma density generated at the focal plane of the telescope versus input peak power, for vortex beams of selected orders. The case of $m = 0$ corresponds to the unmodulated flattop input beam. The capacitive plasma probe used for plasma detection is schematically shown in the inset.

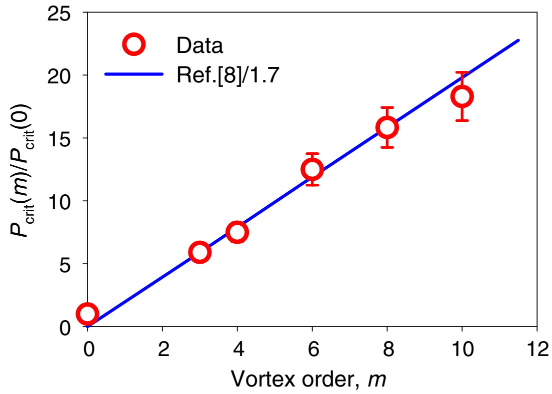

FIG. 3 (color online). Measured critical power for vortex beams of different orders, plot together with the power for self-similar collapse, calculated, for the cw case, according to Ref. [8] and divided by a factor of 1.7.

We note that the way of detecting self-focusing collapse that we employ here is not ideal. Both plasma generation and self-focusing are thresholdlike processes with respect to the optical intensity of the incident beam, and using one for the detection of the other may be associated with some uncertainty. However, we are not interested in the quantification of self-focusing thresholds for vortex beams on the absolute unit scale, but rather in determining these thresholds relative to the threshold for the unmodulated flattop beam. We assume that the onset of plasma production is an indicator of self-focusing that at least allows us to relate the values of the critical power for different beam shapes. Another reason for us to use this approach is simply because we are not aware of an alternative method that would reliably work for arbitrarily shaped beams.

The results for the critical power for self-focusing, for optical vortices of various orders, are summarized in Fig. 3. Error bars in the data points represent variations with respect to physically different realizations of phase masks used to generate each particular vortex-beam order. In all cases, the peak-to-peak intensity variations along the circumferences of the vortex rings are within 10% of the maximum intensity levels. It is evident that the critical power grows approximately linearly with the vorticity order. That growth has a slope that is by about a factor of 1.7 slower than what is expected for the case of self-similar collapse of these vortices in the cw case analyzed in [8].

We point out that the experimental data shown in Fig. 3 are not intended for quantitative comparison with the analytical results of [8]. The theory developed in [8] is for a particular (self-similar) mode of collapse of continuous-wave vortex beams. It is certainly not applicable to the ultrashort-pulse case.

In order to investigate the mode of self-focusing collapse (self-similar versus azimuthal breakup), we visualize the intensity patterns of the beams in the filamentation zone though the production of single-shot burns by the beams on

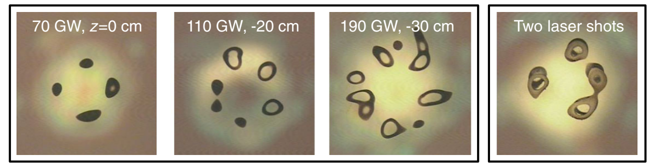

FIG. 4 (color online). Left three images: Single-shot burn patterns produced by the vortex beam of order 3, at different levels of input optical power. Power levels and longitudinal locations, relative to the focal plane of the focusing system, are specified in the individual images. Right image: Burn pattern produced by two consecutive laser shots. The placement of filaments within the beam profile is approximately determined by the static input intensity modulation of the beam profile but slightly fluctuates from one laser shot to another due to the air turbulence.

the front (plastic) surfaces of computer compact disks. This analysis shows that the initially smooth doughnut-shaped intensity patterns of optical vortices break up into individual filaments at power levels above the corresponding measured levels of the critical power.

We point out that the measured values of critical power for the vortices of different orders are likely to be affected by the level of initial transverse intensity modulation of the beam profiles. We were not able to quantify the dependence of the critical power on the level of this modulation as the modulation resulted from imperfections of the phase-mask fabrication process and could not be easily

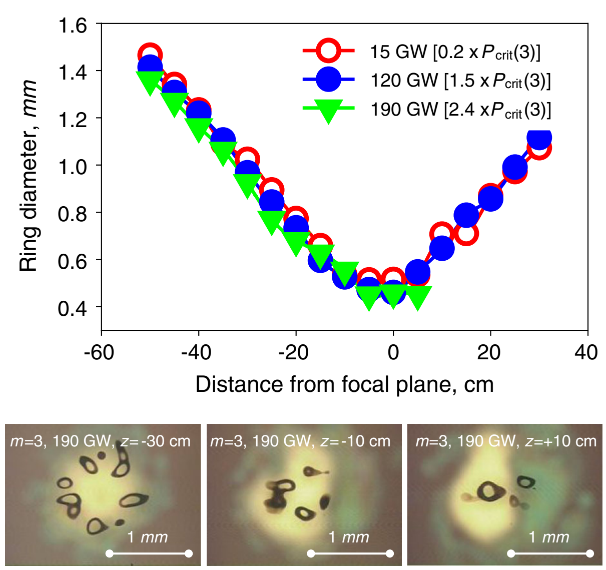

FIG. 5 (color online). Top: Diameter of the ring intensity feature of the vortex beam of order 3, versus distance from the focal plane, for three different values of input optical power. All three curves overlap within the experimental error. The curve corresponding to the highest power of $2.4P_{crit}(3)$ terminates shortly after the focal plane, where the ring filament pattern becomes completely disintegrated. Bottom: Single-shot burn patterns produced by the same vortex beam with the highest available power, at three locations along the propagation direction.

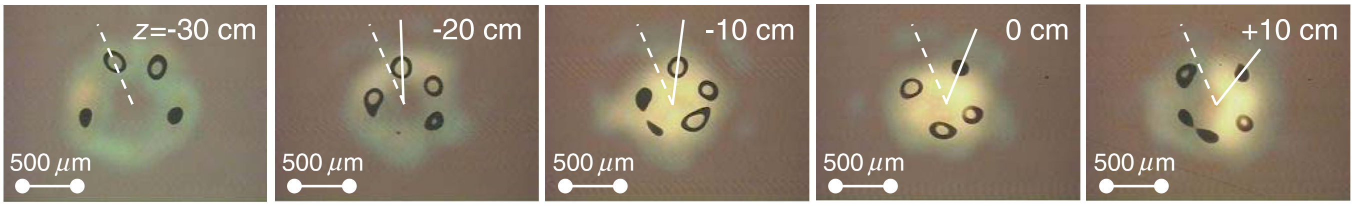

FIG. 6 (color online). Rotation of the filament pattern along the propagation direction, for the vortex beam of order 3 with peak power of 80 GW.

controlled. However, since the azimuthal breakup of the vortex rings is driven by transverse modulation instability, we do not expect the critical power values to be significantly higher for the case of vortex beams with smaller level of distortions than those used in our experiments.

As shown in Fig. 4, the number of the generated filaments, for a particular order of vorticity, grows approximately linearly with the input beam power. The halo in the burn images results from the optical damage of the back (metallic) surface of the compact disk, which is out of focus of the microscope used to record these images. In the rightmost image in Fig. 4, we show a burn pattern produced by two consecutive laser shots with a vortex beam of a particular order. The pattern indicates that the placement of the generated individual filaments is approximately deterministic. It is defined by the spurious intensity variation in the input beam profile and exhibits small shot-to-shot fluctuations due to the air turbulence.

Up until the highest power attainable in our setup, we did not observe any indication of self-similar collapse of the vortices. In Fig. 5, we show the experimentally measured diameter of the vortex ring of order 3, along the propagation direction, at several selected power levels. The highest power in this plot corresponds to about 2.4 times the estimated power for self-similar collapse for that vortex order. Even at that power level, the ring-shaped filament pattern persists all the way to the focal plane, while its diameter remains equal to that of the vortex beam if it propagated linearly. Immediately after the focal plane, the ring filament pattern quickly disintegrates. We attribute this dramatic distortion of the beam pattern to the effect of rapid loss of phase associated with multifilamentation [14].

When the ring intensity feature of an optical vortex breaks up into filaments the resulting filament pattern rotates on propagation in the direction determined by the sense of vorticity. In Fig. 6, we show several snapshots of the filament pattern produced by the vortex of order 3, along the propagation direction. As evident from these images, the rotation rate of the filament pattern, in this particular case, is several degrees per centimeter. Similar rotation rates are observed for vortices of other orders. Rotation of the filament patterns produced through azimuthal breakup of vortex beams is a manifestation of angular momentum conservation. It is a consequence of the fact that a vortex beam can be viewed as a bundle of rays that spiral on propagation around the beam axis. As these spiraling rays start to bunch together due to self-focusing and form filaments, their spiraling motion is imprinted onto the azimuthal motion of the resulting filament pattern.

In conclusion, we have reported the results of experimental study of self-focusing dynamics of ultraintense femtosecond optical vortices in air. Our results confirm that optical vortices are resistant against self-focusing, and that the critical power for self-focusing for these beams grows approximately linearly with the vortex order. With less than 10% of initial spurious intensity modulation of the generated vortex beam patterns, the dominant mode of self-focusing collapse is found to be the azimuthal fragmentation of the vortex rings into individual filaments. The number of the generated filaments, for a particular vortex order, is found to grow approximately linearly with the input beam power. The resulting filament patterns are shown to rotate on propagation in the direction determined by the sense of vorticity.

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