Article

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Abstract

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Ultrahigh power laser pulses delivered by the Alisé beamline (26 J, 32 TW pulses) have been sent vertically into the atmosphere. The highly nonlinear propagation of the beam in the air gives rise to more than 400 self-guided filaments. This extremely powerful bundle of laser filaments generates a supercontinuum propagating up to the stratosphere, beyond 20 km. This constitutes the highest power "atmospheric white-light laser" to date. © *2007 American Institute of Physics*.
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Highly nonlinear effects are expected to prevent long distance propagation of ultrashort and ultraintense laser pulses in the atmosphere. Kerr self-focusing should lead to catastrophic collapse, while laser-induced plasma should defocus the beam. However, at the subjoule and terawatt levels, a subtle balance between Kerr focusing and defocusing by the induced plasma leads to "laser filaments"[1] that are stable over many tens of meters[2] and produce a coherent supercontinuum.[3] We investigated the scalability of this propagation well beyond these energies and powers by launching 26 J, 32 TW laser pulses delivered by the Alisé beamline of the CEA-CESTA in the atmosphere. We show that filamentation still occurs at these extreme levels. More than 400 filaments simultaneously generate a supercontinuum propagating up to the stratosphere, beyond 20 km.

Compared with the propagation of most intense pulses investigated so far using the *Teramobile* facility[4] (400 mJ, 5 TW), we increased the power and energy by one and almost two orders of magnitude, respectively. At the extreme power levels delivered by the Alisé beamline, it is a particular challenge to understand laser propagation. The nonlinear Schrödinger equation used to model the propagation at terawatt levels[5] may be altered by higher order terms, which would prevent the formation of filamentary structures. For instance, over the critical plasma density, inverse bremsstrahlung would stop the beam propagation. Potential applications of filaments stem from their unique properties; the ability of generating a "white-light laser"[3] that can be used in light detection and ranging (Lidar) systems to remotely detect atmospheric pollutants[6] or bioaerosols,[7] creating long conducting plasma channels for lightning control applications,[8,9] and delivering intensities up to 10^{14} W/cm^2 at kilometric distances.[10]

We investigated the vertical propagation in air of pulses from the Alisé laser facility.[11] Alisé was used in a chirped pulse amplification configuration with six stages of Nd:phosphate amplifiers. It provides compressed pulses of up to 26 J energy centered at the wavelength $\lambda_0 = 1053$ nm, with a spectral width of 3 nm full width at half maximum (FWHM). During the experiment, the pulse duration was varied from 520 fs to 65 ps FWHM. We investigated pulses up to 32 TW peak power, corresponding to about 5000 times the critical power for self-focusing [$P_{cr} = \lambda_0^2/(2\pi n_2) \approx 5.8$ GW at 1053 nm, considering $n_2 \sim (3-4)\times 10^{-19}$ cm^2/W in the air[12]]. The beam was emitted vertically into the atmosphere, either collimated (natural divergence of 10 μrad) or slightly focused through lenses ($f=16$ m or $f=300$ m) installed at the exit of the grating compressor. Laser diagnostics included a beam profile analyzer, a single-shot autocorrelator, and a streak camera. A frequency-doubled Nd:YAG (yttrium aluminum garnet) laser, collinear to the Alisé beam, was used as a reference for quantitative estimation of the conversion efficiency into the white-light supercontinuum.

The backscattered white-light signal was detected by a slightly off-axis (50 cm) Lidar system consisting of a 20 cm telescope equipped with detectors sensitive in three spectral ranges in the visible and near-infrared regions. Further spectral selectivity was achieved by using bandpass filters. Simultaneously, the beam was imaged from the side, from an off-axis distance of 5–30 m, by a color-frame, digital charge coupled device camera (Nikon D70).

Once pulses are launched into the air, Kerr effect is initiated in the beam. For the ultrahigh powers ($P \gg 100 P_{cr}$), as is the case in our experiment, multifilamentation occurs through modulational instability that breaks up the beam into periodic cells over very short propagation distances $z_{fil} \approx 2P_{cr}/(\lambda_0 I_0) \approx 1-3$ m for an incident intensity $I_0 \sim 4-6 \times 10^{11}$ W/cm^2. This breakup results in an overall honey-

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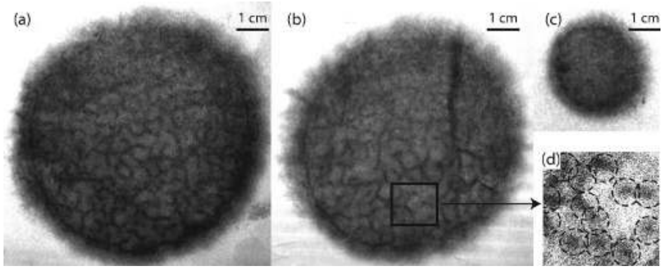

FIG. 1. Beam profile after ~11 m propagation (a) $f=\infty$ ($2550P_{cr}$, 420 filaments), (b) $f=300$ m ($2200P_{cr}$, 290 filaments), and (c) $f=15$ m ($3180P_{cr}$, no filaments distinguishable). (d) Detail of the filamentary structure of (b). Gray circles highlight the filaments.

comb beam structure, the cells of light being separated by "bridges."[13–15] These structures appear as dark straight lines on the beam profile recorded on a photosensitive paper after only 11 m propagation (Fig. 1). Along these structures, hot spots can be observed, which correspond to the onset of mature individual filaments [see Fig. 1(d)]. Their high intensity is confirmed by their ability to locally ablate the surface of a paper screen within a single shot. Calibrated ablation tests showed that the intensity within the filaments is slightly higher than the clamped intensity of 5×10^{13} W/cm^2 observed in subjoule beams at 800 nm.[16] This finding suggests that even at multijoule energies, the filamentation process is governed by the dynamic balance between Kerr effect and plasma defocusing. Hundreds of filaments are observed within the beam profile unless the beam is focused too strongly [Fig. 1(c)]. We counted typically one filament for each 3.5–7.5 critical power P_{cr}, very close to that observed at lower power with the Teramobile ($5P_{cr}$ per filament),[17] although the latter experiments were performed at a wavelength of 800 nm instead of 1.05 μm.

The occurrence of self-guided filaments shows that, as is the case for lower pulse energy, Kerr lens self-focusing does not cause the beam to collapse, but instead promotes a dynamic balance with defocusing induced by the electron plasma generated at the nonlinear foci. This allows the beam to propagate collimated at long distances in spite of strong self-focusing. Filaments generated in the beam emit the white-light continuum forward as a white-light laser,[3] which was clearly visible to the naked eye, propagating to high altitudes in the zenith direction as a collimated beam. Moreover, the laser supercontinuum was observed on Lidar signals over the whole visible spectrum, from 300 to 850 nm, showing that its spectrum is extremely broad. Figure 2 displays the white-light Lidar signal detected in the 300–475 nm spectral region as a function of altitude. Although the acquisition is single shot, the signal can be observed up to 20 km in the stratosphere. This is all the more remarkable that the considered spectral region is more than 600 nm away from the fundamental laser wavelength. This spectacular result constitutes the most powerful Lidar signal acquired so far and definitely assesses the capability of 30 TW pulses to propagate over kilometer-range distances.

To efficiently exploit the possibilities opened by multijoule pulses in the atmosphere, one critically needs to control their propagation. For this reason, we investigated the effect of the pulse duration on the filament location (onset distance and filamentation length). This was performed by adjusting the laser *chirp*, i.e., by tailoring the pulses so that the spectral components of the ultrashort laser beam are launched in a

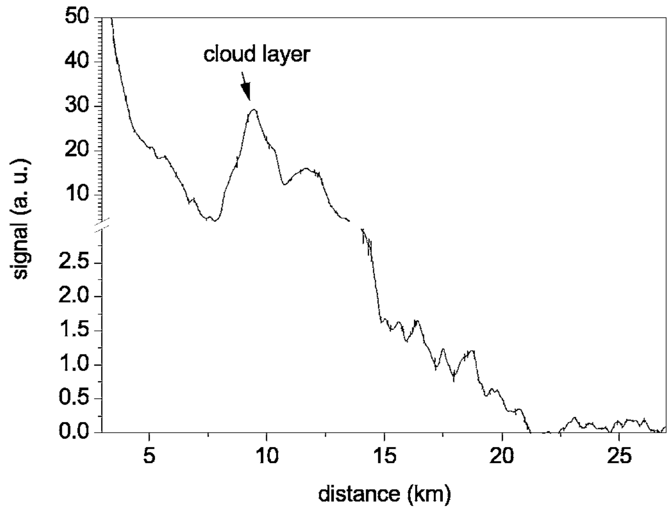

FIG. 2. Single-shot white-light Lidar signal in the 300–470 nm spectral region, displaying signals up to 20 km in spite of a cloud layer (cirrus) around 10 km. Note the dual intensity scale.

sequence, resulting in overall longer pulses with reduced peak power.[4] The effect of chirp on filamentation clearly appears when comparing images of the beam in the visible spectral region (Fig. 3). Filamentation can be identified as regions where a source term for white light is detected. Such a source term is indicated by an increase of the white-light signal compared to the reference YAG laser, which provides a reference for intensity normalization. We observe white light already at the bottom of the image (19 m) for all chirps. However, larger chirps lower the peak powers and yield less efficient white-light conversion per unit length. The shortest pulses of the series (570 fs, i.e., 32 TW) yield shorter filamentation (filament end at 100 m), while 2.1 ps pulses (9 TW) push the filamentation end 350 m away from the laser source. The observed altitude dependence on the pulse duration of the laser beam shows that filamentation of ultrahigh power, multijoule laser pulses can be controlled remotely by changing the laser parameters as is currently performed on smaller laser classes.

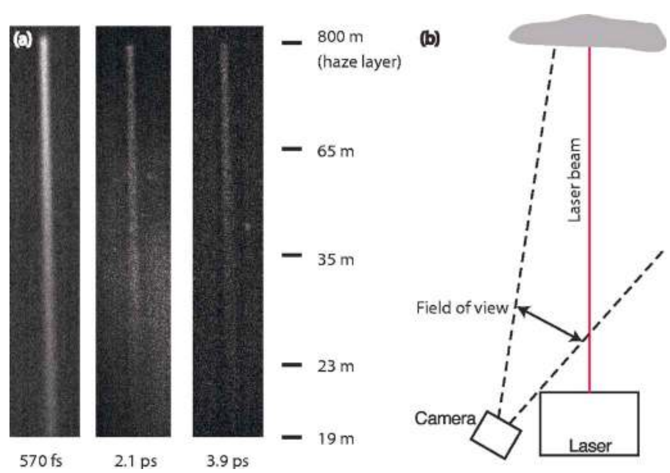

FIG. 3. (Color online) Chirp dependence of the filament onset. (a) Side image of the beam. Signal corresponding to larger initial chirps (lower peak powers) rises more slowly but over longer distances: The white light is still generated at higher altitudes, although filamentation is weaker in this case. (b) Observation geometry.

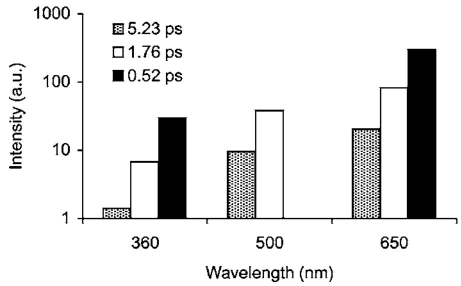

FIG. 4. Averaged Lidar returns from 200 to 300 m as a function of the wavelength and chirp. The emitted pulse energy is ~15 J.

Practical applications of ultrashort lasers in the atmosphere require to control not only the filamentation location but also the build-up of the white-light continuum. We compared (Fig. 4) the Lidar signal in three spectral regions of the continuum (360, 500, and 650 nm, with 10 nm bandwidth) for three chirp values. The analysis shows that the chirp almost does not affect the ratios between different wavelengths. This means that the shape of the spectrum of the continuum generated in the filaments is comparable. Moreover, the signal detected at a given wavelength (hence, the generation efficiency of the white light at this wavelength, at the fixed incident pulse energy of 15 J) is almost inversely proportional to the pulse duration. The reference YAG signal permits us to estimate the absolute value of the signal at 650 nm for the shorter pulses (520 fs) to be 2.2 mJ, corresponding to a conversion efficiency of $\sim 1.5 \times 10^{-5}$ nm^{-1} for 31 TW laser pulses. Considering the width of the continuum and its expected exponential decay[18] away from the fundamental wavelength, this figure leads us to estimate that the overall conversion efficiency from the fundamental into the continuum amounts to a few percent. This conversion efficiency is smaller than may have been expected from extrapolations based on previous measurements at 800 nm at lower power and energy.[18]

Although longer fundamental wavelengths could have been expected to yield more spectral broadening,[19,20] this observation can be understood when considering that the intensity within the filaments is clamped and that their number, which is proportional to the power, does not influence much the white-light spectrum.[21] Spectral broadening is thus governed by the time gradients of the intensity through nonlinear phase variations. These gradients are sharper for shorter pulses, which then yield more efficient broadening.[22] Therefore, further optimization of the white-light generation would require one to increase the peak power by shortening the laser pulses, even at the cost of a reduced pulse energy.

As a conclusion, we have shown that ultraintense laser beams up to 30 TW, 20 J generate multiple (up to 400) filaments through processes remarkably similar to those observed for subjoule pulses.[4] Although conversion into the supercontinuum is less efficient than with shorter pulses (a few percent), the white light propagates up to the stratosphere, i.e., beyond 20 km, constituting the highest power white-light laser to date. These results are encouraging for the use of multijoule, ultrashort laser pulses in both future nonlinear white-light Lidars or applications requiring the remote delivery of high intensities, such as lightning control.

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