APPLIED PHYSICS LETTERS **91**, 171106 (2007)

Propagation of laser filaments through an extended turbulent region

R. Salamé, N. Lascoux,[a] E. Salmon, R. Ackermann, and J. Kasparian
Université de Lyon-Université Lyon 1-CNRS-LASIM UMR 5579, Bâtiment A. Kastler, 43 Boulevard du 11 Novembre 1918, F-69622 Villeurbanne, France

J.-P. Wolf
GAP-Biophotonics, University of Geneva, 20 rue de l'École de Médecine, 1211 Geneva, Switzerland

(Received 12 July 2007; accepted 24 September 2007; published online 23 October 2007)

We show that laser filamentation can be initiated and propagate through strong extended turbulence well above the typical atmospheric values. We suggest that the effect of turbulence on filamentation is characterized by the product of the structure parameter for the refractive index C_n^2 and the length L of the turbulence region. Half of the filaments are transmitted for $C_n^2 L \leqslant 4.4 \times 10^{-10}\ \mathrm{m}^{1/3}$. Moreover, the surviving filaments keep their key spectral properties including correlations inside the white-light continuum. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2799163]

Laser filaments resulting from the propagation of high intensity lasers in air[1] open up exciting perspectives for atmospheric applications[2] such as lidar, remote laser-induced breakdown spectroscopy,[3,4] or triggering and guiding of high voltage discharges in the prospect of lightning control.[5–7] Filamentation might also provide a third option, besides wavelength diversity[8] and spatial diversity,[9,10] to circumvent the effects of turbulence in free-space communications. Such applications are based on the main properties of the filaments, including their ability to deliver high intensities at long distances[11–13] and a broad continuum spectrum. They rely on the capability of filaments to propagate in adverse conditions such as reduced atmospheric pressure,[14] dense clouds,[15,16] or rain,[14] thanks to their energy reservoir[17](or photon bath). Moreover, filaments are still able to guide high voltage discharges under artificial rain.[18]

The performance of imaging or transmission systems is limited by atmospheric inhomogeneities and fluctuations. Temperature and pressure variations associated with turbulent eddies cause random fluctuations of the refractive index, which distort optical waves. The distortions lead to significant blurring, scintillation, and wander of the laser beam. Wave-front distortions are also expected to perturb the dynamic balance between Kerr self-focusing and plasma defocusing in the filaments. Thus, it is crucial to study the influence of turbulence on filaments to evaluate their potential for real-scale applications.

Experiments in the infrared[19] and in the ultraviolet,[12] as well as numerical simulations[20,21] under moderate turbulence have already been reported. They mainly focused on the formation and wandering of the filaments but do not provide a quantitative analysis regarding the dependence on the turbulence strength. More recently, it was shown that filaments can survive a localized turbulence five orders of magnitude above typical atmospheric conditions for localized turbulent regions (2–32 cm length).[22] However, applications require long distance propagation of the filaments in the atmosphere. Beside their ability to deliver high intensities through turbulent atmosphere, filaments should retain their phase stability as well as their spectral properties to be applicable, e.g., to lidar detection of atmospheric species. In this letter, we extend our previous results to an extended turbulent region and we investigate the conservation of the filament spectral properties, including the shot-to-shot spectral correlations reported recently.[23,24]

The experimental setup is similar to that of previous experiments[22] except for the geometry of the turbulent region. A titanium:sapphire chirped-pulse amplification chain[25] provided 200 fs pulses with peak powers between 7.8 and 30 GW at 22.5 Hz. The filament onset, located 3.3 m downstream from the focusing mirror (focal length of 5 m), was chosen as the origin of the z axis. Turbulence was generated along the laser beam by a set of candles placed below it. The turbulent region is extended over a length $L = 1.3$ m, i.e., two-thirds of the filament length. The turbulent region was swept along the propagation axis and its strength was varied by changing the candle geometry.

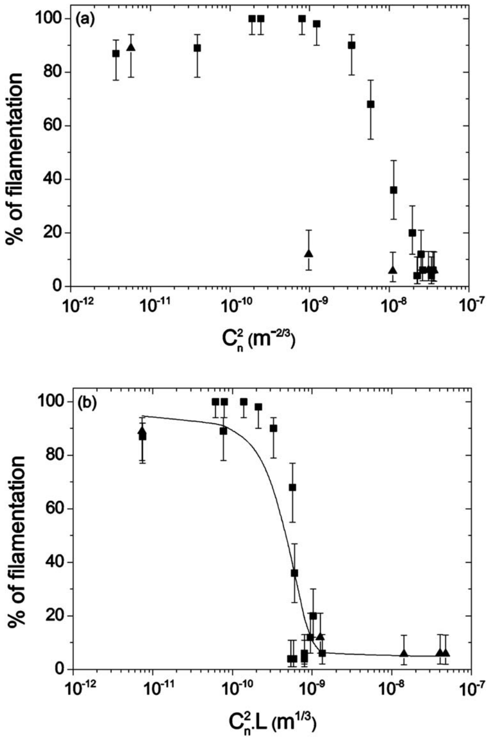

FIG. 1. Percentage of filaments surviving the turbulence as a function of C_n^2, in the case of localized (squares) and extended turbulent regions (triangles) located after the filament onset. (b) Same data plotted as a function of $C_n^2 L$, L being the turbulence length. The line is intended to guide the eye.

---

[a] Author to whom correspondence should be addressed; electronic mail: noelle.lascoux@lasim.univ-lyon1.fr

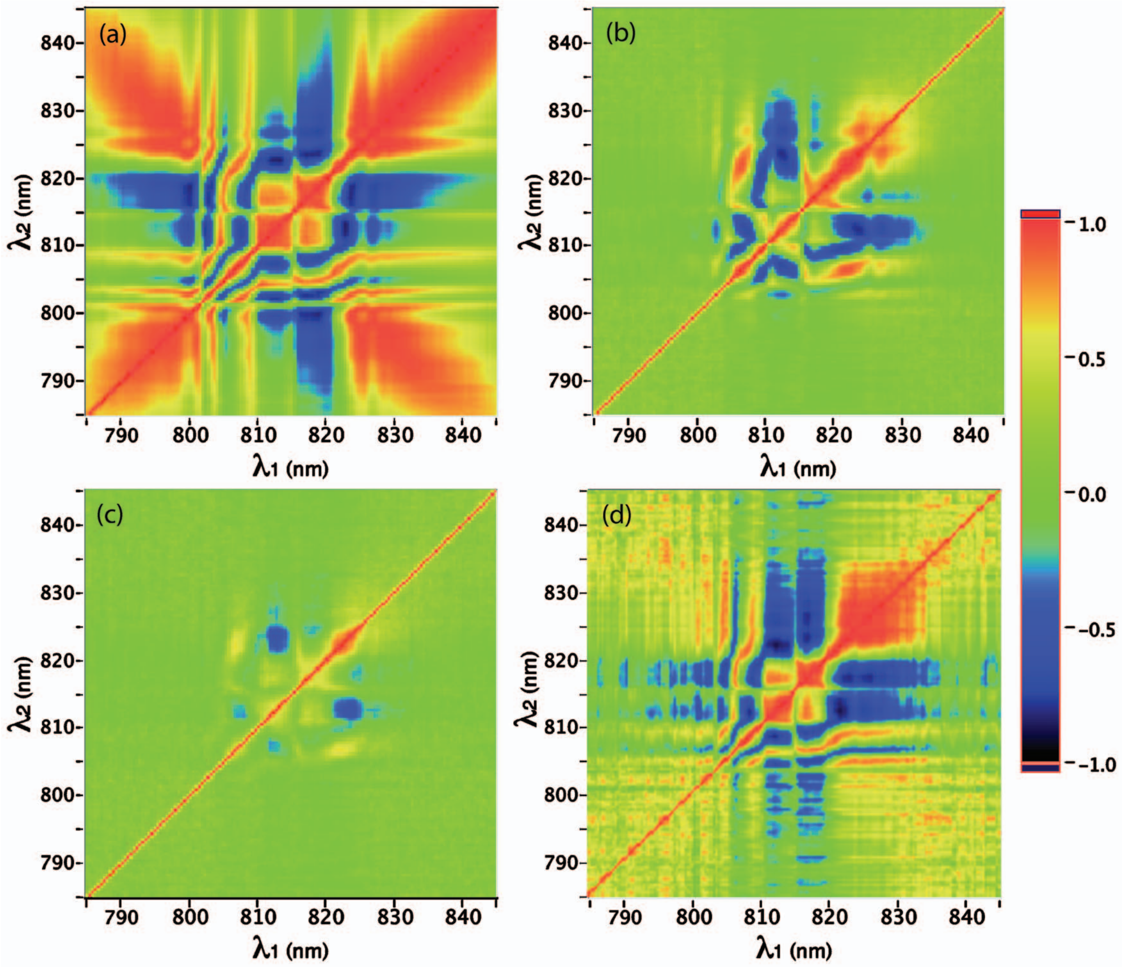

FIG. 2. (Color) [(a)–(c)] Correlation maps obtained for different turbulence strengths located after the filamentation onset location ($z=1$ m), for a peak power of 7.8 GW. (a) $C_n^2=9\times10^{-10}$ m$^{-2/3}$, (b) $C_n^2=2.2\times10^{-8}$ m$^{-2/3}$, and (c) $C_n^2=4.3\times10^{-8}$ m$^{-2/3}$. (d) Correlation map for a subset of the data of panel (b), where only pulses corresponding to filaments surviving through the turbulence are considered, recovering the features of the unperturbed map (a).

Atmospheric turbulence can be described by Kolmogorov's theory,[26] in which the difference in refractive index between two points only depends on the distance between those two points. This theory introduces the refractive index structure parameter C_n^2, which is commonly used to characterize the turbulence strength. Typical values for atmospheric turbulence are $10^{-15} < C_n^2 < 10^{-13}$ m$^{-2/3}$.[27] C_n^2 can be determined experimentally by measuring the pointing stability of the laser beam and using the relation $C_n^2=\sigma_\theta^2\Phi^{1/3}/(2.91L)$, where σ_θ is the standard deviation of the angle of arrival, Φ is the beam diameter, and L is the length of the turbulent path.[18]

The pointing stability was measured on series of 50 single-shot pictures of the beam profile on a screen, located shortly after the filament's end ($z=2.3$ m) with a resolution of 10 μm/pixel. A pointing reference was provided by a red 5 mW helium-neon laser bypassing the turbulent region and hitting the screen near the impact of the main beam. For each picture the presence of a filament was also determined visually.

Figure 1(a) plots the percentage of filaments surviving the turbulence as a function of C_n^2, in the case of both localized (squares) and extended turbulent regions (triangles) located after the filament onset. Both conditions show a transition between a weak turbulence regime where filaments resist turbulence, and a strong turbulence regime where they are destroyed by the turbulence. The C_n^2 threshold for a given filament transmission probability is lower for the extended turbulence, corresponding to the natural idea that a stronger turbulence is required to have the same effect over a shorter turbulent path. Figure 1(b) displays this transition from weak to strong turbulence as a function C_n^2L instead of C_n^2. Although the lengths L of the turbulent region range from 2 cm to 1.3 m, the data points of the two series are aligned on a single curve. This suggests that the rate of surviving filaments is governed by the quantity C_n^2L, rater than by the structure parameter C_n^2 alone. In our conditions, 50% of the filaments survive for $C_n^2L=4\times10^{-10}$ m$^{1/3}$. Since typical atmospheric turbulence never exceed $C_n^2=10^{-13}$ m$^{-2/3}$, this threshold would correspond to the survival of half of the filaments after $L\sim4$ km in the atmosphere. While such large-scale extrapolation from laboratory-scale data may be hazardous, it still suggests, at least qualitatively, that turbulence will not be a limiting factor to transmit filaments through the atmosphere. Note that $C_n^2L=\sigma_\theta^2\Phi^{1/3}/2.91$, meaning that the filament survival is directly linked to the pointing stability of the laser beam. To ensure that this quantity is dimensionless, we expect that it may be proportional to $\lambda^{-1/3}$, λ being the laser wavelength.

Most of the applications rely not only on the existence of filaments but also on their phase stability or their spectral properties such as their power spectra and shot-to-shot spectral correlations. Therefore, we checked that the white-light spectrum after propagation through turbulence is not distinguishable from the nonturbulent one. Also, the generation of third harmonic by the surviving filaments does not appear to be affected by the turbulence. This shows that not only the high intensity of the filaments is transmitted through the turbulent region but also the main $\chi^{(3)}$ processes [self-phase modulation (SPM), four-wave mixing (FWM), and third harmonic generation] taking place within them. In other words, when filaments are transmitted through turbulence, their spectral properties seem unaffected.

This feature is demonstrated more strikingly when investigating the shot-to-shot correlations that have recently been described within the white-light continuum.[23,24] They result from the χ^3 processes including SPM and FWM, which lie at the root of the spectral broadening. These spectral correlations can be used to significantly reduce the laser intensity noise by filtering the spectrum. To assess whether the correlations resist turbulence, which causes shot-to-shot variations to the filament environment, the filaments were scattered on an achromatic target and analyzed by a fiber collection spectrometer (Ocean Optics HR 2000). 1000 spectra were taken for each condition and the correlation maps were calculated as detailed previously.[24]

Figures 2(a)–2(c) represent the correlation maps obtained for different values of turbulence located after the filamentation onset position ($z>0$), for a peak power of 7.8 GW, below the filamentation threshold. Maps much above filamentation threshold exhibit the same behavior, although they are less legible because of ripple structures due to cascaded $\chi^{(3)}$ broadening processes.[23]

Red pixels correspond to correlated wavelengths within the continuum and blue pixels to anticorrelated wavelengths. The prominent features of the unperturbed correlation map include[23] (i) a positive correlation corresponding to the trivial relation $\lambda_1=\lambda_2$, (ii) a negative correlation between the fundamental wavelength at $\lambda_0=815$ nm and the continuum, and (iii) a positive correlations between conjugated wavelengths. The two latter features correspond to the conversion (hence, depletion) of the fundamental wavelength λ_0 into two conjugated spectral components λ_1 and λ_2, with $2/\lambda_0=(1/\lambda_1)+(1/\lambda_2)$. The correlations fade away with increasing turbulence [Figs. 2(a)–2(c)] because of the decrease of the number of surviving filaments, not because transmitted filaments loose their spectral properties. Correlations are observed as long as filaments are transmitted through the turbulent region. The physical origin of the correlations lies in the χ^3 processes governing the continuum generation within the filaments, with shot-to-shot stochastic fluctuations. Therefore, our results suggest that correlations are conserved within all the transmitted filaments. To confirm this assumption, we calculated the correlation map after transmission through turbulence, considering only the subset of the laser pulses which yield a surviving filament [Fig. 2(d)]. This result is indeed comparable to the map obtained in the unperturbed atmosphere [Fig. 2(a)].

In conclusion, we have studied the influence of various configurations of turbulence on the propagation of filaments in air. Filaments proved their robustness by surviving an extended turbulent region three orders of magnitude above typical atmospheric turbulence, over a length comparable with that of the filaments themselves. Moreover, in all conditions where some of the filaments are transmitted, the surviving ones keep their spectral properties, including the third harmonic generation, as well as the shot-to-shot spectral correlations. Therefore, applications relying on the spectral properties of the filaments will not be affected by turbulence. Further work is in progress in order to evaluate the influence of turbulence on the phase stability within the filaments. Besides, a semiqualitative scaling of the laboratory results to the atmospheric scale suggest that a typical atmospheric turbulence would not jeopardize filamentation on a kilometric range. These results show that turbulence is not the limiting factor for atmospheric applications of filamentation.

The authors are grateful for the financial support of the French Agence Nationale de la Recherche (Grant No. NT05 -1-43175).

[1] A. Braun, G. Korn, X. Liu, D. Du, J. Squier, and G. Mourou, Opt. Lett. **20**, 73 (1995).

[2] J. Kasparian, M. Rodriguez, G. Méjean, J. Yu, E. Salmon, H. Wille, R. Bourayou, S. Frey, Y.-B. André, M. Franco, B. Prade, A. Mysyrowicz, and R. Sauerbrey, Science **301**, 61 (2003).

[3] K. Stelmaszczyk, P. Rohwetter, G. Méjean, J. Yu, E. Salmon, J. Kasparian, R. Ackermann, J.-P. Wolf, and L. Wöste, Appl. Phys. Lett. **85**, 3977 (2004).

[4] H. L. Xu, W. Liu, and S. L. Chin, Opt. Lett. **31**, 1540 (2006).

[5] B. La Fontaine, D. Comtois, C.-Y. Chien, A. Desparois, F. Génin, G. Jarry, T. Johnston, J.-C. Kieffer, F. Martin, R. Mawassi, H. Pépin, F. A. M. Rizk, F. Vidal, C. Potvin, P. Couture, and H. P. Mercure, J. Appl. Phys. **88**, 610 (2000).

[6] R. Ackermann, K. Stelmaszczyk, P. Rohwetter, G. Méjean, E. Salmon, J. Yu, J. Kasparian, G. Méchain, V. Bergmann, S. Schaper, B. Weise, T. Kumm, K. Rethmeier, W. Walkner, L. Wöste, and J.-P. Wolf, Appl. Phys. Lett. **85**, 5781 (2004).

[7] P. Rambo, J. Schwarz, and J.-C. Diels, J. Opt. A, Pure Appl. Opt. **3**, 146 (2001).

[8] K. Kiasaleh, J. Opt. Soc. Am. A **23**, 557 (2006).

[9] P. Polynkin, A. Peleg, L. Klein, T. Rhoadarmer, and J. Moloney, Opt. Lett. **32**, 885 (2007).

[10] A. Belmonte, A. Comeron, J. A. Rubio, J. Bara, and E. Fernandez, Appl. Opt. **36**, 8632 (1997).

[11] B. La Fontaine, F. Vidal, Z. Jiang, C. Y. Chien, D. Comtois, A. Desparois, T. W. Johnson, J.-C. Kieffer, and H. Pépin, Phys. Plasmas **6**, 1615 (1999).

[12] M. Rodriguez, R. Bourayou, G. Méjean, J. Kasparian, J. Yu, E. Salmon, A. Scholz, B. Stecklum, J. Eislöffel, U. Laux, A. P. Hatzes, R. Sauerbrey, L. Wöste, and J.-P. Wolf, Phys. Rev. E **69**, 036607 (2004).

[13] J. Schwarz and J.-C. Diels, J. Mod. Opt. **49**, 2583 (2002).

[14] G. Méchain, G. Méjean, R. Ackermann, P. Rohwetter, Y.-B. André, J. Kasparian, B. Pradel, K. Stelmaszczyk, J. Yu, E. Salmon, W. Winn, L. A. Schlie, A. Mysyrowicz, R. Sauerbrey, L. Wöste, and J.-P. Wolf, Appl. Phys. B: Lasers Opt. **80**, 785 (2005).

[15] G. Méjean, J. Kasparian, J. Yu, E. Salmon, S. Frey, J.-P. Wolf, S. Skupin, A. Vinçotte, R. Nutter, S. Champeaux, and L. Bergé, Phys. Rev. E **72**, 026611 (2005).

[16] F. Courvoisier, V. Boutou, J. Kasparian, E. Salmon, G. Méjean, J. Yu, and J.-P. Wolf, Appl. Phys. Lett. **83**, 213 (2003).

[17] M. Mlejnek, M. Kolesik, J. V. Moloney, and E. M. Wright, Phys. Rev. Lett. **83**, 2938 (1999).

[18] R. Ackermann, K. Stelmaszczyk, P. Rohwetter, G. Méjean, E. Salmon, J. Yu, J. Kasparian, G. Méchain, V. Bergmann, S. Schaper, B. Weise, T. Kumm, K. Rethmeier, W. Kalkner, J. P. Wolf, and L. Wöste, Appl. Phys. Lett. **85**, 5781 (2004).

[19] S. L. Chin, A. Talebpour, J. Yang, S. Petit, V. P. Kandidov, O. G. Kosareva, and M. P. Tamarov, Appl. Phys. B: Lasers Opt. **74**, 67 (2002).

[20] S. A. Shlenov and V. P. Kandidov, Atmos. Oceanic Opt. **17**, 565 (2004).

[21] S. A. Shlenov and V. P. Kandidov, Atmos. Oceanic Opt. **17**, 571 (2004).

[22] R. Ackermann, G. Méjean, J. Kasparian, J. Yu, E. Salmon, and J.-P. Wolf, Opt. Lett. **31**, 86 (2006).

[23] P. Béjot, J. Kasparian, E. Salmon, R. Ackermann, and J.-P. Wolf, Appl. Phys. B: Lasers Opt. **87**, 1 (2007).

[24] P. Béjot, J. Kasparian, E. Salmon, R. Ackermann, N. Gisin, and J.-P. Wolf, Appl. Phys. Lett. **88**, 251112 (2006).

[25] D. Strickland and G. Mourou, Opt. Commun. **56**, 219 (1985).

[26] V. I. Tatarski, *The Effects of the Turbulent Atmosphere on Wave Propagation* (Keter, Jerusalem, 1971).

[27] S. Bendersky, N. S. Kopeika, and N. Blaunstein, Appl. Opt. **43**, 4070 (2004).