Dressed optical filaments

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In this Letter we show that by appropriately providing an auxiliary "dress" beam one can extend the longevity of an optical filament by almost one order of magnitude. These optical dressed filaments can propagate substantially further by judiciously harnessing energy from their secondary beam reservoir. This possibility is theoretically investigated in air when the filament is dressed with a conically convergent annular Gaussian beam.

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Since the first experimental observation by Braun *et al.*, [1] optical filamentation in transparent media has been the focus of considerable attention. In general, an optical filament establishes itself through a dynamic balance of Kerr self-focusing effects and defocusing processes caused by multiphoton produced plasma [2]. To maintain this balance the filament must expend its own energy, and as expected once its power dips below a certain threshold, it eventually vanishes. Clearly, it will be important to devise schemes capable of extending the longevity of a filament. To this end, several methods have already been investigated [3–12]. For example, by introducing a negative temporal chirp, one can shift the position where a filament forms and possibly double its corresponding propagation length [3–7]. This same principle when applied to Bessel–Gauss beams has been shown to extend a filament as much as two and a half times its normal distance [11,12]. Yet, if one is to adopt such methods, then the success of filament prolongation is ultimately limited by the amount of power contained in the initial self-focusing wavefront. One avenue to overcome this limitation would be to somehow replenish the energy of the filament during propagation.

In this work, we explore a new approach by which the lifecycle of an optical filament in a transparent medium can be extended by almost an order of magnitude. Because a filament's propagation distance crucially depends on its surrounding energy [13–15], we propose to "dress" a filament with an encompassing low intensity auxiliary beam that will act as a secondary energy reservoir. This "dressing beam" is judiciously tailored so that it continuously resupplies power to the filament in a way that extends its longevity. Even more importantly, the dressing beam is prudently designed to maintain a low intensity profile throughout most of its propagation; this prevents the dress from inducing nonlinear effects by itself. The role of the dress reservoir is solely to support the filament during propagation.

To describe the evolution dynamics of a dressed filament we use the Unidirectional Pulse Propagation Equation (UPPE) solver [16]. The electric field is represented in terms of its temporal and spatial spectral amplitude, $\vec{E}(k_\perp, \omega, z)$, which satisfies the equation

$$\partial_z \vec{E}(k_\perp,\omega,z) = +ik_z\vec{E}(k_\perp,\omega,z) + \frac{i\omega^2}{2\varepsilon_0 c^2 k_z}\vec{P}(k_\perp,\omega,z) - \frac{\omega}{2\varepsilon_0 c^2 k_z}\vec{J}(k_\perp,\omega,z), \quad (1)$$

where $k_z(k_\perp,\omega) \equiv \sqrt{\omega^2\varepsilon(\omega)/c^2 - k_\perp^2}$ with $\varepsilon(\omega)$ standing for frequency dependent permittivity of air. The nonlinear light-medium interactions are included within the polarization and current terms and account for the standard components of femtosecond filaments [2]. We use $n_2 \approx 1\times10^{-23}$ m^2/W for the electronic Kerr effect [17] and neglect the delayed Raman response because of our short pulse durations. The strong-field ionization is parametrized as in [18] with effective power-law rates $\partial_t\rho = (\rho_{at}-\rho)\sigma|E(t)|^{2K}$ with $K_{N_2} = 7.5$, $K_{O_2} = 6.5$, $\rho_{at,N_2} = 2\times10^{25}$ m^{-3}, $\rho_{at,O_2} = 5\times10^{24}$ m^{-3}, $\sigma_{N_2} = 7.9\times10^{-124}$ s^{-1} m^{15}/W$^{7.5}$, and $\sigma_{O_2} = 8.85\times10^{-105}$ s^{-1} m^{13}/W$^{6.5}$. We also include effective current and avalanche terms to model energy loss due to ionization; the defocusing effect of freed electrons is accounted for by a Drude model ($\tau_c = 350$ fs) with the current density driven by the electric field and the total freed electron density (see [19] for details of implementation).

For comparative purposes, we first examine the evolution dynamics of an undressed optical pulse with $\lambda = 800$ nm and a Gaussian envelope $\psi_F(r,t,z=0) = \sqrt{2\eta_0 I_0}\exp[-r^2/w_F^2]\exp[-t^2/\tau_F^2]$, where $\eta_0 = 377\Omega$. For this filamenting field, we choose a beam-width of $w_F = 2$ mm, a pulse duration of $\tau_F = 30$ fs, and a peak intensity of $I_0 = 5\times10^{15}$ W/m^2. This corresponds to a power of about $3.27P_{\text{crit}}$. Two cross-sections, $I_F(x, y=0, t=0, z)$ and $I_F(x=0, y=0, t=0, z)$, resulting from the UPPE simulation are displayed in Figs. 1(a) and 1(b), respectively.

As indicated in Figs. 1(a) and 1(b), a filament forms around 6 or 7 m [20] and propagates for approximately $L_1 = 2$ m with a clamped intensity of a few 10^{17} W/m^2 [21]. As seen, this particular filament only experiences one refocusing cycle.

Next, we introduce an annular Gaussian dressing beam with a negative phase tilt of the form, $\psi_D(r,t,z=0) = \sqrt{2\eta_0 I_D}\exp[-(r-r_0)^2/w_D^2]\exp[-i\delta r]\exp[-t^2/\tau_D^2]$. Note that unlike vortex beams this wavefront involves no

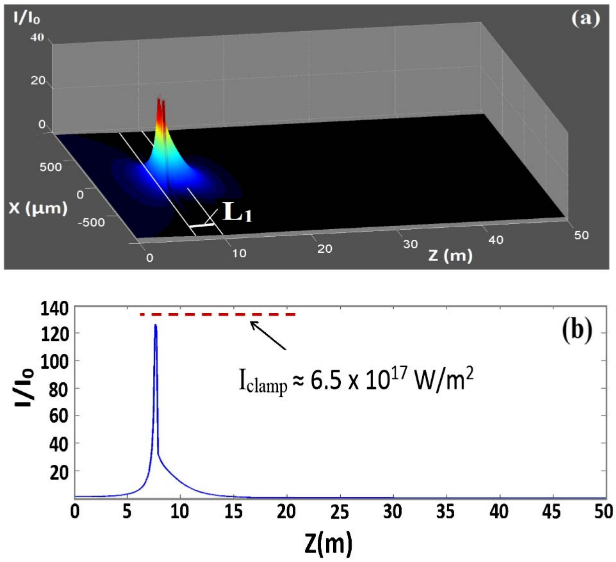

Fig. 1. (Color online) (a) Cross-section, $I_F(x, y = 0, t = 0, z)$, shows the formation of a filament which propagates for a distance, $L_1 \approx 2$ m and (b) inspection along the propagation axis, $I_F(x = 0, y = 0, t = 0, z)$, reveals a self-focusing collapse around 7 meters followed by one intensity clamped refocusing cycle. Intensity values are scaled to I_0 and the intensity limit in (a) is set to $40I_0$.

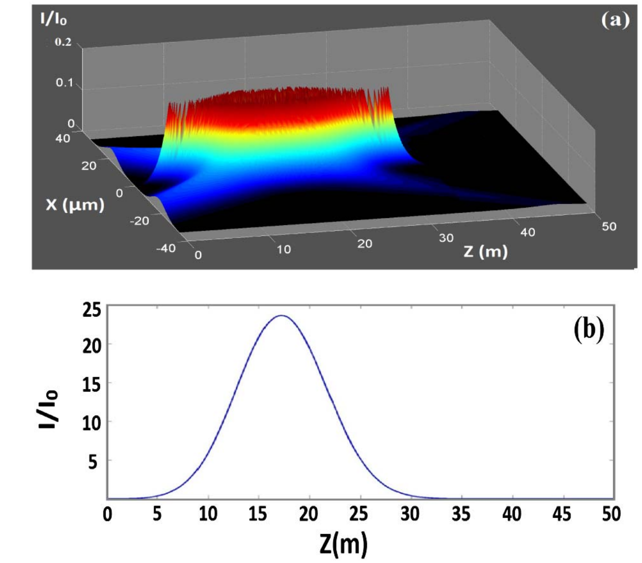

Fig. 2. (Color online) (a) Cross-section, $I_D(x, y = 0, t = 0, z)$, shows the evolution dynamics of the dress beam; note that the maximum intensity of the initial wavefront is only 3% that of the filament and (b) profile $I_D(x = 0, y = 0, t = 0, z)$ indicates that this particular Gaussian dress will supply additional power to the filament when it is necessary.

phase singularity. The parameters for this optical dress are judiciously chosen to be $I_D = 1.5 \times 10^{14}$ W/m^2, $w_D = 1.0$ cm, $r_0 = 1.8$ cm, $\delta = 85$ cm^{-1}, and $\tau_D = 30$ fs. This corresponds to a low intensity wavefront with a large power reservoir containing $22P_{\text{crit}}$. The term $\exp[-i\delta r]$ causes the energy within this dressing beam to gently flow toward the propagation axis, and the parameter δ is tailored so that the dressing beam replenishes the filament (Fig. 2).

Figure 2(a) indicates that the initial maximum dressing beam intensity is quite low ($3\%I_0$) and retains a low intensity profile throughout most of its propagation. An area of concern, however, is along the propagation axis where the intensity can reach higher values. Nevertheless, while the term $\exp[-i\delta r]$ is responsible for channeling the energy toward the center, it also results in rapid defocusing. Consequently, the dress beam itself does not induce lasting nonlinear effects and therefore does not develop a filament during propagation. This becomes evident by monitoring certain features. To begin with, the dress never undergoes self-focusing collapse; additionally, specific to these parameters, the maximum electron plasma densities generated by the dress beam are orders of magnitude less than those anticipated in a filament; lastly, a linear simulation with identical beam parameters produces virtually identical results.

We then synthesize the dressed filament by combining the phase tilted Gaussian dress and the filamenting beam, $\psi_{DF}(r, t, z = 0) = \psi_F + \psi_D$ (intensity cross-section shown in Fig. 3). The evolution dynamics resulting from this initial condition are displayed in Fig. 4. Note that in Fig. 4(a) the dress beam is hardly noticeable since its peak intensity always remains low throughout propagation and is only manifested when it joins the filament beam. We wish to stress that this feature is paramount to the dress beam's efficacy, but also prohibits it from forming its own filament. Nevertheless, the results in Fig. 4(b) show a drastic extension of the filamentation process, which is further confirmed by the presence of plasma and a high intensity core with an average diameter of ≈100 μm. Thus, we are lead to conclude that both the filament and the dress are intimately intertwined during this effect. By comparing Figs. 1 and 4, we clearly see that the auxiliary dress beam replenishes the filament's power and results in many additional refocusing cycles. In this particular example, the filament's length is extended from about 2 meters to 18 meters, a nine fold improvement over the unaided case.

In conclusion, we have shown that one can greatly extend the longevity of an optical filament by judiciously providing an auxiliary dress beam that acts as a secondary energy reservoir throughout propagation. Of interest will be to examine if the filamentation process can be further extended by optimizing the dress beam (e.g., adjusting the shape of the dress beam's intensity). Our results may find application not only in long-range filamentation experiments, but also in settings where higher harmonic generation is possible via these same phenomena [22].

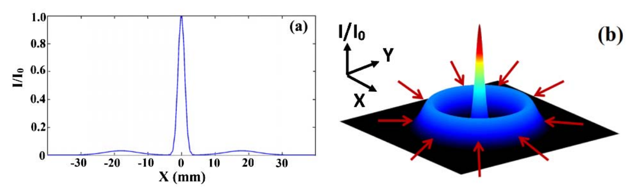

Fig. 3. (Color online) (a) Cross-section of the initial dressed filament, $I_{\mathrm{DF}}(x, y = 0, t = 0, z = 0)$; note that the initial maximum intensity of the dress is only 3% that of the filament beam and (b) because of the negative phase tilt, the dress energy flows inward.

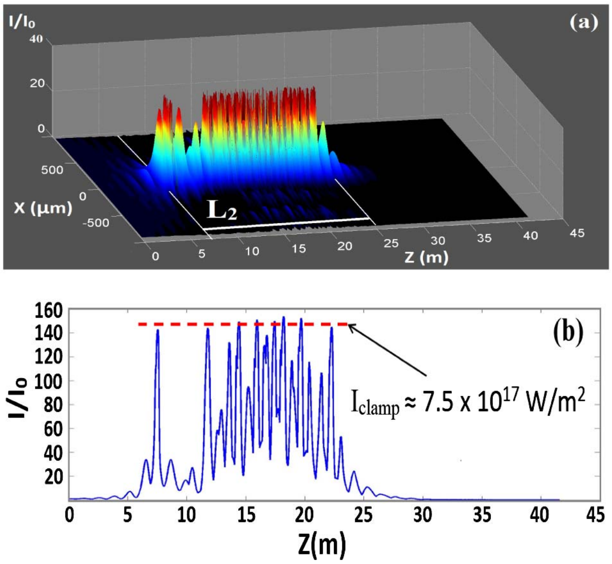

Fig. 4. (Color online) (a) Cross-section, $I_{DF}(x, y = 0, t = 0, z)$, shows the formation of a dressed filament which propagates for a distance, $L_2 \approx 18$ m after the initial focus and (b) inspection along the propagation axis, $I_{DF}(x = 0, y = 0, t = 0, z)$, reveals a self-focusing collapse around 7 meters followed by multiple refocusing cycles. The intensity limit in (a) is set to $40I_0$.

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