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Externally refuelled optical filaments

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Plasma channels produced in air through femtosecond laser filamentation[1–4] hold great promise for a number of applications, including remote sensing[5], attosecond physics[6,7] and spectroscopy[8], channelling microwaves[9–12] and lightning protection[13]. In such settings, extended filaments are desirable, yet their longitudinal span is limited by dissipative processes. Although various techniques aiming to prolong this process have been explored, the substantial extension of optical filaments remains a challenge[14–21]. Here, we experimentally demonstrate that the natural range of a plasma column can be enhanced by at least an order of magnitude when the filament is prudently accompanied by an auxiliary beam. In this arrangement, the secondary low-intensity 'dressing' beam propagates linearly and acts as a distributed energy reservoir[22], continuously refuelling the optical filament. Our approach offers an efficient and viable route towards the generation of extended light strings in air without inducing premature wave collapse or an undesirable beam break-up into multiple filaments[2].

Since the first experimental observation of self-channelling intense femtosecond laser pulses in air by Braun and colleagues[1], optical filamentation has been a topic of intense investigation[23–27]. In general, this process results from the dynamic balance between beam self-focusing effects and the defocusing action of free electrons produced through the photoionization of air molecules. When the energy of an intense laser pulse exceeds a certain threshold, the transverse profile of the beam eventually reshapes into an intense ~100 μm filament core and a surrounding wider, but much less intense, background (photon bath). Remarkably, in this setting, the photon bath continuously feeds energy to the filament, so this self-organized phenomenon can persist over many diffraction lengths[4,28]. Ultimately, however, the finite energy contained in this arrangement is dissipated and the filament vanishes. In other words, only a small fraction of energy is utilized to support the filament core. This represents a fundamental limitation in potential applications such as remote sensing and microwave channelling where long-ranged filaments are often required. Methods to prolong these light strings have been pursued in previous work, and approximately twofold elongations have been reported[17,18]. However, substantially extending the longevity of such entities remains a problem.

In this Letter, we report an order of magnitude extension of an optical filament in air. This is accomplished by appropriately employing a surrounding auxiliary dressing beam, which continuously supplies energy to the filament in a way that considerably protracts its longevity. Our experiments demonstrate that this low-intensity dress acts like an artificial photon bath, the sole purpose of which is to continuously refuel the light string 'in flight'. Rather than concentrating all the available laser energy into a single beam, which can cause either a premature burnout because of ionization losses or chaotic multi-filamentation[29], our scheme provides a versatile route by which to appropriately economize this power consumption to achieve maximum propagation distance. This mode of operation closely resembles that encountered in other dissipative systems associated with a finite amount of combustible material; maximum performance can be achieved by expending this energy at an optimal, gradual rate instead of igniting it all at once. As indicated in our study, such dressed beam configurations are in principle scalable and can thus be used in establishing long-range filaments.

The basic idea behind the proposed method is illustrated in Fig. 1. Figure 1a presents the dynamics of an unaided Gaussian pulsed filament in air. As is clearly shown, this filament can only propagate for a while until dissipation effects deplete its energy after a characteristic length L_1. Beyond this point, the beam irreversibly diffracts. On the other hand, as shown in Fig. 1b, this dynamic balance can be considerably extended, up to a distance of L_2, when this same filament beam is initially surrounded by a low-intensity annular dress. What makes this possible is the fact that the dress wave is radially distributed over a much broader region so as to prevent it from triggering any nonlinear effects. In this scenario,

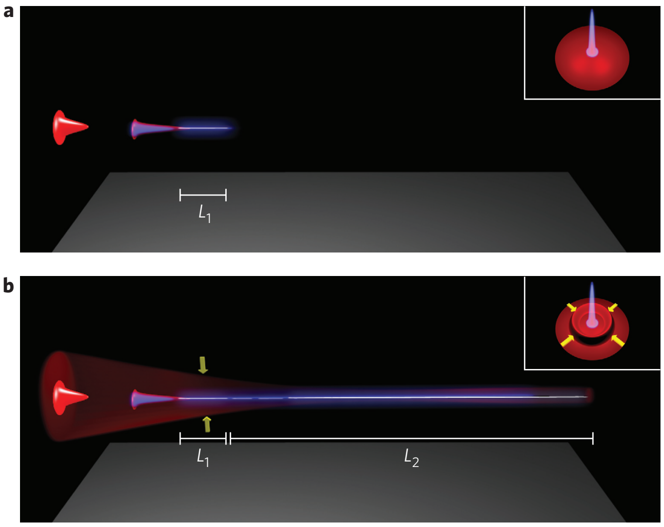

Figure 1 | A dressed filament considerably protracts the longevity of an optical filament. a, A pulsed Gaussian beam (shown in the top inset) with sufficient energy will undergo self-focusing collapse and form a filament that propagates a distance L_1. **b**, If, however, this same beam is appropriately dressed with a convergent annular beam (bottom inset), the filament range can be extended by an additional distance L_2. Yellow arrows in the inset represent the transverse Poynting vector for the energy influx into the filament core.

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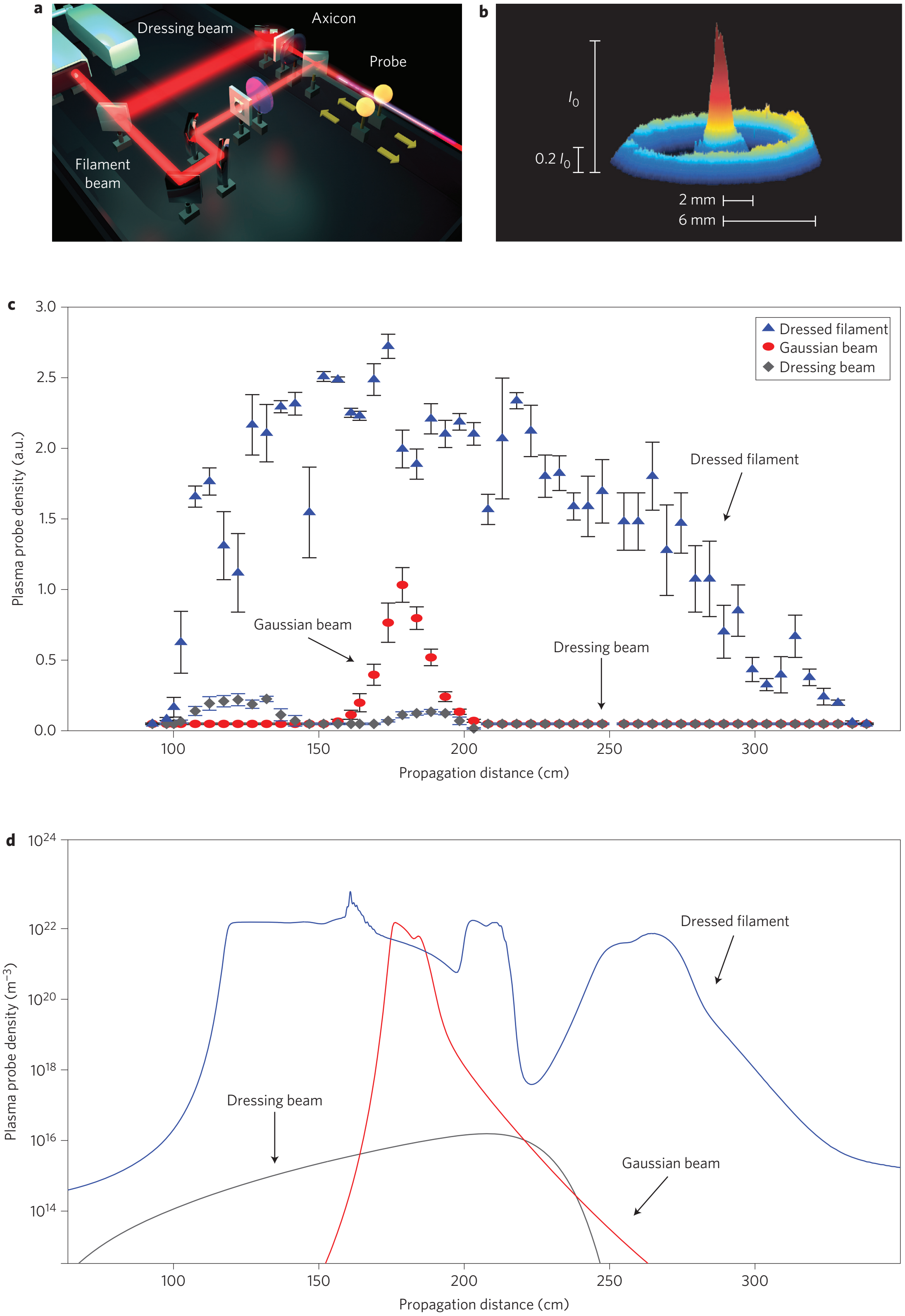

Figure 2 | Experimental investigation of dressed optical filaments. a, Experimental set-up. The input beam is unevenly divided into two parts. The lower-energy portion is focused by a convergent lens with a focal length of 2 m and produces a short plasma filament in air. The higher-energy beam is passed through a shallow axicon lens and assumes the role of the dressing beam. Plasma generation in air is quantified using a capacitive plasma probe. **b**, Intensity profile of the primary and dressing beams together, observed just before the interaction zone. **c**, Experimental demonstration of an extended filament when the primary beam carries an energy of 0.87 mJ and the accompanying dressing beam 3.50 mJ. In this arrangement, the light string propagates for 220 cm, which corresponds to an 11-fold improvement over the unaided filament. Data points were obtained by averaging over 100 laser shots, and error bars represent the corresponding standard deviation. **d**, Plasma density as obtained from numerical simulations for the three cases in **c**. This also corroborates an 11-fold extension of the filamentation process with the aid of a dressing beam.

both beams are coherent with respect to each other, with the spatially chirped dress constantly supplying energy to the high-intensity core.

To demonstrate the aforementioned approach in a laboratory setting, a scaled-down arrangement was used, as shown schematically in Fig. 2a. Both the primary Gaussian filament beam and the accompanying dress are derived from a single Ti:sapphire femtosecond laser system that produces 40 fs pulses at 800 nm. The pulse repetition frequency is 10 Hz and the maximum energy per pulse can reach up to 25 mJ. The output beam from the laser is unevenly split into two, one of which is weakly focused by a lens with a focal length of 2 m and becomes the primary Gaussian filament. Before focusing, this beam is apertured to a diameter of 4 mm. The second wavefront has a much larger diameter (12 mm) and is focused by a conical axicon with an apex angle of 179.8° and undertakes the role of the low-intensity dressing beam. Using this approach, the resulting annular wave acquires a linear spatial chirp in the transverse plane, $\propto \exp(-iCr)$, where C is a constant defined by the geometry of the axicon and r is the transverse radial coordinate. The radial chirp causes a gradual transport of energy from the periphery to the central core of the beam upon propagation, as shown by the transverse Poynting vector arrows, $\vec{S}_t$, in Fig. 1b. In this configuration, the two wavefronts share the same polarization and wavelength and are designed to interact for ~2 m, over which refuelling is expected to take place. The two beams are temporally synchronized using a motorized delay stage and are spatially recombined (Fig. 2a). After accounting for the losses resulting from optical elements in our set-up, the maximum pulse energies delivered in the interaction zone are 0.87 mJ and 3.5 mJ for the filament and dressing beam, respectively. The peak power of the main beam is about twice the threshold power for self-focusing in air. The intensity profile of this filament-dress arrangement just before the Rayleigh zone is shown in Fig. 2b. It should also be noted that relative optical phase fluctuations between the Gaussian and dressing beam result in time-averaged intensity patterns.

Our experimental results are summarized in Fig. 2c. With the primary Gaussian beam acting alone, the length of the generated plasma channel is ~20 cm (see Methods for the measurement technique). The dressing beam, on the other hand, does not by itself produce any measurable plasma and thus does not form a filament. This is anticipated, because the dress energy reservoir is meant to behave linearly so as to discourage the onset of its own filamentation. On the other hand, when the two beams are launched together (with $C = 21\ \mathrm{mm}^{-1}$), the length of the generated plasma channel reaches up to 220 cm, indicating an 11-fold improvement over the former result. As previously indicated, what contributes to this prolongation is the constant refuelling offered by the dress energy tank. In our experiments, we found this interaction to be robust and relatively insensitive to existing imperfections in either beam (Supplementary Section 1). We emphasize again that this interaction involves only one light string and is by no means a multi-filamentary process.

We also conducted similar experiments using different focusing parameters for both the Gaussian and dressing beams. In all cases, the results were found to be qualitatively the same. The dressed filament always outperforms its unaided counterpart. Note that this significant filament elongation is possible in spite of the fact that its range is ultimately limited within the Rayleigh zone of the lens. This improvement can become even more impressive once quasi-collimated dressed filaments are used in long-range arrangements (see discussion associated with Fig. 4). Results from numerical computations corresponding to our experiments are shown in Fig. 2d. Our simulations utilize a femtosecond pulse propagator based on the unidirectional pulse propagation equation[30] (UPPE) (Supplementary Section 2). In all cases, our numerical findings are in good agreement with experiment. The minor differences observed are a consequence of statistical fluctuations in the initial conditions. To demonstrate that the observed plasma elongation is specifically due to the constant refuelling process and is not the outcome of simply increasing the total energy in a pulse, experiments were conducted where energy levels comparable to those used in our previous filament-dress configurations (4.4 mJ) were packed in the same primary filament beam. In every case, the beam collapsed much faster and its energy was inefficiently consumed. In addition, the plasma density generated by the auxiliary beam alone remained several orders of magnitude below the values necessary for the filamentation process. The dependence of the filament's elongation on the dress energy was also investigated in detail (Supplementary Section 3).

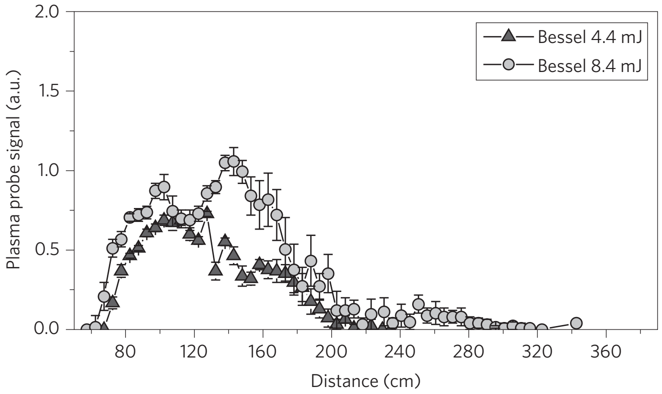

Figure 3 | Plasma density generated by the application of a Bessel beam for different values of laser energy. The length of the plasma filament in this case falls short of that achieved in the dressed filament scenario (shown in Fig. 2c), even when the energy in the Bessel beam is about twice the energy in the Gaussian and dressing beams combined. Data points were obtained by averaging the plasma densities of 100 pulses. The resulting error bars represent the standard deviation of these measurements.

To better understand how the throughput of a dissipative phenomenon like a light string can be externally enhanced, one can offer the following argument. The peak on-axis intensity in a femtosecond laser filament is clamped to a value, I_{clamp}, determined by the onset of plasma generation, which is by nature a threshold-like process[2,4]. If we only consider losses from ionization (that is, by ignoring diffraction/defocusing losses), then in this quasi-steady-state regime, the filament diameter remains almost invariant and, as a result, the rate of the eight-photon oxygen ionization loss, $n_{\mathrm{O}_2}(8\hbar\omega)(\sigma I_{\mathrm{clamp}}^{8})S_f\tau$, is approximately constant. Here, n_{O_2} is the volumetric molecular density of oxygen in air, $8\hbar\omega$ is the energy associated with eight-photon absorption, σ is an eight-photon absorption coefficient, S_f represents the filament cross-sectional area and τ the pulse duration. Interestingly, the performance of any dissipative configuration can always be optimized with respect to the rate at which energy is replenished. For example, this becomes evident even in relatively simple first-order systems where variational principles through Lagrange multipliers can be directly employed (Supplementary Section 4). Under such conditions, one can show that the longevity of such an energy consuming process can be maximized as long as the resupply rate is constant and related to the initial conditions and constraints. In other words, the most efficient rate of energy inflow would be that which just compensates for losses. Supplying any more additional energy would result in wasteful ionization loss, while an insufficient energy in-flow would cause the filament to cease. In regular filaments, the energy flow from the photon bath towards the beam axis is driven by beam self-focusing, an intrinsically unstable nonlinear process that inevitably causes unnecessary local intensity overshooting. On the other hand, in the dressed

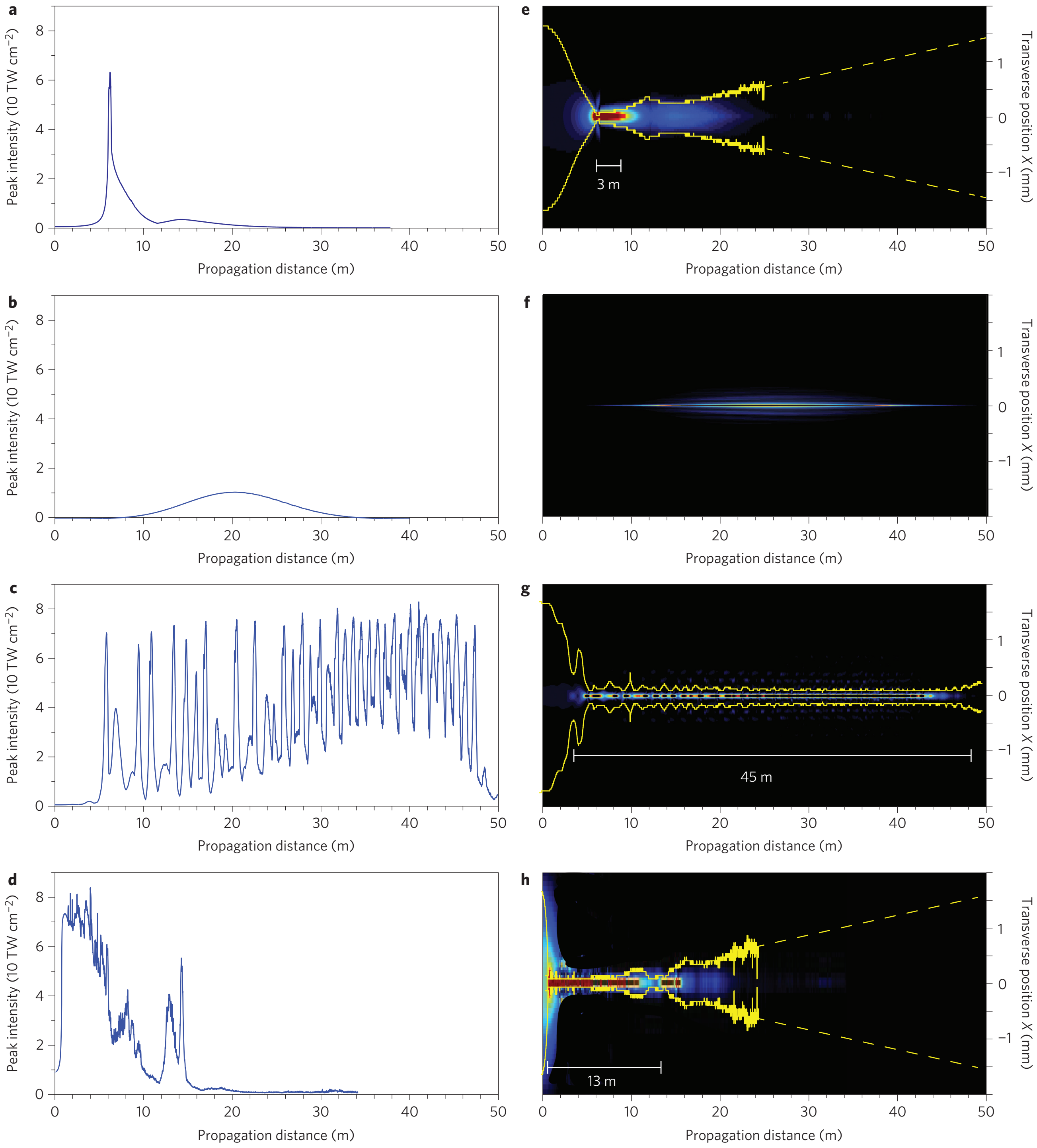

Figure 4 | Dressed optical filaments in long-range settings. a, Numerical simulation of the peak on-axis intensity for a collimated Gaussian beam starting with 2 mm FWHM and 2 mJ of energy. The string decays after $\sim$3 m. **b**, Maximum on-axis intensity when a dressing beam with 26 mJ of energy propagates alone. Even with this large amount of energy, a filament never forms because the dress maintains a low intensity throughout propagation and only refuels the pre-existing filament. **c**, On-axis intensity when the central beam in **a** is aided by the same co-propagating dressing wave in **b**. Here, the dressed filament propagates over 45 m, a 15-fold improvement over the previous result. **d**, Propagation dynamics when all 28 mJ of energy are packed in a Gaussian beam that propagates alone. High on-axis intensity is maintained for only 13 m. **e**–**h**, Intensity cross-sections as a function of propagation distance corresponding to **a**–**d**, respectively. In each case, the propagation varying FWHM of the central beam is indicated by a pair of yellow lines. In **f**, the intensity of the dressing beam propagating alone is considerably lower during propagation. In **g**, the filament maintains an intensity FWHM of $\sim$100 μm over a distance of 45 m (Supplementary Section 9).

filament case, energy from the auxiliary beam flows into the filament core in a controllable manner, which ensures a steady energy resupply rate and results in optimized energy expenditure.

As an alternative to dressed filaments, one could also have used diffraction-free wavefronts, like self-healing Bessel beams, similar to those previously used in other settings[17,31]. Experimental data obtained from intense Bessel beams are depicted in Fig. 3. Clearly, when compared to Fig. 2c, this arrangement still underperforms, even though it contains twice the energy level (8.4 mJ). This is because the transverse energy influx within a Bessel beam is not ideally suited to the prolongation of a filament.

As previously mentioned, the advantage offered by our scheme becomes even more evident in long-range settings (Fig. 4). In this case, both the filament and the dress are almost collimated, thus allowing for extended interaction regions. To demonstrate this possibility, pertinent simulations were carried out using the UPPE method (axicon apex angle of ∼179.9° and clear aperture radius of ∼1 cm). Filament extensions up to 45 m are possible in air using dressed beams containing a total energy of 28 mJ as opposed to a filament alone (carrying 2 mJ) that lasts up to 3 m. This is possible, in spite of the fact that the filament beam is initially launched with a moderate ∼2 mm intensity full-wave at half-maximum (FWHM). Instead, if this same energy of 28 mJ is concentrated in the primary filament, it only propagates 13 m after the onset of self-focusing. In this latter setting, the energy in-flow from the photon bath into the filament core is driven by nonlinear self-focusing, resulting in inefficient energy consumption. We would like to note that, in general, the dynamic balance between the different focusing and defocusing effects is more complex given that it results from a temporal and spectral reshaping of the pulse waveform during propagation (Supplementary Section 5). Finally, a discussion of potential temporal walk-off effects caused by the axicon and a numerical investigation of the time-averaged radial Poynting vector associated with this case can be found in Supplementary Sections 6 and 7.

In summary, we have experimentally demonstrated that the longevity of a femtosecond laser filament in air can be substantially extended by utilizing a co-propagating low-intensity dressing beam that acts as a high-capacity distributed energy reservoir. The proposed approach is scalable and can thus be used in a broad range of applications where elongated filaments are required.

Methods

To characterize the density of the plasma generated along the propagation direction (on a relative scale) we used a capacitive plasma probe[17,32]. Signals returned by probes of this type have been shown to be approximately linear with the local time-integrated plasma density along the filament[32]. All experimental data points shown in Fig. 2c were obtained by averaging over 100 laser shots, while the simulations represent only a single realization. This explains why, in the experiment, the plasma density from the filament alone does not reach the values attained in the dressed case. For a particular laser shot, at a given location along the propagation direction, plasma generation was enhanced by the application of the dressed beam. Integrating the measurement signal over 100 laser shots effectively averaged the pulse-to-pulse fluctuations in the generated plasma density (Supplementary Section 8).

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Author contributions

M.S.M., M.K. and D.N.C. suggested the idea of dressed filaments. M.S.M., M.-A.M. and D.N.C. produced the manuscript, figures and accompanying supplementary information. M.S.M. explored the theoretical aspects of the paper and simulated the process using M.K.'s code. M.S., W.C., J.V.M. and P.P. carried out the experiments reported in this study.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to D.N.C.

Competing financial interests

The authors declare no competing financial interests.