Long-range detection and length estimation of light filaments using extra-attenuation of terawatt femtosecond laser pulses propagating in air

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High-energy femtosecond laser pulses propagating in the atmosphere undergo self-focusing resulting in the appearance of the phenomenon of filamentation. We observed an extra-attenuation of such (terawatt) femtosecond laser pulses propagating in the atmosphere when compared with long pulses (200 ps) with the same energy. This is because, in contrast to the linear propagation of the long pulse, the input femtosecond laser pulse is attenuated owing to either absorption through multiphoton ionization/tunnel ionization or to scattering on the laser-induced plasma; self-phase-modulation and self-steepening further convert partially the energy initially contained in the fundamental bandwidth into the broad side bands of the laser, becoming eventually a white-light laser pulse (supercontinuum). The experimental data allow us to extract an effective extra-attenuation coefficient for an exponential decay of the input pulse energy with the propagation distance. Such a coefficient allows us to estimate an upper bound of the filament length under the experimental conditions used. More generally, our observation leads to a new technique to remotely detect light filaments in the atmosphere. © 2005 Optical Society of America

OCIS codes: 010.1300, 010.1310, 010.3640, 190.4180, 190.5940, 190.7110, 350.5400.

1. Introduction
Filamentation of intense femtosecond laser pulses propagating in the atmosphere, which was observed in 1995 for the first time,1 is currently attracting more and more attention. This is because of the complexity of the fundamental physical processes involved in the formation of a filament, as well as the potential applications followed by such a nonlinear propagation regime. As it is currently defined, a filament is a low-density plasma column that is left behind by an ultrashort laser pulse and is a result of a dynamical balance between Kerr self-focusing of the laser pulse and defocusing by the self-induced plasma through multiphoton/tunnel ionizations (MPI/TI). Both the self-channeling model1 and the moving-focus model5 describe the self-guided propagation of the laser pulse in the filamentation regime. In the time domain, self-phase modulation6 (SPM) and self-steepening7,8 together with self-splitting,9 lead to a transformation of the input laser pulse into a chirped white-light laser pulse (supercontinuum).10,11

For either theoretical understanding or applications, a quantitative measurement of the total extent of the filaments in the atmosphere (i.e., the total effective length of one or more filaments in air) represents an important issue. Using the moving-focus model,5 the starting point of a filament can be predicted as the nonlinear focus of the most powerful slice of the pulse. However, the mechanisms involved in the decay of a filament are not well understood. Intuitively, a filament disappears either because it spatially diverges and temporally disperses or because the feeding energy from the input laser pulse decreases, i.e., becomes attenuated during the propagation. In a filament, the pulse loses its energy owing to linear Rayleigh–Mie scattering, while an extra-
attenuation of the pulse energy occurs as well; i.e., the input laser pulse is either partially absorbed through MPI/TI or scattered by the microsize plasma induced by the laser pulse. SPM further converts the energy initially contained in the fundamental bandwidth into the white-light supercontinuum associated with the filament. When the peak power of the input pulse at the fundamental wavelength becomes lower than the critical power for self-focusing, filamentation can no longer take place. Experimentally, some measurements have been carried out on the filament length up to 200 m in a horizontal propagation configuration, where the filament is defined by checking the hot spots in the beam profile with a screen. Recently, a more precise, effective filament length of more than 100 m was measured in a laboratory environment horizontally. In this case, the lidar (light detection and ranging) technique was used to measure the backsctrattered nitrogen fluorescence from inside the filaments, which are defined as the region where plasma exists. For a vertical propagation in the atmosphere, the lidar remote-sensing technique is the only way to measure the attenuation of a laser pulse during its propagation.

In this paper, we present the experimental evidence of the extra-attenuation for high-energy femtosecond pulses propagating in air. By measuring the extra-attenuation, an upper limit can be estimated for the total length of the filaments in air. We measured the extra-attenuation of an intense femtosecond pulse undergoing filamentation in air by using the lidar remote-sensing technique and comparing it with a linearly propagating pulse with a longer pulse duration and the same energy. This extra-attenuation is much higher than that due to the usual Rayleigh–Mie scattering and leads to a faster energy decrease for the laser pulse undergoing the filamentation. Using an exponential decay law for the laser pulse energy versus the propagation distance to fit our experimental data, an effective extra-attenuation coefficient can be extracted. This coefficient is then used to estimate the total extent of the filaments generated in our experiment.

2. Theoretical Considerations

A. Lidar Return Signal with Linearly Propagating Pulses

For an elastic scattering lidar, the return signal that is due to the Rayleigh–Mie processes, detected at the laser wavelength λ, is proportional to the scattered laser energy received by the detector at a time corresponding to a range R:

\[
E_{\text{Lin}}(\lambda, R) = \frac{A_0}{R^2} \beta(\lambda, R) \xi(R) E_i \exp \left\{ - \int_{0}^{R} [\kappa_1(\lambda, R) + \kappa_2(\lambda, R)] dR \right\},
\]

where \(E_i\) is the initial energy of the laser pulse propagating in the atmosphere, \(A_0/R^2\) represents the acceptance solid angle of the detection system (\(A_0\) being the area of the sensitive surface of the detector), \(\beta(\lambda, R)\) is the volume backscattering coefficient for the wavelength \(\lambda\) at the range \(R\), \(\xi(R)\) is the geometrical form factor determined by the overlap between the laser beam and the field of view of the receiving telescope, and, finally, \(\kappa_1(\lambda, R)\) and \(\kappa_2(\lambda, R)\) are the atmospheric attenuation coefficients in the forward propagation path and the return path (from the range \(R\) to the detector), respectively.

For a classical lidar, using laser with nanosecond or subnanosecond pulse durations, the peak power is not high enough to induce filamentation. In the forward propagation path as well in the return path, the laser pulses undergo linear scatterings such as Rayleigh–Mie processes, or refraction in atmospheric inhomogeneities. Therefore atmospheric attenuations are identical for the forward propagation and the return paths (assuming a static atmosphere in the time scale of the laser pulse propagation): \(\kappa_1(\lambda, R) = \kappa_1(\lambda, R) = \kappa(\lambda, R)\). Over a detection range with a relatively small atmospheric fluctuation, it is reasonable to define a mean attenuation coefficient as follows: \(\tilde{\kappa}(\lambda) = \int_0^R \kappa(\lambda, R) dR / R\). If, in addition, the geometrical form factor \(\lambda(R)\) becomes unitary and the backscattering coefficient is considered constant for the range of interest, Eq. (1) can be written in the form

\[
E_{\text{Lin}}(\lambda, R) = \frac{A_0}{R^2} \beta(\lambda) E_i \exp \left\{ - 2\tilde{\kappa}(\lambda) R \right\}.
\]

The derivative of the logarithm of the range-corrected lidar return signal (signal multiplied by \(R^2\)) yields the mean atmospheric attenuation coefficient:

\[
\frac{1}{2} \frac{d \ln[E_{\text{Lin}}(\lambda, R) \times R^2]}{dR} = \tilde{\kappa}(\lambda).
\]

B. Lidar Return Signal in the Filamentation Regime

For a laser pulse undergoing the filamentation, the plasma channels associated with the filaments introduce extra losses on the pulse energy. There are several underlying physical mechanisms for such losses. The energy initially contained in the fundamental wavelength is attenuated by absorption through MPI/TI, which provides free electrons to create the low-density plasma. Since MPI/TI takes place instantaneously in the front part of the laser pulse, the back part of the pulse is scattered by the plasma. SPM and self-steepening converts the energy contained in the fundamental into the white-light supercontinuum as well. These extra-attenuations should be taken into account when one deals with the propagation of intense femtosecond laser pulses in the atmosphere. On the other hand, the detection of the extra-attenuation indicates the presence of plasma channels, hence the filamentation of the beam. That provides a way to remotely monitor the
presence of filaments and to measure their spatial extent.

Since it is difficult to deal with in detail the contributions of each loss mechanism involved in a filament, an experimentally relevant parameter can be defined that consists of an effective total extra-attenuation coefficient, $\kappa_e(\lambda, R)$. This parameter can be extracted experimentally by fitting the energy decay (in the fundamental bandwidth) of a pulse undergoing filamentation by an exponential law, as in the case of the linear propagation. This parameter covers the attenuations from the MPI/TI absorption, the scattering by the plasma, and the conversion into the white-light supercontinuum by SPM and self-steepening. Note that in this approach, the mechanisms of the losses are not studied. Instead, by using the exponential decay law as in the linear propagation case, we get a direct comparison of the extra-attenuation to that from Rayleigh–Mie scattering. Because all of the losses are included in this effective extra-attenuation coefficient, we should expect a laser-parameter- and atmospheric-condition-dependent property. Different loss mechanisms might depend on such parameters in different ways. To describe the laser-parameter or atmospheric-condition dependences of the extra-attenuation coefficient, a theoretical model dealing with each loss mechanism needs to be developed. Such a model is out of the scope of this paper.

Let us first modify Eq. (1) by including the extra-attenuation coefficient for the ranges after the filaments start. We denote $D_s$ as the starting distance of filamentation from the output of the compressor and neglect the attenuation before the filaments start (small atmospheric attenuation and short distance $D_s$ are assumed):

$$E_{NLin}(\lambda, r) = \frac{A_0}{R^2} \beta'(\lambda, R) \xi(R) E_i \exp \left\{ - \int_{D_s}^{R} [\kappa_1(\lambda, R) + \kappa_e(\lambda, R)] dR \right\}. \quad (4)$$

Over a small range, a mean extra-attenuation coefficient can be defined similar to that for Eq. (1), $\bar{\kappa}_e(\lambda, R) = \left[ \int_{D_s}^{R} \kappa_e(\lambda, R) dR \right] / (R - D_s)$. $\beta'(\lambda, R)$ is different from $\beta(\lambda, R)$ by including the effect of the backward-scattering enhancement that is due to the plasma. We shall neglect the plasma-density modulation along a filament and consider a mean back-scattering coefficient $\beta'(\lambda)$. Theoretical and experimental studies show plasma-density modulations owing to beam refocusing; however, such modulations typically occur over periods of several centimeters. That is too small for the spatial resolution of the detection system used in a typical lidar, which is limited by the photomultiplier tube (PMT) response time (typically a few nanoseconds or $\sim 1$ m).

Under these considerations, the scattered laser energy received by the detector at a time corresponding to a range $R$ in the bandwidth of the fundamental is given by

$$E_{NLin}(\lambda, R) = \frac{A_0}{R^2} \beta'(\lambda) E_i \exp \left\{ - \left[ 2 \bar{\kappa}(\lambda) + \bar{\kappa}_e(\lambda) \right] \right\} \times (R - D_s). \quad (5)$$

Using the same analytical procedure as for an elastic scattering lidar, one can extract the average extra-attenuation coefficient for the pulse energy from the lidar return signal in the filamentation regime as

$$\bar{\kappa}_e(\lambda) = - \frac{d \ln [E_{NLin}(\lambda, R) \times R^2]}{dR} - 2 \bar{\kappa}(\lambda). \quad (6)$$

3. Experimental Setup

Our experiments have been carried out in a 100-m-long corridor in Laval University, Quebec City, Canada. The laser system used in these experiments was built by Spectra-Physics/Positive Light. It consisted of a regenerative amplifier system (Spectra-Physics, spitfire) based on a Ti:sapphire oscillator (Spectra-Physics, Tsunami, pumped by a Millennia), a pulse slicer (Pockels cell), and a four-pass Ti:sapphire amplifier. The laser beam was finally compressed to 42 fs (FWHM) measured using a single-shot autocorrelator (Positive Light SSA). The central wavelength was 810 nm with a bandwidth of 23 nm (FWHM) and a maximum peak power of 1.4 TW with a linear polarization. The beam was sent into the corridor through a pipe containing a primary vacuum. At the last sending mirror (located at $\sim 1$ m from the output window of the vacuum pipe), the laser beam was 2.5 cm in diameter at $1/e^2$ level. Long pulses with 200-ps pulse duration were obtained by bypassing the compressor. The uncompressed beam after the main amplifier was sent directly in the corridor by the same sending mirrors as the compressed femtosecond beam. In the corridor, the paths of the compressed and the uncompressed pulses were superimposed. Both beams propagated in the same direction with the same beam diameter. A beam dump was placed at the end of the corridor, $\sim 100$ m from the last sending mirror.

In our experiments, both the uncompressed and compressed beams had an energy of 51 mJ/pulse. The critical power in air, $P_{\text{crit}}$, can be calculated using the value of $n_2$ in air, $(2.9 \times 10^{-19} \text{cm}^2/\text{W})^{21}$, and the definition of $P_{\text{crit}}$ as $P_{\text{crit}} = 3.77 \lambda^2/8\pi n_2 n_{\text{eff}} = 3.4$ GW. The uncompressed pulses with pulse duration of 200 ps lead to a pulse peak power of 0.25 GW, which is much lower than the critical power. The compressed pulses had a duration of 42 fs, which corresponds to a pulse peak power of 1.2 TW, orders of magnitude higher than the critical power.

Our detection system consisted of a Newtonian telescope, with a primary spherical mirror 16.5 cm in diameter and 90-cm focus length, and a second-
ary elliptical-shape flat mirror with 3-cm and 4.2-cm diameters. The secondary mirror is at 80 cm from the primary mirror. The eyepiece of the telescope was replaced by an optical condenser, which collected the light transmitted through the telescope onto a PMT (Hamamatsu R7400P, 1-ns response time, gain of $7 \times 10^6$) with a sensitive surface 8 mm in diameter. The field of view of the telescope was restricted by a diaphragm of 4-mm diameter installed in front of the PMT to avoid the detection of the light scattered from the walls of the corridor. With the diaphragm, at 100 m, the telescope looked at an area 1 m in diameter smaller than the size of the corridor (approximately 2 m wide and 2 m high). A 45° high-reflectance dielectric mirror for 810 nm was used as a dichroic beam splitter, which reflected light $\sim 810$ nm ($\pm 50$ nm) onto one PMT, and the transmitted light was sent to another PMT. The signal from the PMT detecting the 810-nm light was recorded by a digital oscilloscope. The recorded signal is an average over 500 laser shots. The initial distance and the angle between the axis of the telescope and the laser beam was 20 cm and $\sim 1$ mrad, respectively.

4. Experimental Results

Figure 1(a) shows the lidar signal of uncompressed pulses with a 51 mJ/pulse. This graph is corrected to the baseline, measured with the same PMT, and applies the same experimental conditions without the laser shooting. Figure 1(b) is the range-corrected (multiplied by $R^2$) data of the lidar signal. In Figs. 2(a) and 2(b), the same type of lidar signals are shown for compressed pulses at the same pulse energy.

From the lidar signal with the uncompressed beam that is our reference, the geometrical compression of the signal can be observed, which includes the effects of the overlapping of the laser beam with the receiver optics and the shadow of the secondary mirror. From the range-corrected signal [Fig. 1(b)], we observe that the geometrical detection probability becomes almost unitary after a distance $R$ of 43 m. At larger distances, the range-corrected signal exhibits a hump, which corresponds to a turbulence zone in the corridor. The inhomogeneities in the turbulence contribute to the lidar signal by a backscattering coefficient $\beta_\perp(R)$, which is added to the Rayleigh–Mie backscattering coefficient, $\beta(R)$, and leads a higher backscattered signal. After the turbulence zone,
range-corrected signal falls back to a level similar to the signal before the turbulence. Over the detection range, the average attenuation owing to the Rayleigh–Mie scattering is small. This is expected because, in a standard clear atmosphere at the sea level, the atmosphere attenuation coefficient for 810 nm is given by 0.14 km\(^{-1}\), which leads to an attenuation of 1.4% of the incident pulse energy over 100 m.

When the compressed beam propagated in the corridor, we observed multiple filaments formed in the laser beam. We measured the backscattered fluorescence signal from nitrogen molecules and ions, which showed that the filaments started at a distance of \(-10\) m from the last sending mirror and extended until the beam dump.

From the lidar signal with the compressed pulses, a similar geometrical compression feature is observed, and the geometrical form factor becomes unitary at a distance of 38 m, which is slightly different from that for the uncompressed beam. A simulation shows that a 0.5-mrad difference in alignment is enough to induce such a difference in the geometrical compression distances, which gives the precision of the alignment between the compressed and uncompressed beams in our experiments. The turbulence zone is also detected. However, after this zone, the range-corrected signal decreases significantly, showing an effective loss of the laser energy in the fundamental bandwidth over the detection range. That is the evidence of the extra-attenuation of a laser pulse undergoing filamentation.

5. Data Analysis

In order to extract the mean extra-attenuation coefficient from the lidar signals, we remove the turbulence contribution on the signal of the compressed pulses. That is done by extracting the turbulence contribution from the range-corrected lidar signal of the uncompressed pulses, for which variations by Rayleigh–Mie processes is well known. We expect a flat signal over our 100-m detection range for distances larger than the geometrical compression distance. Then we subtract the turbulence contribution from the range-corrected lidar signal for the compressed pulses. The range-corrected and turbulence-corrected signal for the compressed pulses is plotted in Fig. 3 with a logarithmic vertical scale. Slight fluctuations of the turbulence zone during the period when we recorded the uncompressed and compressed signals introduce some noise on the turbulence-corrected signal.

We fit the corrected signal by exponential decreasing functions in the form \( A \exp[-\alpha(R - D_S)] \), where \( A \) is a constant (\( A = 1.3 \) depending on the scale used in Fig. 3), \( D_S \) is the filament starting distance (\( D_S \) fixed at 10 m), and \( \alpha \), according to Eq. (5), is the total attenuation coefficient (including extra- and Rayleigh–Mie attenuations) for the compressed pulses. As shown in Fig. 3, our fits yield a value of \( \alpha = (0.0077 \pm 0.0012) \) m\(^{-1}\). This value is orders of magnitude larger than the Rayleigh–Mie attenuation coefficient for the 810-nm light (0.00014 m\(^{-1}\)). We can thus deduce the value of the mean extra-attenuation coefficient of \( \bar{\kappa_e} = (0.0077 \pm 0.0012) \) m\(^{-1}\). This value is comparable to the attenuation coefficient for a linearly propagating beam in the atmosphere in a thick haze condition.

6. Discussion

In our experiments, the filaments continued beyond the end of the corridor of 100 m. The direct observation of the end of the filaments required a longer propagation distance. The attempt to estimate the total filament length using our 100-m data is made complicated mainly by the dynamics of the spatio-temporal profile of a pulse undergoing filamentation. Theoretical calculation and experiments showed that the high-power femtosecond pulse will go through pulse splitting, deformation from to the nonlinear processes including MPI, group-velocity dispersion, space–time defocusing, self-steepening, and self-splitting, when a single filament is formed during the propagation. For a multi-TW femtosecond pulse propagating in air, multifilaments will be created unavoidably owing to the inhomogeneity of the initial beam profile and the medium. Therefore the pulse will go through rather complicated deformation processes.

In spite of this, the extra-attenuation in the filaments would allow an estimation of the effective filament length using the measurement on the energy loss of a pulse through the filamentation propagation. Since self-focusing is a power-dependent process, the end of a filament cannot be determined directly by the energy of the pulse. However, as the pulse self-focuses, the competition between the self-focusing
and defocusing effect caused by the plasma leads to temporal reshaping of the pulse, i.e., there is a sharp leading pulse with a smoother back component, and, with further propagation, a second pulse appears at the back of the leading pulse. The sharp leading edge is a new pulse, which might have a shorter duration than the original pulse. Thus we could take, for an estimation of the filament length, the original pulse duration as our upper limit for the pulse duration to estimate the peak power \( P \) at a given distance.

With such a simplistic consideration, if any other mechanisms do not destroy the filaments beforehand, they will vanish at a distance where the peak power of the input laser pulse is attenuated to be lower than \( P_{\text{crit}} \). With the laser parameters used in our experiments, initial laser energy \( E = 51 \) mJ and pulse duration \( \tau = 42 \) fs, one gets an initial peak power of \( P_0 = E/\tau = 1.21 \) TW. Using the extra-attenuation coefficient of \( \alpha = 0.077/\text{m} \), the propagation distance \( L \) is calculated to be 763 m for \( P/P_0 = 1 \). This value represents the upper bound for the effective filament length according to our experimental data and the simple model used to take into account the pulse spatio-temporal shape evolution. Now if we consider another simplistic case where two identical pulses are formed in the filament, a filament length of 673 m is estimated. That provides a range of the maximal filament lengths that we can expect. Further splitting of the pulse would make the filament length even shorter. It is clear that for a precise estimation of the filament length using the extra-attenuation on the pulse energy, a theoretical model is necessary to take into account the exact pulse-shape evolution.

In the atmosphere with an open-path propagation, the end of the filaments can be determined by observing the change of the slope in lidar return signals. When laser pulses propagate through a long distance in the atmosphere, the lidar signal would show two types of behavior, depending on whether filamentation persists before or after the backscattered signal becomes lower than the noise level of the detection. If the backscattered signal is stronger than the noise level at the end of filamentation, we expect that the slope of the range-corrected lidar signal would change (becoming flat) when the filaments reach their end and the propagation becomes linear again. If the lidar signal becomes lower than the noise before the filamentation ends, we could use the estimation presented in the previous paragraph to determine an upper limit of the effective filament length.

Finally, the extra-attenuation measurement can be combined simultaneously with the backscattered nitrogen fluorescence measurement\(^{14} \) using a multichannel detection system, for a precise remote detection of the spatial extent of the filaments. This will be done in the future.

7. Conclusion
We have demonstrated the extra-attenuation of intense femtosecond laser pulses propagating in the atmosphere using the lidar remote-sensing technique. This extra-attenuation is the result of the non-linear optical processes, such as the absorption through multiphoton/tunnel ionization, the scattering on the laser-induced low-density plasma, and the conversion into the white-light supercontinuum. The consequence of this extra-attenuation is a loss of the energy for the incident pulse of orders of magnitude faster than a low-intensity linearly propagating beam. This fast decay of the peak power sets a bound on the maximum effective length of the filaments.

The data from our experiments using 1.2-TW (51 mJ/pulse, 42 fs) pulses allowed us to determine a value of \( \alpha = (0.0077 \pm 0.0012)/\text{m} \) of the extra-attenuation coefficient, assuming exponential decay of the pulse energy. This attenuation is equivalent to that in a thick haze in the atmosphere for a linearly propagating beam. The measured extra-attenuation coefficient would depend on laser parameters as well as atmospheric conditions. Such dependences would be better understood with a theoretical model dealing with the different loss mechanisms contributing to the observed extra-attenuation on the laser pulse energy. The use of the measured extra-attenuation coefficient has allowed us to estimate an upper limit of the filament length, 763 m in our experimental conditions.

For the propagation of ultrashort and ultraintense pulses in the atmosphere, the results presented in this paper provide a new technique to remotely detect the filaments. With an open propagation path, the change in the scattering regime around the end of the filaments would allow a remote determination of the spatial extent of the filaments. For the cases where the slope change is not observable for the reasons of short propagation distance or of limited detection sensitivity, the end of the filaments can be estimated by extrapolating the lidar signal to a pulse energy low enough to avoid any filamentation. Owing to the complicated evolution of a pulse undergoing the filamentation, a theoretical model is clearly necessary to precisely predict its spatio-temporal and energetic behaviors.

We would like to acknowledge J.-P. Wolf and J. Kasparian for helpful discussions. We also would like to acknowledge the technical support of M. Martin. This work was supported in part by Natural Sciences and Engineering Research Council of Canada, Defense Research and Development Center-Valcartier, Canada Research Chairs, Canadian Institute for Photonic Innovations, and Fonds de Recherche sur la Nature et les Technologies. J. Yu was supported by the Teramobile Project, jointly funded by the French Centre National de Recherche Scientifique and the German Deutsche Forschungsgemeinschaft, for his sabbatical leave in Quebec city. He also thanks C. & E. for the partial financial support of his stay in Quebec City.

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