Multiple filamentation induced by input-beam ellipticity

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We provide what is to our knowledge the first experimental evidence that multiple filamentation (MF) of ultrashort pulses can be induced by input beam ellipticity. Unlike noise-induced MF, which results in complete beam breakup, the MF pattern induced by small input beam ellipticity appears as a result of nucleation of annular rings surrounding the central filament. Moreover, our experiments show that input beam ellipticity can dominate the effect of noise (transverse modulational instability), giving rise to predictable and highly reproducible MF patterns. The results are explained with a theoretical model and simulations. © 2004 Optical Society of America

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The propagation of high-power ultrashort pulses in transparent media with cubic nonlinearity is currently one of the most active areas of research in nonlinear optics, promising various potential applications. In experiments, narrow white-light filaments in air,[1] in fused silica,[2] and in water[3] of a typical width of 20–100 μm have been observed to propagate over distances exceeding many Rayleigh lengths. Although the effect of powerful laser beam filamentation (self-trapping) was discovered in the early years of nonlinear optics,[4] the underlying physics is still not completely understood. In particular, since 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's cylindrical symmetry, it has to be initiated by a symmetry-breaking mechanism. The standard explanation for MF of large beams in the literature has been that it is initiated by input beam noise [modulational instability (MI)].[5] Since noise is, by definition, random, this implies that the MF pattern will be different from shot to shot, i.e., the number and the location of the filaments are unpredictable. However, it has been demonstrated experimentally that the random nature of complete beam breakup could be regularized either by particular focusing geometry of cw beams[6,7] or through wave envelope modulation.[8]

Although MI is a universal phenomenon that applies to a propagating beam as a whole, depending on initial conditions (beam size, shape, polarization, etc.) different MF situations can be assessed (see Ref. 9 and references therein). One particular MF case is a result of MI on the annular ring structure, which surrounds the central filament. In contrast with complete beam breakup, new filaments emerge through the nucleation of annular rings, while the central spike remains stable during propagation. Recently it was predicted theoretically that input beam ellipticity can regularize the nucleation of annular rings and lead to deterministic MF patterns, i.e., patterns that are reproducible from shot to shot.[10,11]

Most recent studies of MF of intense laser beams were conducted in connection with atmospheric propagation[12–15] and addressed to MF through complete beam breakup. In the experiments reported in this Letter we provide what is to our knowledge the first experimental evidence that input beam ellipticity can induce a deterministic MF pattern in ultrashort pulses in water, which are not a result of complete beam breakup. The results show that sufficiently large ellipticity can dominate the random nature of MI in the determination of the MF pattern.

A 170-fs, 527-nm pulse was provided by a second-harmonic compressed Nd:glass laser system (TWINKLE, Light Conversion, Ltd., Vilnius, Lithuania) operated at a 33-Hz repetition rate. A spatially filtered beam was focused into an ~85-μm FWHM beam waist at the entrance of a water cell by means of an $f = +500$ mm lens. The 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 parameter $e = a/b = 1.09$. A highly elliptical beam ($e = 2.2$) was formed by insertion of a slightly off-axis iris into the beam path. The output face of the water cell was imaged onto a CCD camera (8-bit dynamic range, Pulnix TM-6CN and frame grabber, 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 ($\sim 0.7 L_{\mathrm{DF}}$, $L_{\mathrm{DF}} = n k_0 r_0{}^2/2$) as we increased the incident power. Two cases were examined: a near-circular input beam ($e = 1.09$) and an elliptical

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beam ($e = 2.2$); see Fig. 1. Several important conclusions can be drawn: (1) MF starts as a nucleation of an annular ring, which contains the power that was not trapped in the central filament (visually, this is more evident for $e = 1.09$). (2) At power levels moderately above the threshold for MF, in addition to the central filament there occur two filaments along the major axis of the ellipse. At higher powers there occur 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. (3) The MF patterns shown in Fig. 1 were reproducible from shot to shot, so they were not induced by random noise. (4) The threshold power for MF is much less for an elliptical beam. (5) The number of filaments increases with input power.

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 elliptical 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, 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 consist of only a combination of a single on-axis central filament, pairs of identical filaments located along the ellipse major axis at $(\pm x, 0)$, pairs of identical filaments located along the minor axis at $(0, \pm y)$, and quadruples of identical filaments located at $(\pm x, \pm y)$.

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 was $6P_{cr}$ for the elliptical beam and $4.9P_{cr}$ for the near-circular beam. 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.[16]

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 elliptical 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 perpendicular direction at $P = 14P_{cr}$. Rotation of the filamentation pattern with ellipse rotation thus confirms that the MF in these experiments is indeed induced by the intrinsic beam ellipticity.

We note that it was recently shown that polarization effects could also lead to a reproducible MF pattern.[17,18] 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 ~20 μm.

The propagation dynamics of the MF structure is shown in Fig. 3. Between $z = 15$ mm and $z = 30$ mm the MF structure is robust in terms of propagation—each of the filaments propagates as an independent entity. Secondary filaments decay much faster than the central one. This can be explained by a reduced amount of power contained within secondary filaments; therefore, they survive only until losses unbalance the trapping process. Evidence for the

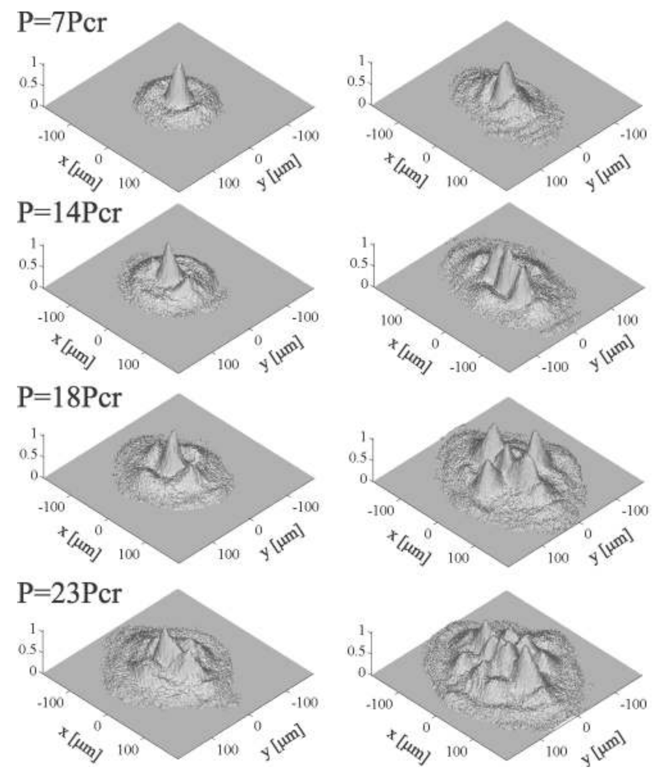

Fig. 1. Normalized three-dimensional views of filamentation patterns at $z = 31$ mm recorded with a circular incident beam ($e = 1.09$, left-hand column) and an elliptical incident beam ($e = 2.2$, right-hand column). The major axis of the ellipse lies along the x axis of each plot. $P_{cr} = 3.77\lambda^2/(8\pi n n_2) = 1.15$ MW.

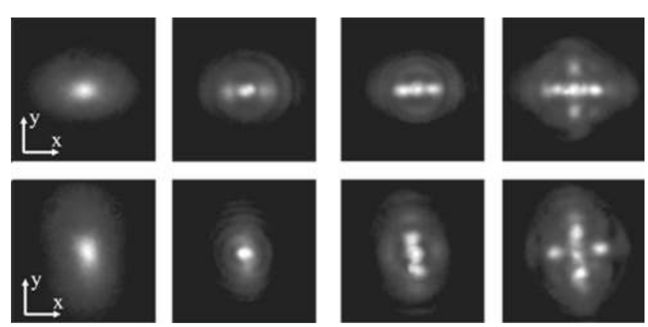

Fig. 2. CCD camera images of the filamentation patterns of elliptical beams with different transverse orientation (denoted by the x and y axes) at $z = 31$ mm. The image area is 330 μm × 330 μm, and the incident power is (from left to right) 5, 7, 10, and $14P_{cr}$.

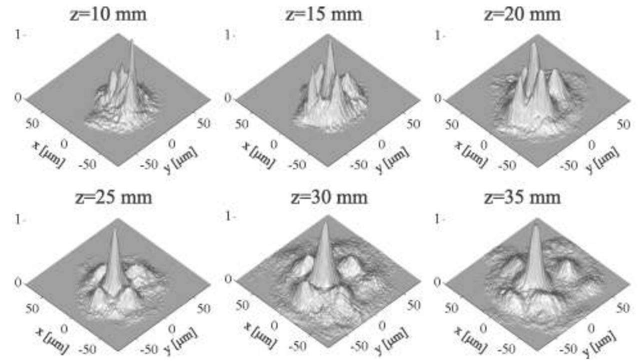

Fig. 3. Propagation of the MF structure. $e = 2.2$, $P = 15P_{\mathrm{cr}}$.

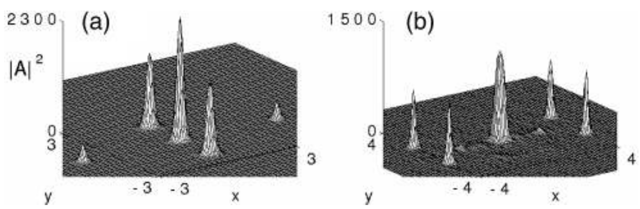

Fig. 4. Solution of Eqs. (1) with $\epsilon_{\mathrm{sat}} = 0.005$ and $P = 66P_{\mathrm{cr}}$. (a) $e = 1.09$ and $z = 0.9$. (b) $e = 2.2$ and $z = 0.7$.

transient (in z) dynamics that precedes the filaments formation can be seen at $z = 10$ mm, where we observe a double central spike with two secondary filaments along the x axis.

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

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

$$A(0,x,y) = \mathrm{const}\, \exp(-x^2/e^2 - y^2). \quad (1)$$

Despite the model's simplicity, numerical simulations of Eqs. (1) reproduced the most important qualitative features that were observed experimentally. For example, in Fig. 4(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. 4(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. In both cases the MF structure is robust in terms of propagation. 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 even small input beam ellipticity can lead to fully deterministic MF patterns. Unlike noise-induced MF, the filamentation pattern is reproducible and consists of only 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 some of the previous MF experiments, in which the filamentation pattern was reproducible.

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Note added in proof: After this Letter was accepted, we learned that similar results were observed in a medium with a quadratic nonlinearity.[19]

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