Formation and evolution of intense, post-filamentation, ionization-free low divergence beams

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1. Introduction

Soon after it was first observed [1], in the mid 90s, filamentation [2–7] resulting from femtosecond laser pulses propagation in air attracted a lot of scientific interest. Indeed, the unique properties exhibited by filaments make it a potentially useful tool for multiple atmospheric applications [3]. Plasma filaments were used to remotely deliver high intensity pulses at [8], and over [9] long distance. Among the most popular remote atmospheric applications, we have detection and identification of airborne contaminants [10,11], generation of THz [12] and ultrabroadband [13] pulses, guiding and triggering of electric discharges [14].

In air, filaments primarily appear due to a dynamic equilibrium between Kerr self-focusing and defocusing by the self-generated low-density plasma produced from multiphoton/tunnel ionization of the air molecules. Indeed, for a non-uniform laser intensity distribution (Gaussian, for example) with peak power higher than the critical power for self-focusing [15], the Kerr effect acts as a lens that focuses the light pulse until its intensity is sufficiently high to ionize the medium in which it propagates. Once the plasma is sufficiently dense to counteract the Kerr lens effect, the laser pulse starts to defocus. The defocusing nature of the plasma limits and stabilizes the light intensity in each of the filaments (intensity clamping). In air, for 800 nm laser light, the clamped intensity is approximately 50 TW/cm² [16,17].

Filaments in air are normally defined as the segment of propagation where plasma is left behind by the laser pulse [18]. However, high intensity ionization-free light channels, extending beyond hundreds of meters after the ionization zone, were observed by Méchain et al. [9]. This work was performed using the Teramobile facility in a 2.3 km long outdoor horizontal field. They observed that, after the ionization zone, multiple hot spots with intensity below the ionization threshold of air, could survive over several hundreds of meters. Their work revealed that these ionization-free channels allowed the delivery of intense pulse over long distances with limited energy losses. However, no complete explanation as to how these ionization-free channels formed was provided.

The experiment described in this paper attempted to explain, from another point of view, how these ionization-free light channels form and survive over long distances. It was discovered that they are initially induced by diffraction of the post-filament energy reservoir onto the plasma. In fact, near the end of the filament, the plasma blocks the remaining energy reservoir similar to a circular opaque obstacle inserted in the center of a laser beam which induces an axial, Bessel-like hot spot of extremely good quality. However, even though this diffraction plays a determinant role in the formation of these high intensity structures, self-focusing remains important to stabilize and maintain the intense core over long distances.

2. Experimental scheme and results

2.1. Setup

Laser pulses centered at 803 nm with 22 nm spectral width were emitted at a 10 Hz repetition rate from a typical commercial Ti:Sapphire
amplifier and compressed to a transform-limited duration of 45 fs. The pulse energy was fixed at 5 mJ such that a single and stable filament, originating from a hot spot in the initial transverse profile, formed at almost every laser shot. The laser pulses, elliptical in shape, were characterized with 3.6 mm and 2.5 mm transverse diameter at full width at half maximum (FWHM).

The near-collimated laser pulses were launched in a 25 m long corridor and then reflected by an aluminum-coated reflector at the opposite end of the corridor to provide ~50 m long propagation. The evolution of the laser pulses was characterized by measuring the beam patterns at the fundamental wavelength as a function of distance. To do so, the experimental unit shown in Fig. 1 was translated along the beam’s propagation axis to capture the beam patterns with a CCD camera. In order to avoid damages to the screen and the camera, the front surface of a fused silica wedge (W), with a 3° angle between the two surfaces, directed a weak reflection of the incident beam towards a flat spectral response white diffuser. The CCD camera was protected with adequate neutral density (ND) filters and an interference bandpass filter (BP), with a 10 nm wide transmission window centered at 800 nm FWHM. BP at 800 nm was selected to properly observe the evolution of the post-filament fundamental wave.

The filament’s plasma distribution was measured by monitoring the molecular N2 fluorescence [19] emitted by the plasma string left behind the laser pulse. This measurement, performed over a dynamical range of four orders of magnitude, revealed that the filament started at 8 m and ended at 13 m after the pulse compressor.

2.2. Post-filamentation core vs energy reservoir

Fig. 2 presents beam patterns measured after the ionization zone (16 m from the compressor) using bandpass filters with 10 nm transmission window centered at 850 nm (a) and 800 nm (b). Fig. 2a presents the spatial distribution of the perfectly circular red-shifted filament core [20,21] measured in this spectral range. This is a rather indirect representation of the core because it was observed only on a 10 nm bandwidth window approximately 50 nm from the pulse’s initial peak wavelength (λ0=803 nm) and the post-filament core peak wavelength should be in the vicinity of 2λ0. However, as will be explained shortly, this spectral window provides a good representation of the post-filament core’s behavior.

This measured beautiful beam pattern is the result of spatial filtering during filamentation caused by the self-focusing of the beam’s fundamental mode into the filament core [21–23] together with the Raman shift [21]. The Raman frequency red shift phenomenon, being nonlinear, occurs only in the high intensity filament core; hence, perfectly circular. On the other hand, the pattern in Fig. 2b is the result of the diffraction of the back part of the pulse including the background reservoir [24] by the cylindrical plasma filament left behind by the front part of the pulse. Even though the core profile of the 850 nm pattern is of excellent quality, its energy content is rather weak. For comparison, we need to use a higher filter transmission (1.25%) to obtain the picture in Fig. 2a while in Fig. 2b, the filter transmission was approximately 10 times lower (0.15%). The measured filter transmission includes the combined transmission of ND and BP. For our purpose of properly observing the evolution of the post-filament, intense spectral components of the pulse, BP at 800 nm was selected.

Chen et al. [25] performed a similar experiment up to 12 m after the pulse compressor. However, beam patterns as in Fig. 2b were not observed because the bandpass filter used for this experiment had a larger transmission window (bandwidth = 40 nm FWHM). As a result, the patterns reported consisted in a superposition of the intense circular core (Fig. 2a) and the diffracted energy reservoir (Fig. 2b). In their experiment, they monitored the weak core diameter up to 12 m after the pulse compressor and obtained a divergence of 0.23 mrad.

The choice of BP at 800 nm was further confirmed by measuring on-axis spectra using a fiber spectrometer, an integration sphere and a 4 mm diameter metallic pinhole. The latter ensured that only the axial hot spot went into the sphere, thus neglecting the conical emission and the diffraction rings. The setup was translated along the beam after ionization and the spectra are presented in Fig. 3. The black curve corresponds to the initial pulse spectrum measured after the pulse compressor. Soon after the filament (14.8 m), the spectral distribution was strongly asymmetric showing an intense peak with a long extension on the red side of λ0 whereas the blue side of the central wavelength is characterized with strong modulations.

This distribution is a direct consequence of group velocity dispersion induced by the propagation in a dispersive medium (air). Indeed, when an initially transform limited pulse propagates in the atmosphere, the pulse’s blue spectral components perceive a larger index of refraction than the red components such that after a certain distance, the pulse is positively chirped. Since filamentation occurs on the leading edge of the pulse [24], only the spectral components whose wavelengths were larger than λ0 displayed the behavior of an intense filament core while the shorter wavelengths presented signs of diffraction on the plasma. Consequently, after the filament, the on-axis spectrum is mainly broadened towards the red side. However, as measured in Ref. [25] the red-shifted core rapidly diverged due to insufficient intensity which resulted in strong on-axis depletion (21.8 m) of the spectral energy for wavelengths larger than 2λ0. After a certain distance (24.3 m), mainly the pulse’s fundamental frequencies remained on the axis, thus justifying the choice of BP at 800 nm to monitor the spectral components of the pulse’s fundamental wavelength.

2.3. Post-filament beam evolution

Fig. 4 presents characteristic events of the propagation of these laser pulses. The top, left-hand side image shows the initial beam pattern, prior to the plasma filament, 5.5 m after the compressor. The two images captured at 10.8 m and 11.4 m, show the circular filament core produced with such pulses where there is ionization.

From these two pictures, the measured core diameter is significantly larger (700 μm–1 mm) than what would normally be expected (~100 μm). This is attributed to the long distance that the reflected pulse traveled from the front surface of the wedge W to the sensitive surface of the CCD (distance ≈ 90 cm). Indeed, after W, the reflected core intensity being significantly reduced, linear diffraction took over self-focusing and resulted in the detection of a larger filament diameter. The dark axial circular hole and the concentric rings observed 12.2 m and 16 from the compressor indicate that there was diffraction from a circular opaque obstacle, the plasma.
Fig. 5 presents the central spot diameter as a function of distance. Between 12 m and 25 m, a clear axial hot spot could not be observed due to strong diffraction effects and no data points were placed in this range. Beyond 25 m, the plot shows that the post-filament hot spot evolved over 20 m with a low divergence of 0.03 mrad. A comparison with the post-filament weak core divergence (0.23 mrad) reported in Ref. [25] reveals that the energy reservoir is indeed the source of the low divergence ionization free hot spot.

3. Spatio-temporal numerical simulations of the long-distance filamentation and post-filament guiding

Numerical simulations of the pulse filamentation and post-filament divergence have been performed based on the slowly evolving wave approximation [26] modified with consideration of the laser-produced plasma generation. The equation for the slowly varying light field amplitude $A(r,z,t)$ is given by

$$2 i k_0 \left( \frac{\partial A}{\partial z} + \frac{1}{2} \frac{\partial A}{\partial r} \right) = \left( 1 - i \frac{\partial}{\partial z} \right) \Delta A - k_0 \left( k^2 + \frac{1}{2} \sum_{n=1}^{\infty} \frac{1}{(\nu_n^2 - 1)} \Delta n_n \right) \frac{\partial^2 A}{\partial t^2} +$$

$$+ \left( 1 - i \frac{\partial}{\partial z} \right) \Delta n_n + \left( 1 - i \frac{\partial}{\partial z} \right) \left( \text{Re} \Delta n_n + i \text{Im} \Delta n_n \right) \Delta n_n A - i k_0 \alpha A$$

(1)

The first term on the right-hand side of the Eq. (1) describes the beam diffraction (here $\Delta z = r^{-1} \partial / \partial r (r \partial / \partial r)$ is transverse Laplacian under the axial symmetry assumption) and the space-time focusing, the second and the third terms describe material dispersion, where $k_0 = \omega_0 n_0 / c$ is a wavenumber at the laser central frequency $\omega_0$, corresponding to $\lambda_0 = 800$ nm, $n_0 \approx 1$ is the refractive index of air for the case of linear
light propagation, \( k(\omega) = \omega n(\omega)/c \), \( v_g = (\partial k(\omega)/\partial \omega) \) is the group velocity, \( \tau_n = (\partial^2 k(\omega)/\partial \omega^2) \) is the second order dispersion coefficient, \( n(\omega) = (2726.43 + 3.46 \times 10^{-7} \omega^2) \cdot 10^{-7} + 1 \) \cite{27}. The fourth, the fifth and the sixth terms grouped in square brackets on the right-hand side of Eq. (1) describe the contribution of the Kerr nonlinearity, self-steepening and the plasma to the pulse transformation. The seventh term describes the pulse energy loss due to the ionization.

The Kerr nonlinearity of neutrals far from the atomic and molecular resonances is defined by anharmonic response of the bound electrons and the stimulated Raman scattering on rotational transitions of molecules:

\[
\Delta n_r(r,z,t) = \frac{1}{2} n_e \left( |E|^2 + \int_{-\infty}^{t} H(t-t')|E(t')|^2dt' \right),
\]

where the response function \( H(t) \) measured in Ref. \([28]\) was approximated based on the damped oscillator model in Ref. \([24]\). In the simulations we used \( n_e = 1.8 \times 10^{-16} \text{ cm}^2/\text{W} \), which gives a critical power for self-focusing \( P_{cr} \) \((28)\) equal to \( 10 \text{ GW} \) for a 55 fs pulse in agreement with measurements \([15]\).

In the case of a femtosecond pulse propagation in atmospheric air the imaginary part of the plasma contribution to the refractive index \( \text{Im}(\Delta n_p) \) can be neglected, while the real part is represented by:

\[
\text{Re} \left( \Delta n_p(r,z,t) \right) = -\omega_p^2(r,z,t) / (2n_e e^2 \omega_0^2),
\]

\[
\omega_p(r,z,t) = \sqrt{4\pi e^2 N_r(r,z,t)/m_e};
\]

The function \( \alpha(r,z,t) \) is responsible for the ionization energy loss:

\[
\alpha(r,z,t) = \frac{\hbar c}{2m_e} \left( m_0^2 \cdot \frac{\partial N_0}{\partial t} + m_e^2 \cdot \frac{\partial N_e}{\partial t} \right)
\]

In the Eqs. (3)–(5) \( m_e \) and \( e \) are electron mass and charge, respectively, and \( m_0^2 = 8 \) and \( m_e^2 = 11 \) are the numbers of photons necessary for the multiphoton ionization of oxygen \( \text{O}_2 \) or nitrogen \( \text{N}_2 \) air molecules, respectively. \( I(r,z,t) = \frac{c n_0}{\hbar c} |A(r,z,t)|^2 \) is the light field intensity. The electron densities \( N_0^{\text{O}_2}(r,z,t), N_0^{\text{N}_2}(r,z,t) \) are calculated according to the rate equations with the ionization probability \([29]\).

At the entrance to the nonlinear medium the pulse is Gaussian both in space and time:

\[
A(r,z=0,\tau) = A_0 \exp \left( -\frac{\tau^2}{2\tau_0^2} \right) \times \exp \left( -\frac{r^2}{2\sigma_0^2} \right),
\]
where \( \tau = t - z/v_g \). The initial pulse duration \( 2\tau_0 = 54 \) fs at \( e^{-1} \) intensity level (45 fs FWHM), initial beam size is \( 2a_0 = 4.6 \) mm at \( e^{-1} \) intensity level (3.8 mm FWHM), and the energy \( W_0 = 5 \) mJ in agreement with the experiment. Axially symmetric simulations allowed us to use the large background reservoir size of 4 cm and to properly consider both the filament core and the post-filament beam divergence with the spatial resolution of 1 \( \mu \)m.

In the filament zone the simulated transverse beam patterns are in agreement with the experimental ones (compare Fig. 2a and Fig. 2c and e, Fig. 2b and Fig. 2d and f). The maximum spectral intensity of the spatially cleaned distribution at 850 nm (Fig. 2c and e) is by a factor of 6 lower than the maximum spectral intensity at 800 nm (Fig. 2d and f). The beam pattern at 800 nm in Fig. 2d reveals a system of the background rings due to the diffraction on the laser-produced plasma.

Post-filament divergence was studied numerically by “propagating” the pulse far beyond the position \( z \approx 22 \) m, where the plasma ends. The solid line in Fig. 5 shows the evolution of the simulated FWHM diameter of the radiation filtered at 800 nm. The filament starts 3 m earlier in the simulations as compared to the experiment (filled circles in Fig. 4) due to the purely Gaussian and not elliptical initial intensity distribution given by the Eq. (6). As mentioned earlier, the larger post-filament diameter observed in the experiment was caused by the diffraction the weak reflected pulse suffered during its propagation between the wedge and the CCD. At the same time the divergence angle after the end of the filament is in quantitative agreement with the experimental result. The physical reason for the slow divergence is the \( \chi^3 \) Kerr nonlinearity of the neutral air molecules, which prevents the post-filament beam to diverge as if it were in vacuum (compare the solid and the dashed curves in Fig. 5).

4. Analysis and discussion

4.1. Numerical description of a Gaussian beam incident on a circular obstacle

In this section, we investigate numerically how diffraction of the post-filament energy reservoir on the plasma can induce a circular axial hot spot. For this purpose, the situation was simply reduced to a simple beam with a transverse Gaussian distribution of cylindrical symmetry, incident on a circular, sharp-edged opaque obstacle. Nonlinear effects were not considered. After the obstacle, the radial transverse electric field distribution \( E(r,z) \) can be approximated, as a function of distance \( z \), by [30]:

\[
E(r,z) \approx -\frac{q_0}{q(z)} e^{-\left(\frac{w}{a} \right)^2} e^{-j\pi rc/a^2} J_0(2\pi Nr/a)
\]  

(7)

where \( a \) is the obstacle radius, \( w_0 \) is the Gaussian beam radius FWHM measured at the waist and \( r \), is the transverse radial coordinate, \( J_0 \) is a zero order Bessel function and \( N \), the Fresnel number, is defined as \( N = \frac{a^2}{(z-z_0)} \). \( q(z) = q_0 + z \) is the complex radius of curvature of a Gaussian beam with initial value \( q_0 = \frac{w_0}{\lambda z_0} \).

The images on the top row of Fig. 6 present the transverse fluence distribution of the beam, after the opaque obstacle, obtained from this model. Immediately after the obstacle, diffraction induces a central minimum that rapidly develops into an intense central spike surrounded by Bessel rings. This axial maximum, often referred to as Arago’s spot is present everywhere along the propagation axis in the exact center of the dark shadow left behind by the opaque circular obstacle. A comparison with the beam patterns measured (bottom row Fig. 6) reveals that this mechanism is indeed the source of the light channels. This mechanism is similar to what has been observed in Ref. [31] where filaments were self-healed after interacting with spherical water droplets.

However, the two far-right images show that this only mechanism cannot explain how the hot spot maintained its diameter over several tens of meters. Indeed, from the calculation, the post-obstacle induced “linear” hot spot diverged much faster (0.45 mrad) than what had been measured in the laboratory for the post-filament axial hot spot (0.03 mrad). Therefore, self-focusing must have played a dominant role to maintain the intense core over long distances.

4.2. Linear diffraction compensation by self-focusing

In order to understand how self-focusing can maintain the diameter of high intensity post filament beam without ionization,
was estimated to 0.5 TW/cm² which is not too far from the value for the critical power for self-focusing. We argue that the power contained in the intense core is neighboring the threshold power. For uncompressed beams, the linear divergence of our uncompressed beam is measured in Ref. [9].

This is exactly how the divergence of the intense post-filamentation beam could be maintained around 0.03 mrad over several tens of meters. Moreover, it was found that self-focusing played an important role to maintain slowly diverging, intense beams over long distances. Moreover, the effects of self-focusing on beam divergence could be observed for powers as low as 1 MW. Below this limit, no noticeable change in the divergence could be observed. From this measurement, we could say that the linear divergence of our uncompressed beam is neighboring 0.253 mrad.

This is how the divergence of the intense post-filamentation beam could be maintained around 0.03 mrad over several tens of meters. Moreover, because its divergence is close to zero, one could argue that the power contained in the intense core is neighboring the critical power for self-focusing \( P_c \). Indeed, \( P_c \) is defined as the pulse’s peak power necessary to change the effect of linear divergence and in air it is \(-10 \text{ GW}\) [15]. Therefore the core intensity of the 2 mm diameter post-filamentation beam measured at 51 m (Fig. 5) was estimated to 0.5 TW/cm² which is not too far from the value measured in Ref. [9].

5. Conclusions

The formation and evolution of intense post-filamentation ionization-free beam were investigated experimentally for collimated femtosecond pulses propagating over 50 m in air. It was found that the formation of this high intensity post-filament beam was initiated by diffraction of the back part of the pulse by the produced plasma. Indeed, we demonstrated both experimentally and numerically that this diffraction induced an intense axial peak which evolves into a hot spot. However, self-focusing still played a dominant role to maintain the intensity of this narrow, low divergence hot spot (0.03 mrad). In fact, the numerical simulation revealed that the diffraction induced hot spot cannot maintain its diameter over long distances without the presence of self-focusing. Moreover, it was found that self-focusing affects the divergence of laser pulses propagating in air for powers as low as 1 MW. The intensity of the hot spot measured 51 m from the pulse compressor, was estimated to 0.5 TW/cm².

Acknowledgments

We acknowledge the support from NSERC, DRDC–Valcartier, CFI, FQRNT, Canada Research Chair, RFBR #09-02-01200a, RFASI #02.74011.0223 and the President of the RF Grant MK-2213.2010.2.

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