Ultraintense light filaments transmitted through clouds

François Courvoisier, Véronique Boutou, Jérôme Kasparian, Estelle Salmon, Guillaume Méjean, Jin Yu, and Jean-Pierre Wolf[a)]
Laboratoire de Spectrométrie Ionique et Moléculaire (LASIM), UMR CNRS 5579, Université Claude Bernard Lyon 1, 43 Boulevard du 11 Novembre 1918, F69622 Villeurbanne Cedex, France

(Received 6 February 2003; accepted 14 May 2003)

We demonstrate that ultrashort and ultraintense light filaments survive their interaction with water droplets as large as 95 μm and that they are transmitted through water clouds having an optical thickness as high as 3.2 (transmission 5%). In contrast with linear optics, this remarkable transmission through optically dense media results from a dynamic energy balance between the quasisolitonic structure and the surrounding laser photon bath, which acts as an energy reservoir. Implications for free-space laser communications, remote sensing, and telemetry are discussed. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1592615]

Transmission of laser beams through fog and clouds is a key issue for free space laser communication, Lidar detection of atmospheric pollutants,[1] telemetry, range finding, active imaging, guiding, and even for probing general relativistic effects in the gravitational field of the Earth.[2]

An attractive means of overcoming the usual atmospheric optical limits, such as turbulence, dispersion, or heavy scattering, could be the use of high intensity ultrashort laser pulses. Above a critical power P_c ($P_c \sim 3$ GW), ultrashort laser beams form stable light filaments that can propagate in a quasisolitonic way through the air.[3] These localized structures in the beam (typically 150 μm in diameter, more than several hundreds meters in length)[4] result from a subtle dynamic balance between Kerr self-focusing and self-defocusing by multiphoton ionization of the air molecules. The high intensity ($\sim 10^{14}$ W/cm^2) and electron density ($\sim 10^{15}$ cm^{-3}) inside a filament modify the medium properties while propagating, which gives hope for a relative insensitivity to external conditions variations. For example, the nonlinear variations Δn of the air refractive index induced by the light filament (typically $\Delta n \sim 10^{-5}$) are larger than thermal fluctuations due to turbulence. Concerning the interaction and the propagation of light filaments through clouds, no experimental or theoretical investigations were carried out so far.

In this letter, we demonstrate that light filaments survive the interaction with water droplets as large as 95 μm, and that they can be transmitted through water clouds having an optical thickness as high as 3.2 (transmission 5%). These results open perspectives for transmitting optical data through turbid media, in which heavy multiple scattering usually prevents reliable communication.

A set of experiments has been performed to observe the interaction of a light filament with a single, isolated water droplet. An ultrashort laser (7 mJ/pulse, 120 fs pulse duration at 810 nm) is slightly focused by a 5 m focal length spherical mirror in the air, to produce a light filament of typically 150 μm in diameter that can propagate over more than 3 m (corresponding to more than 30 Rayleigh lengths). For a given laser power, the location of the onset of filamentation is stable within a few centimeters. This stability allows us to define this point as origin or the propagation distance d.

At $d=1$ m, the light filament interacts with a calibrated micrometric water droplet. The microdroplets of controlled diameter a are generated by a piezodriven nozzle (piezoceramics squeezing a capillary tube) that is fired synchronously with the laser (repetition rate 20 Hz) so that each laser pulse interacts with a single fresh droplet. The droplet diameter can be chosen between 30 and 100 μm (representative of cloud droplets) by adjusting the electric pulse voltage and duration on the piezonozzle. We define the impact parameter b, i.e., the distance between the filament axis and the center of the droplet. The experimental reproducibility on a and b, checked by both forward elastic scattering and direct observation with a microscope, is excellent: $\Delta b/a < 0.1$, $\Delta a/a < 0.05$. This setup was already successfully used to observe the generation of a nanometric plasma within water microdroplets.[5,6]

We first measured the intensity profile of the freely propagating laser beam (i.e., without droplet), as shown in the insets to Fig. 1. Only a fraction of the energy is used to form the filament while the remaining laser energy surrounds this highly localized structure and propagates collimated with it. At the location where the interaction with the droplet occurs ($d=1$ m) the filament carries some 35% of the total energy. 1 m further this fraction drops to ~13%. The surrounding "photon bath" (about 2 mm in diameter) accordingly gains energy with propagation and acts as an energy reservoir[7] that is in dynamic balance with the filament.

We then determined the energy contained only in the filament as a function of propagation distance d by letting the filament drill its own aperture in a foil (aluminum or cellulose) and by measuring the transmitted energy with a bolometer. Due to fluctuations in the foil thickness, the measurement accuracy is 4% between different experimental runs. However, the statistical error is limited to 1% when using the same location of a given foil. The energy transported by the filament [Fig. 1, curve (a)] decreases from 2.7 mJ at $d=1$ m to 0.25 mJ at $d=3$ m. Beyond this distance, the local intensity is insufficient to pierce the target foil, and

a)Electronic mail: wolf@lasim.univ-lyon1.fr

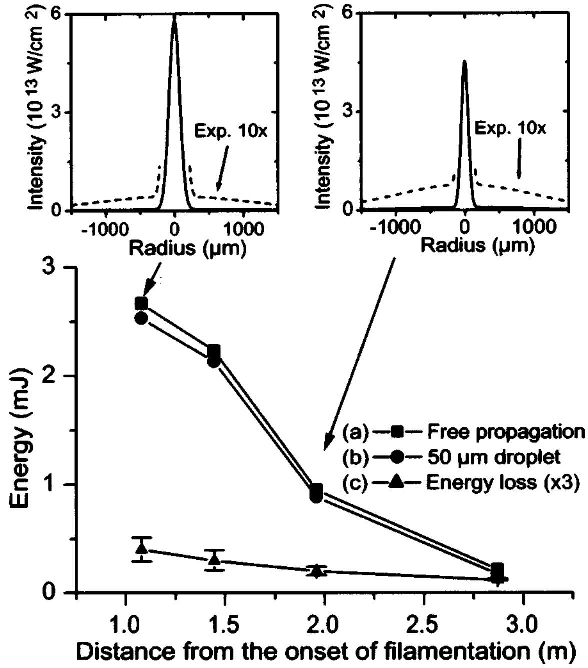

FIG. 1. Interaction of a light filament with a 50 μm water droplet. Energy contained in the filament as a function of propagation distance d (relative to the onset of filamentation at $d=0$): (a) without and (b) with droplet. The insets are measured intensity profiles of the freely propagating filament as a function of distance. Expanded scale curves (intensity $\times 10$, dashed line) show the contribution of the surrounding photon bath. The filamentary structure globally loses energy to the surrounding photon bath. However, curve (c) displays the difference (a)–(b) (energy loss) and suggests that some energy is regained by the filament from the photon bath while propagating after the interaction with the droplet. The error bars in curve (c) account for statistical errors of the energy measurement only. Systematic errors of measurements with and without droplets are balanced since the same foil is used.

therefore can be considered as the end of the filamentation process.

A 50 μm diameter water droplet was precisely placed in the center of the filament at a distance $d=1$ m from the filamentation starting point. Surprisingly, the filament was completely unaffected by the presence of the droplet even though the balance between Kerr self-focusing and defocusing by the self-generated plasma should be highly critical because of the nonlinear nature of the processes. In order to better understand this remarkable result, the energy carried by the filament along the direction of propagation [Fig. 1, curve (b)] was measured in the same way as for the free propagation. Since the same foil aperture was used for measurements both with and without droplet, the $\pm 1\%$ accuracy in the energy measurements results in an accuracy of the energy loss, $\Delta(E_{\text{free}}-E_{\text{droplet}})/(E_{\text{free}}-E_{\text{droplet}})$ of $\pm 30\%$–$\pm 7\%$, depending of the relative loss value (see error bars on Fig. 1). A slight energy loss of 130 ± 40 μJ is observed just after the interaction ($d=1$ m) but the balance is quickly reestablished. The filament seems to regain energy while propagating, so that the energy difference is only 40 ± 3 μJ (compared to the free propagating beam) at the end of the filamentation process ($d=3$ m). This suggests that the filament is replenished by the surrounding photon bath while it continues to propagate [Fig. 1, curve (c)]. Theoretical predictions[7,8] depicting nonlinear propagation processes of ultrashort laser pulses corroborate this interpretation of a dynamic energy balance between the filament and the surrounding energy bath.

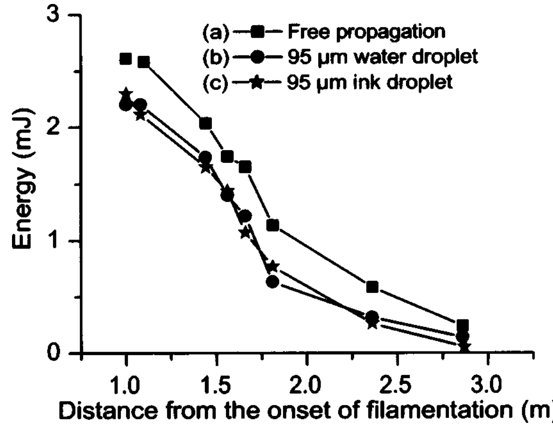

FIG. 2. Size and internal absorption dependence. The filament survives the interaction with a droplet as large as 95 μm (b), even when the droplets are stained with black ink (c). The energy losses (c)–(a) and (b)–(a) compared to free propagation (a) scale with the obstacle geometrical cross section.

The robustness of the filamentation process was tested further with larger and absorbing droplets. Even using droplets up to 95 μm in diameter, which block the major part of the 150 μm filament, the filament survives and propagates almost unaffected along the entire 3 m distance (Fig. 2). No significant difference is observed for transparent and absorbing (black ink containing) droplets. Measuring the energy loss as a function of d confirms that the filament regains energy (0.2 mJ) from the photon bath upon propagating away from the droplet. The initial energy loss just after the droplet ($d=1$ m) is respectively 300 ± 35 and 370 ± 35 μJ for transparent and absorbing 95 μm droplets. Hence, its size dependence roughly scales with the obstacle geometrical cross section and not with its volume. The fraction of the filament that hits the droplet is lost regardless of subsequent volume interactions. This is confirmed by the fact that high internal absorption does not significantly increase the energy loss.

These experiments with a single droplet show that an energy balance is reached between the filament and the unfocused part of the beam. The surrounding photon bath feeds or even partially rebuilds the filament (if the remaining power of the photon bath is sufficient), allowing further propagation. This conclusion is consistent with recent experiments,[9] which showed that if an aperture blocks the photon bath, the filament stops propagating.

An important question arising from these considerations concerns the effect of the photon bath energy loss by elastic scattering of a distribution of droplets. To answer this question, a second set of experiments was performed: we let the filament through an open cloud chamber of 0.35 m length and measured the transmitted energy. The droplet size distribution is simultaneously monitored by forward Mie scattering [mean diameter 4 μm, full width at half maximum (FWHM)=2 μm], and the cloud optical thickness τ [$\tau=\ln(1/T)$, where T is the transmission] by the transmission of a HeNe laser.

As shown in Fig. 3, the filament propagates throughout the cloud, even for an optical thickness τ as high as 3.2 (corresponding to a droplet concentration of 4×10^5 cm^{-3}). However, after a few centimeters of further propagation in

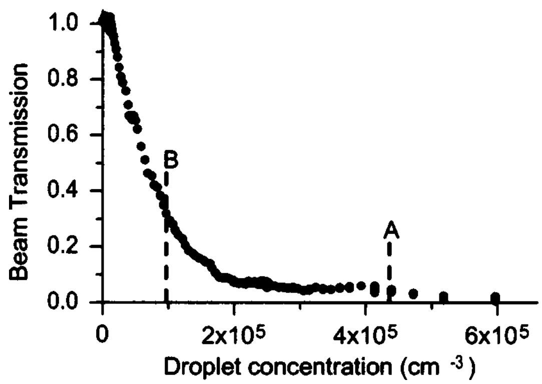

FIG. 3. Transmission of light filaments through a cloud (droplet mean diameter 4 μm, FWHM=2 μm). The filaments propagate throughout the cloud for an optical thickness τ as high as 3.2 (droplet concentration 4×10^5 cm^{-3}, label A). However, it does not further propagate on emerging from the cloud because the energy loss in the photon bath by elastic scattering is too high. Conversely, almost unaltered filamentation is observed for τ=1.2 (10^5 cm^{-3}, label B).

clear air, filamentation stopped. The reason for this behavior is the energy loss in the photon bath due to elastic scattering. At the cloud exit the energy is no longer sufficient to enable further propagation of the filament. The transmitted power in the beam is only 2.3 GW, which is lower than the power P_c needed for Kerr focusing.

Conversely for an optical thickness of 1.2 (10^5 droplets/cm^3) the filament is fully transmitted and further propagates almost unaffected (the filamentation length is close to the one in clear air).

Notice that the filament transmission exponentially decreases with the droplet concentration (Fig. 3), as expected for linear scattering. This indicates that the energy loss in the photon bath by Mie scattering dominates the process and constitutes the main limitation for filament transmission through clouds. However, the maximum optical thickness measured in our experiments corresponds to values typical of cumulus or stratocumulus clouds.[10] These results are most promising, particularly when taking into consideration the modest laser energy (7 mJ). Further experiments will be performed directly in the atmosphere with higher pulse energies using the Teramobile,[11] which is the first mobile terawatt laser system (400 mJ/80 fs).

The authors acknowledge support from the CNRS, the French Research Ministry, the Institut Universitaire de France, and the French-German project Teramobile, jointly funded by the CNRS and the DFG. They also wish to thank Professor S. L. Chin (Laval University), Professor M. Beniston (Univ. Freiburg, Swizerland), and Dr. A. Ross (Univ. Lyon 1) for very fruitful discussions and M. Neri and M. Kerleroux for their technical support.

[1] P. Rairoux, H. Schillinger, S. Niedermeier, M. Rodriguez, F. Ronneberger, R. Sauerbrey, B. Stein, D. Waite, C. Wedekind, H. Wille, L. Woste, and C. Ziener, Appl. Phys. B: Lasers Opt. **71**, 573 (2000).
[2] L. Iorio, Class. Quantum Grav. **19**, 175 (2002).
[3] L. Bergé and A. Couairon, Phys. Rev. Lett. **86**, 1003 (2001).
[4] B. La-Fontaine, F. Vidal, Z. Jiang, C. Y. Chien, D. Comtois, A. Desparois, T. W. Johnston, J. C. Kieffer, H. Pepin, and H. P. Mercure, Phys. Plasmas **6**, 1615 (1999).
[5] C. Favre, V. Boutou, S. C. Hill, W. Zimmer, M. Krenz, H. Lambrecht, J. Yu, R. K. Chang, L. Woeste, and J. P. Wolf, Phys. Rev. Lett. **89**, 035002 (2002).
[6] S. Borrman and J. Curtius, Nature (London) **418**, 826 (2002).
[7] M. Mlejnek, E. M. Wright, and J. V. Moloney, Opt. Lett. **23**, 382 (1998).
[8] M. Mlejnek, E. M. Wright, and J. V. Moloney, Opt. Express **4**, 223 (1999).
[9] S. L. Chin, A. Brodeur, S. Petit, O. G. Kosareva, and V. P. Kandidov, J. Nonlinear Opt. Phys. Mater. **8**, 121 (1999).
[10] World Climate Research Program (WCRP) classification; see for example http://isccp.giss.nasa.gov/cloudtypes.html.
[11] H. Wille, M. Rodriguez, J. Kasparian, D. Mondelain, J. Yu, A. Mysyrowicz, R. Sauerbrey, J. P. Wolf, and L. Wöste, Eur. Phys. J.: Appl. Phys. **20**, 183 (2002).