Light Filaments Without Self Guiding

Audrius Dubietis, Eugenijus Gažauskas, Gintaras Tamiošauskas, and Paolo Di Trapani

1 Department of Quantum Electronics, Vilnius University, Saulėtekio al. 9, LT-2040 Vilnius, Lithuania
2 Istituto Nazionale di Fisica della Materia (INFM) and Department of Physics, University of Insubria, Via Valleggio 11, IT-22100 Como, Italy

An examination of the propagation of intense 200 fs pulses in water reveals light filaments not sustained by the balance between Kerr-induced self-focusing and plasma-induced defocusing. Their appearance is interpreted as the consequence of a spontaneous reshaping of the wave packet form a gaussian into a conical wave, driven by the requirement of maximum localization, minimum losses and stationarity in the presence of non-linear absorption.

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Since its discovery by Braun et al. [1] in 1995, the spontaneous filament formation accompanying intense fs-pulse propagation in air has received rapidly increasing attention, both for the generation of coherent, soft X-rays [2], IR [3], as well as sub-terahertz [4] radiation, and for remote sensing in the atmosphere [5]. More recently research has been extended to the case of filament formation in condensed matter: namely, in fused silica [6] and water [7, 8], mainly in connection with fundamental investigation in the soliton field [9, 10]. 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 only contains a small fraction of the total beam power, limited by the so-called “intensity clamping effect” [11], while the residual excess remains in the filament periphery with no apparent trapping.

Two major approaches have been proposed for the modeling, description and understanding of the underlying physics: the first interprets the filament as a genuine soliton-like, self-guided beam, whose stationarity is supported by the dynamical balance between Kerr-induced self-focusing and plasma-induced defocusing, where plasma formation is due to multi-photon absorption (MPA) [12]. In this scenario the role of the non-trapped radiation is marginal. In fact, although compensation of MPA-induced power losses by external radiation has been addressed experimentally [13], this refilling effect was only interpreted as perturbative, i.e., useful for prolonging the filament life while not being structural to its existence. The second approach, in contrast, only considers the filament as an optical illusion related to the use of time-integrated detection. The models, based on moving focus [14] or dynamic spatial replenishment [15], interpret the filament as continuously absorbed and regenerated by subsequent focusing of different temporal slices of the pulse.

FIG. 1: Profiles of (a) clipped, (b) stopped and (c) free filaments for 20 mm< z < 40 mm. The input peak power is \( P_p = 13 P_{cr} \).

In this letter we demonstrate how, for the case investigated of 200 fs filaments in water, energy refilling by the surrounding radiation is so important that one can by no means consider the filament in terms of a genuine, self-guided beam. Our results indicate that filament regeneration can well be described within the framework of a purely spatial process, with the fake self-guided beam as resulting from subsequent focusing of different spa-
tial coronas of the beam. The key picture we propose as a physical interpretation of the entire dynamics addresses the spontaneous transformation of a Gaussian into a Bessel-type beam, driven by the requirements of minimum (non-linear) losses, maximum stationarity and maximum localization.

The criterion we adopted for distinguishing between a true (e.g., self-guided) filament and a fake (e.g., strongly refilled) is based on the simple assumption that a genuine filament should survive (for at least 2–3 diffraction lengths) after transmission through a pinhole that removes the non-trapped 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 non-linear 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. We note that this was not the case for the experiment in air quoted above [13], where a very large (e.g., 1 mm) pinhole was used.

The experiment was performed by launching a 527 nm, \( \sim 3 \) \( \mu \)J, 200 fs, spatially filtered beam with an approximately 0.1 mm FWHM waist located at the input facet of a water-filled cuvette, and then monitoring the output-beam fluence profile. The wave packet launched was provided by an SHG-compressed, CPA Nd:glass laser (TWINKLE, Light Conversion Ltd.), operated at a 33 Hz repetition rate. The cuvette was made of 1 mm thick, syringe-shaped quartz, which allowed continuous tuning of the sample length in the range \( z = 5–40 \) mm. The output beam was imaged onto a CCD camera (8-bit Pulnix TM-6CN) by an \( f = +50 \) mm achromatic objective, with 8\( \times \) magnification. The results highlighted the appearance of a single filament with almost constant \( \sim 20 \) \( \mu \)m FWHM diameter in the \( z = 15–40 \) mm range investigated.

Figure 2(a) shows the effect of inserting a 55 \( \mu \)m-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 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 \( \mu \)m beam stopper, printed on a 100 \( \mu \)m-thick BK7 glass plate and inserted into the beam path at \( z = 20 \) mm. As depicted in Fig. 2(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. 2(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 soliton, beam self-guiding effect.

![Figure 2](image)

**FIG. 2:** Transient stage of the filament formation: (top) experimental, \( P_0 = 17 P_{cr} \); (bottom) numerical, \( P = 25 P_{cr} \), \( \beta^{(4)} \sim 2.0 \times 10^{-34} \) cm³/W³.

In what follows, we intend to demonstrate how the key features of the filament-formation process may be interpreted as the effect of spontaneous evolution of the input wave-packet toward a non soliton-like, but still stationary, profile, an hypothesis that has never before been considered. In order to make the point clear, we propose here the simplest possible model that fully supports such a scenario, by adopting the quite severe CW approximation, though a priori exclusion of a possible contribution of temporal or spatio-temporal (ST) effects was not possible. In fact, the results shown in Fig. 2 are also compatible with standard, moving-focus or dynamic spatial-replenishment models (this can be understood by noting that if different temporal slices are focused at different planes, pinholes or stoppers could have different effects on different temporal portions of the wave-packet). Indeed, close inspection of ST wave-packet profiles by means of a high-resolution (20 fs) 3D-mapping technique (in the case of input pulses shorter by a factor two) revealed a dynamics that requires the full 3D model to be described precisely. However, such ST effects, the importance of which dramatically increases on shortening the pulses, are not necessary for filament formation. From the experimental viewpoint, this claim is strongly supported by the measurements with five times longer pulses (we do not present the data here), whose dynamics appeared to be very similar to the present case, espe-
cially in the asymptotic regime. Further support comes a posteriori from the rather good matching achieved between experiment and CW calculations. As a second, highly qualifying, approximation, we have neglected the role of the plasma-defocusing effect, thus avoiding the occurrence of any self-guiding regime. In so doing, we wish to focus attention on the final stage of the dynamics, where plasma-induced effects are supposed to play only a minor role, seeking the occurrence of a “final state” that behaves as an “attractor” for the entire dynamics. The only non-linear terms included in the model are, therefore, those of self-focusing and MPA. Within the framework of the paraxial approximation adopted, the resulting CW, elliptical, modified non-linear Schrödinger equation for the field amplitude $A$ reads:

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

where $z$ is propagation distance, $n_2 = 2.7 \times 10^{-16}$ cm$^2$/W is the non-linear refractive index, and $\beta^{(K)}$ is the MPA coefficient. In our model we took $K = 4$ in order to account for three-photon absorption (water band-gap $W_0 = 6.5$ eV, photon energy $2.4$ eV) and, to a first approximation, for further absorption due to the photo-induced plasma. We verified that similar results are also obtained with different $K$. Owing to the over-simplification of our model, which does not allow for ab initio evaluation of parameters, for the absorption coefficient $\beta^{(4)}$ we took the value that better fitted the experimental results (see the figure caption). The fit led to a slight dependence of $\beta^{(4)}$ on input beam power, which may be understood as owing to the different role played by plasma absorption. We consider evolution of a linearly polarized beam propagating with central frequency $\omega_0$ and wave-number $k = \omega_0 n/\omega$, with $n = 1.334$. The resulting critical power for CW beam collapse is $P_{cr} = 3.77 l^2 (8\pi n n_2)^{1/2} = 1.15 \times 10^3$ MW. The input beam profile was taken as Gaussian with a 0.12 mm diameter at FWHM. Note the rather impressive capability of our model in describing the apparent stationary-filament regime, in the absence of any defocusing effect. The persisting toroidal lens, however, keeps refilling the spike, thus establishing a quasi stationary regime (filament), which remains as long as most of the beam power is coupled to the central spike.

Figure 3(a) presents a comprehensive summary of the measured and calculated dynamics, by plotting the FWHM beam diameters in the entire (i.e., transient plus quasi-stationary) range investigated. Both the free-

$$\text{FIG. 3: (a) HWHM beam radius vs. z: experiment (full circles) and simulation (dashed line). Open circles and solid line: the same in the case of a 55 µm pinhole only transmitting the central spike. (b) Calculated transverse intensity profiles for the clipped (left), free (center) and stopped (right) filament case. Experiment: $P_0 = 13 P_{cr}$. Numerical values: $P = 15 P_{cr}$; $\beta^{(4)} \simeq 1.25 \times 10^{-14}$ cm$^2$/W$^3$.}$$

 filament and the 55 µm clipped filament are considered.

Note the rather impressive capability of our model in describing the apparent stationary-filament regime, in the absence of any defocusing effect. Note also how the model predicts 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). Note that here the case
of the 55 μm beam stopper is also depicted (right).

In order to elaborate the physical interpretation of the entire dynamics, in Fig. 4(a) we plot the (measured and calculated) peak fluence $F_p$ and intensity $I_p$, and the (calculated only) 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 MPA. After that, however, while $I_p$ ($F_p$) keeps a high and almost constant value, a sharp drop of $dP/P$ occurs. Close inspection of the results in Fig. 4(b) indicates that the beam has undergone an important transformation: from a Gaussian to Bessel-like profile, which has preserved appreciable localization (e.g., high $I_p$) and stationarity while minimizing the non-linear losses (MPA). In fact, owing to the presence of "cold", slowly decaying tails, which contain most of beam power, a conical wave is provided with a large reservoir that can refuel the "hot" central spike and so preserve stationarity, in spite of the presence of non-linear losses. If the robustness of the Bessel profile under Kerr-induced spatial phase modulation is accounted for [17], one could foresee that there might indeed exist a Bessel-like, infinite-power, exact stationary solution of Eq. (1) that behaves as strong attractor for the entire non-linear beam transformation.

In conclusion, by clipping or stopping a light filament while it propagates in water we have shown experimentally that it does not behave as a self-guided wave packet, being structurally sustained by a strong energy flux from the surrounding beam. The matching obtained between the experimental results and those based on a CW model that only accounts for self-focusing and non-linear losses provides a strong indication that all the temporal effects as well as all those related to plasma-induced defocusing are not essential to the occurrence of the apparent guiding effect. In contrast, the quasi-stationary filament appears as the dynamical balance between sharp focusing of the very external periphery of the beam (skin focusing effect) and non-linear losses, which continue to absorb the generated spike. We interpret the entire dynamics as the attempt of the wave-packet to readjust its shape, due to the non-linear coupling, according to the requirements of maximum localization, minimum losses and stationarity. We predict the existence of an exact, infinite-power, Bessel-like stationary solution of the modified CW non-linear Schrödinger equation in the presence of non-linear losses.

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