Control of multiple filamentation in air

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In this Letter we provide what is believed to be the first experimental evidence of suppression of the number of filaments for high-intensity laser pulses propagating in air by beam astigmatism. We also show that the number, pattern, and spatial stability of the filaments can be controlled by varying the angle that a focusing lens makes with the axial direction of propagation. This new methodology can be useful for applications involving atmospheric propagation, such as remote sensing.

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The propagation of high-power ultrashort pulses through the atmosphere is currently one of the most active areas of research in nonlinear optics, with potential applications such as remote sensing of the atmosphere and lightning control. In experiments[1,2] narrow filaments have been observed to propagate over distances of hundreds of meters, i.e., over many Rayleigh lengths. Inside the filament the pulse undergoes temporal and spectral changes due to the linear and nonlinear nature of the medium, self-phase modulations, and Raman scattering.[3] Pulses with energies greater than 10 mJ at 100 fs undergo self-focusing collapse in air and produce a highly intense light filament with a diameter of 100 μm and a length of several meters. At higher initial power such pulses exhibit pulse splitting, multiple collapse,[4] and repeated filamentation over distances greater than 10 km into the atmosphere.[5] Propagation of filaments over such long distances is known to be the result of the dynamic balance between the focusing Kerr nonlinearity, diffraction, and the defocusing effect of plasma formation due to multiphoton ionization. The initial stage of propagation during which filaments are formed, however, is much less understood. In particular, since in these experiments the laser power is many times the critical power for self-focusing P_{cr}, a single input beam typically breaks into several long and narrow filaments, a phenomenon known as multiple filamentation (MF). Since MF involves a complete breakup of the beam's cylindrical symmetry, it must be initiated by a symmetry-breaking mechanism. The standard explanation for MF in the literature has been that it is initiated by input beam noise.[6] Since noise is by definition random, this explanation implies that the MF pattern should be different from shot to shot; i.e., the number and location of the filaments is unpredictable. This constitutes a serious drawback in applications in which precise localization is crucial or in experiments in which one wants to measure the filament properties (power, transverse profile, etc.) after some propagation distance. Although significant efforts have been made to reduce the noise level in high-power lasers, it is not easy to eliminate it to a degree that will lead to a deterministic MF pattern.

In several studies it was predicted theoretically[7–9] and observed for laser pulses propagating in sodium vapor[7] and in water[10] that input beam astigmatism can also lead to a deterministic MF pattern, i.e., a pattern that is reproducible from shot to shot. In this Letter we provide the first experimental evidence that input beam astigmatism can induce a deterministic MF pattern for intense laser pulses propagating in air. This shows that sufficiently large astigmatism can dominate noise in the determination of the MF pattern in atmospheric propagation. In other words, rather than trying to eliminate noise, one can control the MF pattern by adding sufficiently large astigmatism. In this study we also introduce a new approach to controlling the MF pattern by use of a tilted lens setup. Our experiments show that this simple setup can control the number and pattern of filaments. In particular, it enabled us to suppress MF in air for a noisy 65.5-GW beam, achieving instead a single filament whose transverse position was highly stable.

There is a fairly developed theory for propagation of a single laser pulse whose power is moderately above the critical power,[11] which is based on the fact that the collapsing solution assumes the universal self-similar Townesian profile.[12] No such theory exists, however, for MF of high-power laser beams, because there is no universal profile at these power levels.

Nevertheless, one can predict the MF patterns induced by input beam astigmatism based on symmetry arguments.[10] Consider an elliptic input beam of the form $E_0(x, y, t) = F(x^2/a^2 + y^2/b^2, t)$. If the filamentation pattern is induced by input beam ellipticity, it can consist only of a combination of (1) a single on-axis central filament, (2) pairs of identical filaments located along the ellipse major axis at $(\pm x, 0)$, (3) pairs of identical filaments located along the minor axis at $(0, \pm y)$, and (4) quadruples of identical filaments located at $(\pm x, \pm y)$.

In our experiments we used a Ti:sapphire laser system with 0.5 TW of power ($\lambda = 800$ nm) at a 10-Hz repetition rate. For laser propagation experiments the input power was 65.5 GW ($\sim 20\ P_{\mathrm{cr}}$), and the pulse duration was set to be 200 fs. The input beam spatial profile was noisy and elliptical with an eccentricity of $b/a = 2.27$ ($a = 0.8$ cm, $b = 1.82$ cm; see Fig. 1). The laser pulse was focused by a lens with a focal distance of 200 cm whose purpose was (1) to shorten the collapse distance and (2) to modify the beam's astigmatism. The lens was set on a rotating holder, allowing us to create an angle φ between the lens surface and the beam's transverse plane, thus controlling the amount of astigmatism. A long plasma channel, beginning at $\sim$150 cm after the lens, was observed, out of which several filaments emerged. A camera was set up at a fixed propagation length of 500 cm after the lens ($\sim$30 Rayleigh lengths) to record the transverse pattern of the filaments (Fig. 2).

In the first series of experiments the lens was set in the traditional way, i.e., perpendicular to the beam's optical axis ($\varphi = 0°$). A typical filamentation pattern can be seen in Fig. 3 (top left): a strong central filament with two additional weaker filaments along the ellipse minor axis. Averaging over 1000 shots (Fig. 3, top right) shows that the central and lower filaments are stable but that the upper filament sometimes disappears or merges with the central one. It is remarkable that despite the high noise level (see Fig. 1) the filamentation pattern is stable. Since noise leads to a random filamentation pattern, we conclude that the filamentation pattern was predominantly determined by the input beam astigmatism. Indeed, the filamentation pattern is close to the theoretical prediction for an ellipse, based on the symmetry argument mentioned earlier. Noise does have some effect, though, since in the case of an ideal noiseless elliptical beam the two side filaments must be identical.

In the second series of experiments we tested our new approach to controlling MF through a tilted lens setup, which can be viewed as a variable astigmatism source. As we changed the lens angle with the direction of propagation to $\varphi = 5°$, we observed that the two side filaments moved farther away from the central filament along the minor axis (see Fig. 3). In addition, around the central filament the beam became elongated along the major axis. With further rotation to $\varphi = 10°$ the two filaments along the minor axis disappeared. Instead, two strong filaments appeared along the major axis, and the central filament became weaker than the side filaments. The left filament is stronger than the right filament, but both are stable. Finally, at $\varphi = 20°$ we observe a single filament, which is highly stable in space. We measured the filament energy to be 0.9–1.2 mJ, i.e., $\sim$10% of the total beam energy.

A well-known difficulty in experiments with high-power lasers is that the transverse location of the filaments can change from shot to shot due to the random nature of the noise that leads to MF. Our results show that large astigmatism can remedy this problem. For example, even in the traditional setup ($\varphi = 0°$), astigmatism leads to a stable pattern, in which the standard deviation of the location of the strong central filament is 0.15 ± 0.08 mm and 0.75 ± 0.04 mm along

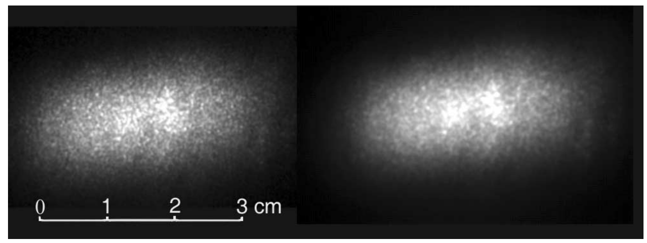

Fig. 1. Input beam spatial profile. Left, typical single shot; right, averaged over 100 shots.

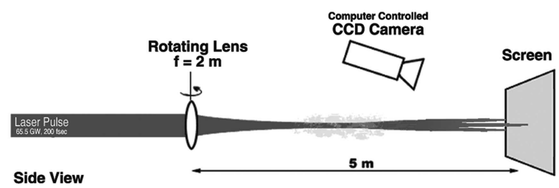

Fig. 2. Experimental setup.

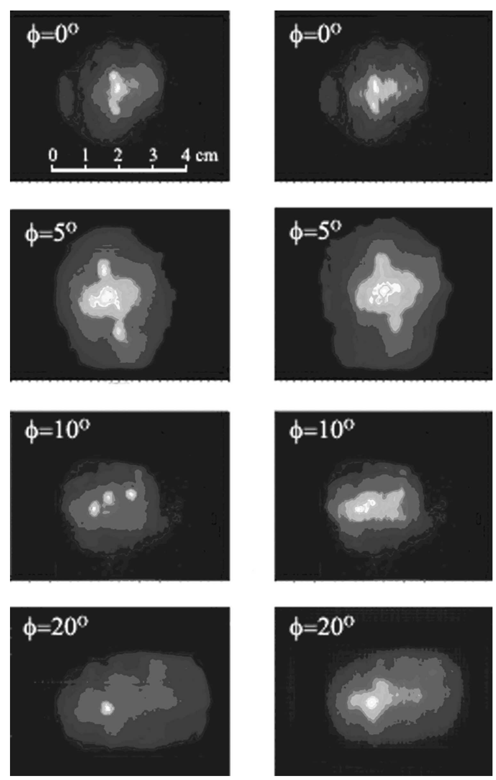

Fig. 3. Filamentation pattern. Left, typical single shot; right, averaged over 1000 shots.

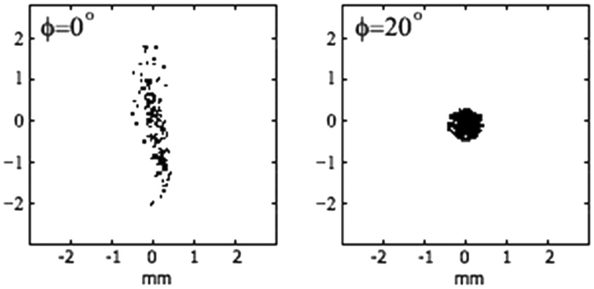

Fig. 4. Location of the central filament in 320 shots.

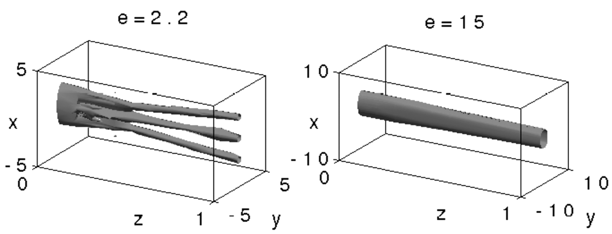

Fig. 5. Solution of Eq. (1) with $\varepsilon_{\text{sat}} = 0.005$ and input power of $15P_{\text{cr}}$.

the direction of the minor and major axes, respectively (Fig. 4). At $\varphi = 20°$ the (single) filament is extremely localized, with a standard deviation of 0.14 ± 0.04 mm in both directions. We have thus demonstrated that the random process of creating a MF pattern can be controlled through beam ellipticity and a tilted lens setup. Rotating the lens enabled us to transfer the MF pattern from the minor to the major axis of the ellipse and to completely suppress MF while achieving a single strong filament that was localized to a high level of precision from shot to shot. This led to the surprising observation of a 65.5-GW beam ($\sim 20P_{\text{cr}}$) that, while propagating in air, does not break into multiple filaments but continues instead as a single stable filament. To the best of our knowledge, this is the first experimental report of such a level of stability at this power level.

The similarity between the results of our experiments and those of Refs. 7 and 10 for propagation in sodium and in water suggests that the role of astigmatism in MF does not depend on the specific linear and nonlinear properties of the medium, which are different for air, sodium, and water. Unlike in Refs. 7 and 10, we made no attempt to reduce the significant noise level present in our input beam, yet we observed that the MF pattern is predominantly determined by the astigmatism. To further support the interpretation of our findings, we performed numerical simulations. Ideally, we should have solved the $(3 + 1)D$ equations for the slowly varying envelope of the electric field $A(x, y, z, t)$. This, however, is a formidable computational task, since one cannot use cylindrical symmetry in MF simulations. Therefore we adopt the approach of mimicking the interplay between the focusing Kerr nonlinearity and the defocusing plasma with a saturable nonlinearity[13] and simulate MF-induced astigmatism by solving the dimensionless nonlinear Schrödinger equation with a saturable nonlinearity:

$$iA_z(z, x, y) + \Delta A + |A|^2/(1 + \varepsilon_{\text{sat}}|A|^2)A = 0\,,$$
$$A(0, x, y) = c\,\exp(-x^2/e^2 - y^2)\,. \tag{1}$$

Numerical simulations of this equation (Fig. 5) show that, indeed, large astigmatism can eliminate the side filaments, thus reducing the number of filaments from three to one. It it remarkable that, despite the differences between the experimental conditions and the mathematical model used in the simulations, there is a striking similarity with regard to the role of astigmatism in MF.

In conclusion, we have investigated the collapse dynamics for a laser beam at power levels much greater than the critical power for collapse. Using an elliptically shaped laser beam and introducing high astigmatism with a titled lens setup enabled us to achieve a single, intense laser filament that propagates in air with a high pointing stability.

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