Light Filaments without Self-Channeling

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(Received 7 July 2003; revised manuscript received 26 April 2004; published 23 June 2004)

The propagation of intense 200 fs pulses in water reveals light filaments not sustained by static balance between Kerr-induced self-focusing and plasma-induced defocusing. Numerical calculations outline the occurrence of a possible scenario where filaments appear because of spontaneous reshaping of the Gaussian input beam into a conical wave, driven by the requirement of maximum localization, maximum stationarity, and minimum nonlinear losses.

DOI: 10.1103/PhysRevLett.92.253903 PACS numbers: 42.65.Tg, 42.65.Jx

Since the first observation of self-trapping of optical beams at the very dawn of the nonlinear optics [1], many of the related phenomenological issues are still poorly understood and attract considerable attention of the scientific community. Since 1995, the spontaneous filament formation accompanying intense fs-pulse propagation in air [2] has received rapidly increasing attention both for the generation of coherent, soft x rays [3], IR [4], as well as subterahertz [5] radiation, and for remote sensing in the atmosphere [6]. More recently research has been extended to the case of filament formation in condensed matter, namely, in transparent solids [7] and water [8]. In spite of the different power and length scales that the process exhibits, two key features emerge, which are substantially the same in all media investigated: (i) for powers well exceeding the critical value for continuous-wave (cw) self-focusing, a light filament appears and propagates in the absence of diffraction or optical breakdown for several to many diffraction lengths and (ii) the filament contains only a small fraction of the impinging-beam power, while the residual excess remains in the filament periphery with no apparent trapping [9].

Two major approaches have been proposed for the modeling, description and understanding of the underlying physics: the first interprets the filament as a genuine solitonlike, self-channeled beam, supported by the *static balance* among diffraction, Kerr-induced self-focusing, and plasma-induced defocusing [2,10]. In this scenario the role of the nontrapped radiation is marginal. The second approach considers the filament as an optical illusion related to the use of time-integrated detection. Here the models, based on moving focus [11] or dynamic spatial replenishment [12], address a dynamic balance where the filament appears continuously regenerated by subsequent focusing of different *temporal* slices of the pulse. We note that nonlinear losses (NLL) were either neglected in the models (because they do not directly act on the field phase) or supposed to be relevant just for the plasma excitation (via multiphoton ionization) or for the quenching of beam collapse. To the best of our knowledge, the hypothesis that NLL might also play a relevant role in reshaping the beam toward the filament formation has never been considered in the literature.

In this Letter, we provide experimental evidence that light filaments formed with 200 fs pulses in water require such an important energy refilling by the surrounding radiation that one can by no means consider them in terms of genuine, solitonlike beams. Moreover, numerical experiments preformed in the frame of a cw model that accounts only for diffraction, Kerr focusing, and NLL outline the occurrence of a spontaneous transformation of the Gaussian into a Bessel-type beam, which fulfils the requirements of minimum (nonlinear) losses, maximum stationarity, and maximum localization.

The criterion we adopted for distinguishing between a solitonlike filament and a strongly refilled one is based on the simple assumption that a genuine solitary beam should survive for at least a few diffraction lengths after transmission through a pinhole that removes the nontrapped part of the radiation and transmits most of the filament energy content. The Kerr medium that we have chosen is water; with respect to solid-state media, it has the key advantages of being free from damage problems, of allowing easy and continuous scanning of sample length, and of permitting the insertion of pinholes along the beam path *inside* the nonlinear media; in comparison with air, water has much less turbulence, which results in higher beam-pointing stability and so allows the use of pinholes of comparable size to the filament. In a previous experiment in air (where 1 mm pinhole was used) the compensation of NLL losses by external radiation was addressed [13] but interpreted only as a perturbative effect, i.e., useful for prolonging the filament life, while not being structural to its existence.

The experiment was performed by launching a 527 nm, $\sim$3 μJ, 200-fs, clean beam, with $\sim$0.1 mm FWHM diameter, onto a water-filled, syringe-shaped, cuvette (with 1 mm thick quartz windows), which allowed continuous tuning of the sample length in the range $z = 5$–40 mm while keeping the beam waist onto the input facet. The measurements consisted in monitoring the output-beam fluence profile by means of a $8X$, $f = +50$ mm achromatic objective and a charge coupled device (CCD) detector (8-bit Pulnix TM-6CN). The wave packet launched was provided by a second-harmonic-compressed, chirped-pulse-amplification Nd:glass laser (TWINKLE, Light Conversion Ltd.), operated at a 33 Hz repetition rate. The results highlighted the appearance of a single filament with almost constant ~ 20 μm FWHM diameter in the $z = 15$–40 mm range investigated.

Figure 1(a) shows the effect of inserting a 55 μm-diameter pinhole in the water cuvette at $z = 20$ mm. The energy transmitted by the pinhole was 20% of the total incident energy. Although the transmitted beam attempted to focus after a short distance (e.g., within one diffraction length; see the plot at $z = 22$ mm), the filament survived no further and we observed a rapid decay with divergence $\sim 2\times$ larger than that of a Gaussian beam of the same FWHM diameter. It is necessary to double-check whether, in the absence of a pinhole, the filament survives just because it is strongly supported by energy refilling from the outside beam. To do this, we also performed the complementary experiment, by blocking the central spike with the sole aid of a 55 μm beam stopper, printed on a 100 μm-thick BK7 glass plate and inserted into the beam path at $z = 20$ mm. As depicted in Fig. 1(b), a central spike of the original dimensions reappeared at $z = 25$ mm, gaining power as it propagated. The profiles measured in the case of "free-filament" propagation are reported in Fig. 1(c) for comparison, in the same z range. Note how the effect of the beam stopper is barely detectable after only 20 mm of propagation. These results unequivocally show that the observed filament can by no means be described in terms of a solitonlike beam self-channelling effect.

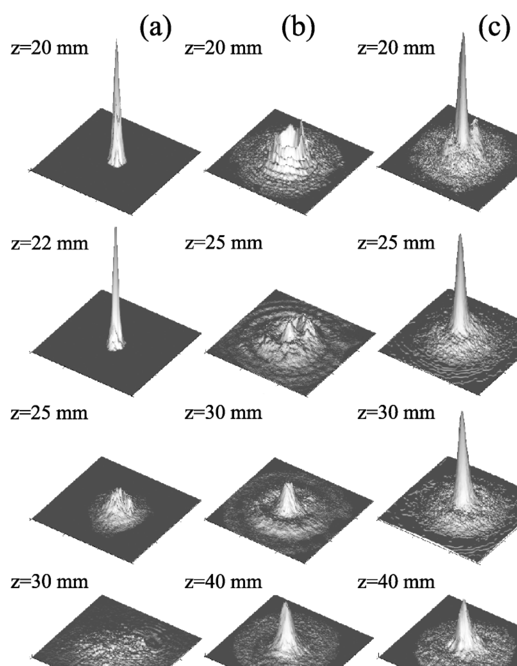

FIG. 1. Fluence profiles for the clipped (a), stopped (b), and free (c) filaments for $20 < z < 40$ mm. Frame size: 280×280 μm^2; fluence units are the same in all insets. Input peak power: $P_p = 13P_{cr}$.

In what follows we present the results of a second, *numerical* experiment aimed to characterize an operating regime dominated by sole diffraction, Kerr focusing, and NLL (i.e., in operating conditions for which plasma defocusing, saturation of the nonlinearity, as well as temporal effects are supposed to play a negligible role). In the frame of a cw and paraxial model the resulting modified nonlinear Schrödinger equation for the field amplitude A reads

$$\frac{\partial A}{\partial z} = \frac{i}{2k}\left(\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2}\right) + \frac{i\omega_0 n_2}{c}|A|^2 A - \frac{\beta^{(K)}}{2}|A|^{2K-2}A, \tag{1}$$

where z is propagation distance, n_2 is the nonlinear refractive index, K gives the order to the NLL (multiphoton absorption) process, and $\beta^{(K)}$ is the NLL coefficient. In our calculations we took $n_2 = 2.7 \times 10^{-16}$ cm^2/W, which is the measured value for water, and $K = 4$, which accounts for a four-photon absorption process [14]. We verified that the results do not depend strictly on the value of K. As for the absorption coefficient $\beta^{(4)}$, we took it as a free parameter by choosing the value that better fit the experimental results (see the captions in Figs. 2 and 3). The fit led to a slight dependence of $\beta^{(4)}$ on input beam power (which may be interpreted as a different role played by plasma absorption at different pumping). We consider the evolution of a linearly polarized beam propagating with central frequency ω_0 and wave number $k = \omega_0 n/c$, with $n = 1.334$. The resulting critical power for cw beam collapse is $P_{cr} = 3.77\lambda^2/(8\pi n n_2) = 1.15$ MW. The input beam profile was taken as Gaussian with a 0.12 mm diameter at FWHM. Note the slightly larger diameter

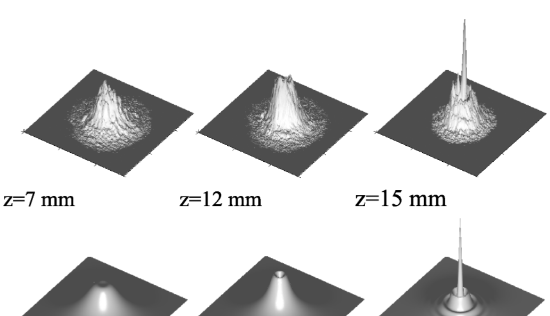

FIG. 2. Transient stage of the filament formation: (top) experimental, $P_p = 17P_{cr}$; (bottom) numerical, $P = 25P_{cr}$, $\beta^{(4)} \simeq 2.0 \times 10^{-34}$ cm^5/W^3.

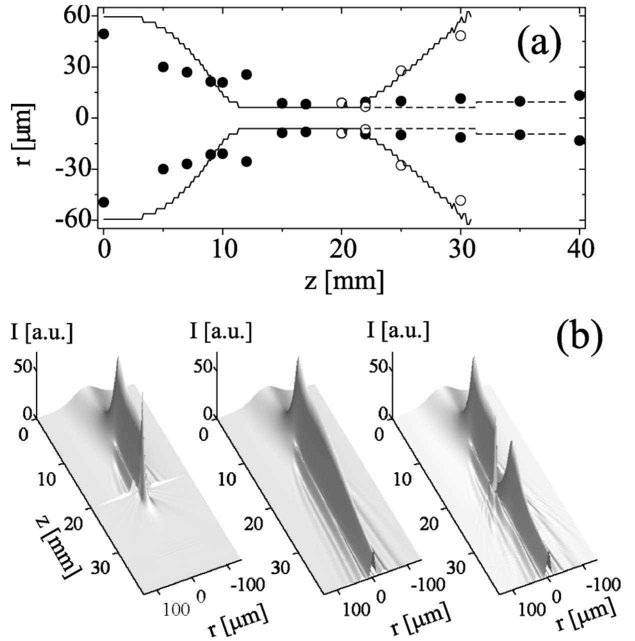

FIG. 3. (a) HWHM beam radius vs z: experiment (full circles) and simulation (dashed line). Open circles and solid line: the same in the case of a 55 μm pinhole only transmitting the central spike. (b) Calculated transverse intensity profiles for the clipped (left), free (center), and stopped (right) filament case. Experiment: $P_p = 13P_{cr}$. Numerical values: $P = 15P_{cr}$; $\beta^{(4)} \simeq 1.25 \times 10^{-34}$ cm^5/W^3.

(and also larger powers; see the figure captions) that had to be taken with respect to the experiment, in order to compensate for a slight overestimation of the losses by our model. Equation (1) was solved numerically by means of the fast Fourier transform Runge-Kutta split-step method.

The calculated beam profiles *in the transient regime* ($7 \le z \le 15$ mm) are presented in Fig. 2 and compared with the experimental ones. The earliest stage of propagation appears to be dominated by NLL, which flattens intensity profile. As a consequence, the Kerr response produces a flattop phase profile, too, while large phase modulation occurs *in the outside corona of the beam,* where the intensity gradient is larger. This phase modulation causes an inner power flux from the beam periphery toward the center, which forms the sharp ring on the beam top (see the *volcano* profile) and finally builds an intense spike at the beam center. As clearly outlined in [15], where the early stage of the process was already considered in the frame of the same model here adopted, NLL dramatically enhance the role of diffraction (especially in conjunction with Kerr response), making it dominating over a much smaller distance than the natural beam-diffraction length. This means that NLL can act as an indirect phaselike effect, even in the absence of any photogenerated plasma. Here the effect is so important that one can by no means reduce the role of NLL to the simple quenching of the collapse at the very end of a catastrophic process. In fact, a genuine catastrophic dynamics requires the self-focusing to act on the entire beam at once, which in turn requires an input beam shape close to the Townes profile [9]. Owing to the NLL-induced disturbance, only the external ‘‘skin’’ of the beam is self-focused. In this scenario, the beam-profile evolution is ruled therefore by a much more controlled and stationary dynamics, with the entire beam acting as a large reservoir that drops power from the outside toward the hot central spike, where NLL losses take place. We note that ‘‘partial self-focusing’’ has been pointed out also in previous investigations, where NLL were not taken into account, as a consequence of disturbances in the launched (elliptical or noisy [9] as well as flattop [16]) beam profiles. Figure 3(a) presents a comprehensive summary of the measured and calculated dynamics in both the transient and the quasistationary range. The HWHM beam radii are plotted both for the free-filament and the 55 μm clipped beams. Note the rather impressive capability of the model in describing the apparent stationary-filament regime, as well as in predicting the quenching of the filament, when the pinhole is inserted. For a more complete description of the dynamics, the corresponding calculated transverse intensity profiles vs z are reported in Fig. 3(b), where the case of the 55 μm beam stopper is also depicted (right).

The modeling of the ultrashort-pulse dynamics in focusing Kerr media is one of the most formidable physical and computational tasks in nonlinear optics (see also [17–21]). To date, the main effects that have been considered as capable of reshaping the beam, counteracting the collapse, and eventually leading to (quasi) stationary regime are those *acting directly on the phase* of the field, e.g., plasma defocusing, saturation of the nonlinearity, and group-velocity dispersion. The surprising capability that our ‘‘toy’’ model has shown in retrieving the experiment in the absence of any of these terms demonstrates that NLL might also contribute in forming the filament, which was never considered before, and that this occurs independently from the presence of plasma, which requires inclusion of the direct effect of NLL in the models. With very short pulses, for example, it is possible to obtain extremely high intensities (and so high NLL) at fairly low fluences, which would make plasma to play indeed a minor role. Moreover, the result raises the natural question on the possible dominance of NLL over all other terms, in our settings. Answering this question is by far out of the purpose of this work, since it requires experimental access to the spatiotemporal profiles (in order to measure all dynamical effects) and the availability of a complete model (where the relative weight of each term can be separately addressed).

In order to outline the most peculiar feature of the regime ruled by Eq. (1) we interpret the resulting dynamics as the spontaneous evolution toward a weakly

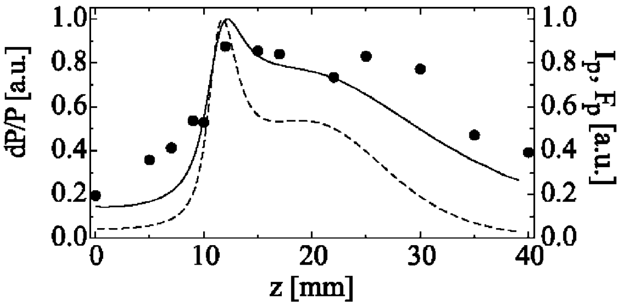

FIG. 4. Calculated peak intensity I_p (solid line); measured peak fluences F_p (full circles); calculated fractional power losses (dashed curve), for the same conditions as in Fig. 3.

localized (e.g., non-soliton-like) stationary solution, which might exist in spite of the presence of NLL. To this end we note that a close inspection of the results in Fig. 3(b) indicates that the beam has undergone an important transformation: from a Gaussian to Bessel-like (i.e., conical) profile, featured by slowly decaying, oscillating tails. This transformation has indeed preserved appreciable localization (e.g., high peak intensity) and stationarity while minimizing NLL. In Fig. 4 we present the measured peak fluence, F_p, the calculated peak intensity, I_p, and the calculated fractional power losses dP/P vs z. The results clearly indicate the occurrence of two different regimes: for $z < 12$ mm, both I_p (F_p) and dP/P increase due to the overall effect of self-focusing and of NLL. After that, however, while I_p (F_p) keeps (for a while) a high and almost constant value, a sharp drop of dP/P occurs. This trend is consistent with a transformation of the beam shape from Gaussian to conical. Indeed owing to the presence of "cold" (e.g., linear) and extended tails, where most of the beam power is contained, a conical wave is provided with a large reservoir that can refuel the "hot" central spike and so preserve overall stationarity, in spite of relevant NLL.

In conclusion, by clipping or stopping a light filament while it propagates in water we have shown that it does not behave as a self-channeled wave packet, being structurally sustained by a strong energy flux from the surrounding beam. A numerical experiment in the frame of a cw model that accounts only for diffraction, Kerr focusing, and nonlinear losses draws a possible scenario where all temporal effects as well as those related to plasma-induced defocusing or saturation of the nonlinearity could be not essential to the occurrence of the apparent guiding effect, which results as the spontaneous transformation of a Gaussian into a conical wave driven by the requirement of maximum localization, maximum stationarity, and minimum nonlinear losses. While further investigation is required in order to clarify the actual dominance of nonlinear losses as a beam-reshaping mechanism in real settings, our results provide a compelling argument about the need of accounting for their direct (e.g., nonplasma mediated) impact in the models. We forecast the existence of an exact, weakly localized, Bessel-like stationary solution of the modified, elliptical, cw nonlinear Schrödinger equation in the presence of nonlinear losses [22].

The authors acknowledge assistance in numerical calculations by A. Parola, M. Porras, and A. Beržanskis, discussions with R. Danielius, A. Piskarskas, A. Couairon, A. Gaeta, and F. Wise, technical support in the measurements by E. Kučinskas, and financial contribution by MIUR (FIRB01) and EC CEBIOLA (ICA1-CT-2000-70027) contracts.

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