Control of the filamentation distance and pattern in long-range atmospheric propagation

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Abstract: We use the double-lens setup [10, 11] to achieve a 20-fold delay of the filamentation distance of non-chirped 120 fs pulses propagating in air, from 16m to 330m. At 330m, the collapsing pulse is sufficiently powerful to create plasma filaments. We also show that the scatter of the filaments at 330m can be significantly reduced by tilting the second lens. To the best of our knowledge, this is the longest distance reported in the Literature at which plasma filaments were created and controlled. Finally, we show that the peak power at the onset of collapse is significantly higher with the double-lens setup, compared with the standard negative chirping approach.

OCIS codes: (010.1300) Atmospheric propagation, (190.7110) Ultrafast nonlinear optics

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1. Introduction

The possibility to send high-power ultrashort laser pulses into the atmosphere that would propagate over several kilometers [1] has sparked the interest of many researchers in nonlinear optics. As a result, atmospheric propagation of high-power lasers is currently a very active area of research, with potential applications such as remote sensing of the atmosphere using LIDAR techniques and lightning control [2, 3, 4]. Typically, Terawatt laser pulses can propagate only several meters in the atmosphere before they collapse. Quite often in atmospheric applications, however, one would like to be able to delay and to control the filamentation/collapse distance, so that it would be anything from a few meters up to several kilometers. Until very recently, the only approach to achieve that was by negatively chirping the pulses, see e.g., [1, 2].

In general, the collapse can be arrested by various effects. Since the threshold for detectable air ionization is $8 \cdot 10^{12} W/cm^2$ [5], plasma-induced defocusing can arrest the collapse only if the intensity is clamped at intensities above this value. In particular, for a 800nm laser, when the light intensity exceeds $\sim 4 \cdot\ 10^{13}$ W/cm^2, the "post-collapse" filaments are characterized by the presence of plasma [5]. If the intensity at which collapse is arrested is lower, the mechanism for the arrest of collapse is different (e.g., GVD, Raman scattering or nonlinear absorption) [6]. Therefore, following Ref. [7], we distinguish between high intensity (above 10^{13} W/cm^2) *plasma filaments* when air ionization occurs, and lower intensities ($10^{10} - 10^{12}$ W/cm^2) *light filaments*, which are localized light pulses with no ionization [7, 8].

The effect of negative chirping on the location and intensity of the filaments was studied numerically [9] and experimentally [7]. Méchain *et al.* [7] showed that creation of *plasma filaments* can be delayed from a few meters for 0.2ps pulses (whose peak power P is ≈ 190 times the critical power for collapse P_{cr}) up to $\approx$ 250m for 6ps negatively chirped pulses ($P \approx 6P_{cr}$). At longer pulse durations (e.g., 9.6ps pulses) no air ionization was detected and "only" *light filaments* were observed. Therefore, the results of Méchain *et al.* suggest that there may be an upper limit of a few hundred meters to the maximal distance at which *plasma filaments* can be created with negative chirping.

In Ref. [10], we developed a novel method to delay and control the filamentation distance, by using a double-lens setup that consists of a defocusing lens followed by a focusing lens, see Fig. 1(a). By varying the distance d between the two lenses, we were able to achieve a continuous control over the filamentation distance, and to delay the filamentation distance inside the lab by a factor of ≈ 4, from 12m to 50m. In these experiments, the filamentation distance was defined as the shortest distance from the first lens at which a burn mark is created on a Polyvinyl-Chloride (PVC) target. Since air ionization requires intensities higher than $8 \cdot 10^{12} W/cm^2$ [5], the $\approx 1.2 \cdot 10^{13} W/cm^2$ damage threshold of the PVC ensures that air is ionized at this location. Thus, the burn mark indicates the presence of a *plasma filament* and not "just" *light filament*.

Independently of Ref. [10], Liu *et al.* [11] proposed a similar setup that consisted of a convex mirror followed by a focusing lens and used it to delay the filamentation distance up to 90m. The

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presence of plasma filaments in those experiments was detected by measuring the backscattered Nitrogen fluorescence (BSF) emitted by the air-ionized plasma.

In Ref. [10], we also derived a simple algebraic formula for the filamentation distance. This derivation is based on two observations: First, that prior to pulse collapse, the propagation in the atmosphere is essentially determined by the Kerr nonlinearity and diffraction, as other effects (multiphoton absorption, plasma formation, Raman scattering, etc.) become important only after the pulse has collapsed. As a result, the collapse point can be calculated with the relatively simple two-dimensional, cubic Nonlinear Schrödinger model (NLS). Second, the effect of a focusing/defocusing lens in the two-dimensional, cubic NLS is exactly the same as in diffractionless, linear propagation (Geometrical Optics), a property known as the lens transformation [12]. Hence, the filamentation distance $z_c^{(d)}$ as a function of the distance d between the two lenses is given by

$$z_c^{(d)} = d + F_2 \frac{z_c(F_1 - d) - dF_1}{(F_1 + F_2)z_c + F_1F_2 - d(z_c + F_1)}, \tag{1}$$

where z_c is the filamentation distance of the original pulse, and F_j are the focal lengths of the lenses. These results were found to be in excellent agreement with our experimental results.

Equation (1) shows that in principle, the filamentation distance can be delayed to any distance. This is in sharp contrast to the upper limit observed for negatively chirped pulses [7]. Furthermore, unlike the negative chirping method, the filamentation distance $z_c^{(d)}$ obtained by Eq. (1) is independent of the pulse duration, hence it describes the filamentation distance of ultrashort pulses as well as of CW beams.

2. Experimental results

2.1. *Control of the collapse distance*

The maximal filamentation distance obtained in previous studies with the double-lens setup [10, 11] was limited by the size of the laboratories and was below 90m. In this study we report on the results of a new outdoor experiment in which we use the double-lens setup to further delay the filamentation distance of 0.3TW non-chirped 120fs pulses at 800nm with radius $r_0 = 6$mm. As in Ref. [10], the formation of *plasma* filaments is detected by the burn marks created on a PVC target. In the absence of the double-lens setup, the 0.3TW pulses ($\approx 60P_{cr}$) collapse at a distance of $z_c = 16$m. The double-lens setup allows us to delay the filamentation distance by a factor of up to 20 to $z_c^{(d)} = 330$m, see Fig. 1(b). In principle, the filamentation distance could be delayed even further, see Eq. (1). However, 330m is the maximal distance that we are able to measure due to topography limitations. To the best of our knowledge, this is the longest distance reported in the literature for the starting point of a *plasma filament*, see Refs. [7, 11]. The experimental results are in good agreement with the analytical formula (1), see Fig 1(b).

2.2. *Control of the filamentation scatter*

In order to measure the scatter of the filaments at $z_c^{(d)} = 330$m, we put the PVC target at the same place for 30 seconds, which gives the overall damage made by 300 shots, see Fig. 2(a). The scatter occurs mainly due to fluctuations of the pulse power and shape. Most burn marks are located within an area of 6×7mm. In order to achieve an even better localization, we follow [13, 14] and rotate the second lens so that it makes an angle of $\phi = 5^\circ$ with the transverse plane of the pulse, see Fig. 1(a). As a result, the area over which most burn marks are located decreased by a factor of ≈ 4, see Fig. 2(b). We note that the tilting results in a residual change of the filamentation distance, which we compensated for by a re-adjustment of the distance d between the lenses.

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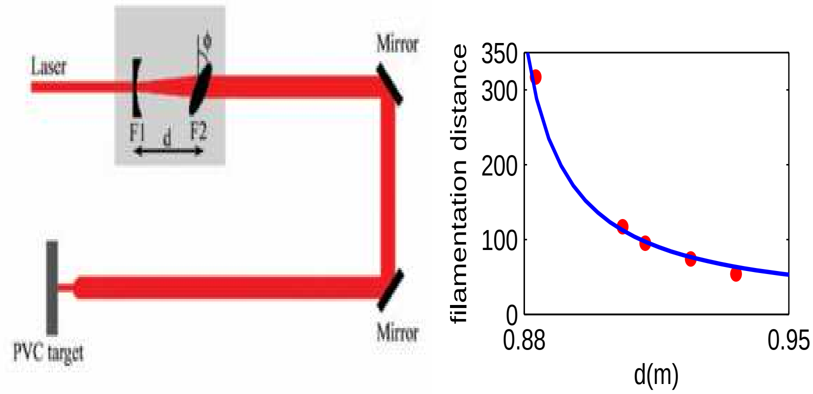

Fig. 1. (a) Experimental setup - laser pulse passes through a defocusing lens (F_1) followed by a (possibly tilted) focusing lens (F_2). (b) Experimental data (red dots) vs. theoretical prediction (blue solid line) for filamentation distance $z_c^{(d)}$ as a function of distance between the lenses d.

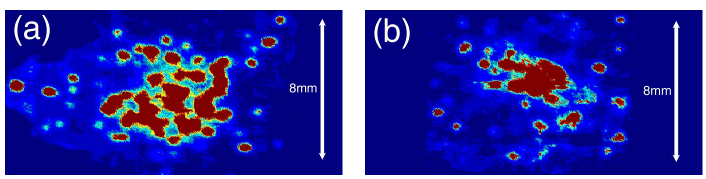

Fig. 2. Burn marks on a PVC target created by ≈ 300 laser shots at $z = 330m$ for an (a) untilted, and (b) tilted second lens.

3. Comparison with the negative chirping technique

In order to compare the double-lens approach with the negative chirping approach, we solved the Nonlinear Schrödinger Eq. with normal group velocity dispersion ($\beta = 22\text{fs}^2/\text{m}$) numerically. Initially, the parameters in the numerical simulations were chosen to be the same as in the experiment, i.e., $r_0 = 6$mm, $\lambda = 800$nm, $t_0 = 120$fs and $P_0 = 60P_{cr}$. For these parameters, numerical simulations show that the non-chirped pulse collapses at $z_c = 16$m, which is the same distance measured in the experiment. We then added negative chirping, and found that the amount of negative chirping needed to delay the collapse to 330m is $C = -44$, see Fig. 3(a). For this amount of chirping, the pulse duration increases to

$$t_0^{(C=-44)} = t_0\sqrt{1+C^2} = 5.3ps. \tag{2}$$

Hence, the peak input power of the pulse reduces to

$$P_0^{(C=-44)} = \frac{60}{\sqrt{1+(-44)^2}}P_{cr} \approx 1.36P_{cr}.$$

Comparison of the dynamics of the chirped-pulse with the dynamics of a CW beam with the same input power ($1.36P_{cr}$) shows that they are nearly identical, see Fig. 3(a). This implies that when collapse is delayed to 330m using negative chirping, the temporal dynamics is negligible and that chirping affects the dynamics only by reducing the input power. This observation may

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seem to be counterintuitive, since one can expect to have a considerable temporal compression in the presence of strong negative chirping. Indeed, researchers using the chirping technique often believe that filamentation distance of chirped pulses is delayed because the delayed red components in the chirped pulse, which are faster, must first catch up the blue components before large peak powers can trigger nonlinear effects. Hence, the idea of the pulse chirping technique is that of taking advantage of the temporal dynamics so as to precede the short self-focusing stage by a linear chirped-pulse compression stage in the dispersive air [15].

In order to understand why the temporal dynamics is negligible for our experimental setup, we recall that the increase of the pulse duration leads to an increase of the dispersion length from $L_{disp} = t_0^2/\beta_2 = 654$m for the non-chirped pulse with $t_0 = 120$fs to $L_{disp}^{(C=-44)} = \left(t_0^{(C)}\right)^2/\beta_2 \cong$ 1250km for the chirped pulse with $t_0 = 5.3$ps. In addition, the distance at which the minimal pulse duration T_{min} is reached is given by [2]

$$z(T_{min}, C=-44) = \frac{|C|}{2(1+C^2)} L_{disp}^{(C)} \cong 28km.$$

Therefore, temporal effects are negligible over a distance of 330m. In other words, for the conditions of our experiment, chirping the pulse essentially results in a delay caused by spatial effects (i.e. self-focusing of a pulse with reduced peak power). Only for much shorter pulses, negative chirping will temporally compress the pulse prior to its collapse.

An important consequence of the absence of temporal dynamics is that the peak pulse power remains essentially unchanged along the propagation. Indeed, Fig. 3(b) shows that the power at the collapse point is only 1% higher than the input peak power.

We now estimate the power of the non-chirped pulse as it collapses at 330m using the double-lens setup. Since for the non-chirped pulse $L_{disp} = 654$m, the pulse duration increases only by $\approx 20\%$ at a distance of 330m ($\approx L_{disp}/2$). Thus, the power at the collapse point of the non-chirped pulse decreases from $P \approx 60P_{cr}$ to $P \approx 50P_{cr}$. This shows that the pulse peak power at 330m obtained by the double-lens technique is ≈ 35 times higher than the power obtained at 330m by the negatively chirped pulse. This power difference can have a large effect on the filamentation properties (number of filaments, length of filament, plasma generation, supercontinuum generation, conical emission etc.). Naturally, these differences can be very important in applications.

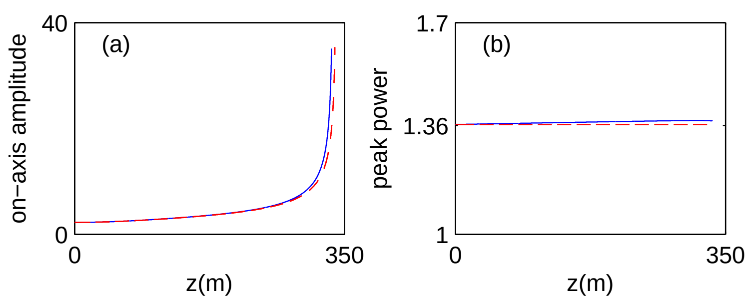

Fig. 3. Numerical solution of NLS with time dispersion with $P_0^{(C)} \approx 1.36P_{cr}$ (solid black line) and numerical solution of NLS without time dispersion (CW beam) with the same input power (dotted blue line). (a) On-axis amplitude (b) peak power.

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4. Summary

In this study we combined the double-lens setup with the tilted lens setup. This allowed us to delay the creation of *plasma filaments* to a distance of 330*m* while achieving high localization. This distance is longer than the maximal distance at which *plasma filaments* were created by negative chirping [7] and almost 4 times longer than the maximal distance at which *plasma filaments* were previously created by a double-lens setup [10, 11].

Since using the double-lens setup suppresses the need to negatively-chirp the pulse, the pulse power at the onset of filamentation in our experiment is considerably higher than for the negatively-chirped ps-long pulses. Finally, our results are found to be in good agreement with the theoretical formula (1) for the location of the collapse. Note that no such simple formula is available for the delay of collapse by negative chirping.

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