Multiple filamentation induced by input-beam ellipticity

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The standard explanation for multiple filamentation (MF) of intense laser beams has been that it is initiated by input beam noise (modulational instability). In this study we provide the first experimental evidence that MF can also be induced by input beam ellipticity. Unlike noise-induced beam breakup, the MF pattern induced by ellipticity is reproducible shot to shot. Moreover, our experiments show that ellipticity can dominate the effect of noise, thus providing the first experimental methodology for controlling the MF pattern of noisy beams. The results are explained using a theoretical model and simulations.

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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, narrow filaments of typical width of 100-µm have been observed to propagate over distances of hundreds of meters, i.e., over many Rayleigh lengths. The stability of a single filament over such long distances is nowadays 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, a single input beam typically breaks-up into several long and narrow filaments, a phenomenon known as multiple filamentation (MF). Since MF involves a complete breakup of the beam cylindrical symmetry, it has to 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, see also Ref. 3 for a review. Since noise is, by definition, random, this implied that the MF pattern would be different from shot to shot, i.e., the number and location of the filaments is unpredictable. This constitutes a serious drawback in applications where precise localization is crucial (e.g., laser eye surgery) or in experiments where one wants to measure the filament properties (power, transverse profile, etc.) after some propagation distance. Unfortunately, noise is always present in such high-power lasers, and is not easy to eliminate to a degree that will lead to a deterministic MF pattern.

Recently it was predicted theoretically that input beam ellipticity can also lead to MF. In this case the MF pattern is deterministic, i.e., reproducible from shot to shot. In this study we provide the first experimental evidence that input beam ellipticity can indeed induce a deterministic MF pattern. Moreover, although a certain amount of noise is present in our beam, we observe that the MF pattern is nearly identical from shot to shot. This shows that sufficiently large ellipticity can dominate noise in the determination of the MF pattern.

In other words, rather than trying to eliminate noise, one can control the MF pattern by adding sufficiently large ellipticity to a noisy input beam.

Most recent experimental studies of MF of intense laser beams have been performed in connection with atmospheric propagation. Despite some important differences (nonlinear response, dispersion, etc.) between gases and condensed media, it is expected that the physical processes leading to MF are very similar in both cases. Indeed, some of the present authors have recently demonstrated self-guided propagation of femtosecond light pulses in water for distances exceeding several Rayleigh lengths. In the experiments reported in this study, we increase the incident beam power and modify its spatial parameters, resulting in MF in water.

A 170-fs, 527-nm pulse was provided by second-harmonic compressed Nd:glass laser system (TWINKLE, Light Conversion Ltd., Lithuania) operated at 33 Hz repetition rate. Spatially filtered beam was focused into ~ 85-µm FWHM beam waist at the entrance of water cell by means of f=+500 mm lens. Incident energy was varied by means of a half-wave plate and a polarizer. The focused beam has a small intrinsic ellipticity, which was evaluated as a parameter $e=\sqrt{a/b}=1.09$. Highly elliptical beam ($e=2.2$) was formed by inserting slightly off-axis iris into the beam path. The output face of the water cell was imaged onto the CCD camera (Pulnix TM-6CN and frame grabber from Spiricon, Inc., Logan, Utah) with
7× magnification by means of an achromatic objective 

(f=+50 mm). In the first series of experiments we recorded transverse distribution patterns at fixed propagation length 
z=31 mm (∼0.7L_{DF}, L_{DF} = nko_{0}/2) as we increased the incident power, see Fig. 1. Two cases were examined; a near-circular input beam (e=1.09) and an elliptic beam (e=2.2). Several important conclusions can be drawn: 1) The threshold power for MF is much less for the elliptic beam, 2) The number of filaments increases with input power, 3) At power levels moderately above the threshold for MF, in addition to the central filament, there are two filaments along the major axis of the ellipse. At higher powers there are additional filaments in the perpendicular direction. At even higher powers (P=23P_{cr}) one can observe a quadruple of filaments along the bisectors of the major and minor axes. 4) MF starts as nucleation of an annular ring, which contains the power that was not trapped in the central filament (this is more evident for e=1.09). 5) Since the MF patterns shown in Fig. 1 were reproducible from shot to shot, they were not induced by random noise. 6) Investigation of dynamics of the MF structure (data not presented here) showed that it is robust in terms of propagation, i.e., after an initial transient each of the filaments propagates as an independent entity.

In Fig. 1 we observe that the side filaments are always pairs located symmetrically along the major and/or minor axis, and/or quadruples located symmetrically along the bisectors of the major and minor axes. This observation can be explained based on the following symmetry argument. Consider an elliptic input beam of the form 

\[ E_0(x, y, t) = F(x^2/a^2 + y^2/b^2, t) \]

Since the medium is isotropic, the electric field E should be symmetric with respect to the transformation \( x \rightarrow -x \) and \( y \rightarrow -y \). Therefore, if the filamentation pattern is induced by input beam ellipticity, it can only consist of a combination of 1) a single on-axis central filament, 2) pairs of identical filaments located along the ellipse major axis at \((±x, 0)\), 3) pairs of identical filaments located along the minor axis at \((0, ±y)\), and 4) quadruples of identical filaments located at \((±x, ±y)\). Whereas ellipticity decreases the threshold power for MF, it increases the threshold power for the formation of a single filament. Indeed, the threshold for observing a single filament at z=31 mm were 6P_{cr} and 4.9P_{cr} for the elliptic and the near-circular beams, respectively. This ∼ 20% increase is in good agreement with the theoretical prediction for the increase in the threshold power for collapse (of cw beams) due to beam ellipticity.

In the experiment shown in Fig. 2 we produced two input beams with the same ellipticity parameter (e=2.2), but with different orientations in the transverse plane. In both cases we observe that the beam is elliptic and still focusing at P=5P_{cr}, a single central filament at P=7P_{cr}, an additional pair of comparable-power secondary filaments along the major axis of the ellipse at P=10P_{cr}, and a second pair of weaker filaments in the perpendic-

![FIG. 1: Normalized 3D views of filamentation patterns at z=31 mm recorded with circular incident beam (e=1.09, left panel) and elliptical incident beam (e=2.2, right panel). The major axis of the ellipse lies along the x-axis of the plots. P_{cr} = 3.77\lambda^2/(8\pi n_2) = 1.15 MW](image1)

![FIG. 2: CCD camera images of the filamentation patterns of elliptical beams with different transverse orientation (denoted by x and y axes) at z=31mm. Image area is 330 × 330\(\mu\)m², incident power is 5, 7, 10, and 14P_{cr}, as seen from left to right.](image2)
ular direction at $P = 14 P_{cr}$. The rotation of the filamentation pattern with the ellipse rotation thus confirms that the MF in these experiments is indeed induced by the intrinsic beam ellipticity.

We recall that it was recently shown that polarization effects could also lead to reproducible MF pattern [11]. In that case, however, the orientation of the filamentation pattern is determined by the direction of linear polarization. To check that, we changed the direction of linear polarization of the incident beam and verified that it has no effect on the orientation of the MF pattern. Indeed, polarization effects are important only when the radius of a single filament becomes comparable with the wavelength. This is not the case in our experiments, as the FWHM diameter of a single filament is $\sim 20 \mu m$.

In our simulations we used a simpler model of propagation of cw beams in a medium with a saturable nonlinearity, i.e.,

$$iA_z(z, x, y) + \Delta A + \frac{|A|^2}{1 + \epsilon_{sat}|A|^2} A = 0, \quad (1)$$

$$A(0, x, y) = c e^{-x^2/e^2-y^2}.$$

This model is considerably simpler than the physics governing propagation of intense ultrashort pulses in water. Nevertheless, numerical simulations of equation (1) reproduced the same qualitative features observed experimentally. For example, in Fig. 3(a) the MF pattern consists of a strong central filament, a pair of filaments along the minor axis, and a second pair of weaker filaments along the major axis. In Fig. 3(b) the MF pattern consists of a central filament, a quadruple of filaments along the lines $y = \pm 0.37x$, and a pair of very weak filaments along the major axis. These simulations, therefore, suggest that MF induced by ellipticity is a generic phenomenon that does not depend on the specific optical properties of the medium (air, water, silica, etc.) or on pulse duration.

In conclusion, we have demonstrated for the first time that input beam ellipticity can lead to MF. Unlike noise-induced MF, the filamentation pattern is reproducible and consists only of a central filament and/or pairs of identical filaments lying along the major and/or minor axes of the ellipse, and/or quadruples of identical filaments along the bisectors of the major and minor axes. The effect of ellipticity on MF seems to be generic, i.e., independent of the optical properties of the medium. Since a certain amount of astigmatism is always present in experimental setups, this observation may explain previous MF experiments, in which the filamentation pattern was reproducible. In addition, this study shows that one can overcome the random nature of noise and control the MF pattern simply by adding large ellipticity to the input beam.

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