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Characteristics of multiple filaments generated by femtosecond laser pulses in air: Prefocused versus free propagation

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The characteristics of the multiple filaments formed by prefocused and freely propagating femtosecond laser pulses are investigated and compared. It is shown in our experiments that the diameter, length, stability, and interaction for the two cases can be quite different. The filaments formed by prefocused beam indicate dynamic spatial evolution with higher laser intensity and electron density. They have a typical diameter of 100 μm are of shorter length. In the free propagation case, the filaments exhibit interesting properties such as hundred-meter propagation distance and mm-size diameter. Moreover, only the interaction of the filaments with the energy background affects the evolution of the filaments. Filament-filament interactions such as the filament splitting and merging were not observed in this case.

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I. INTRODUCTION

The development of ultraintense femtosecond (fs) laser technology has made the long-distance propagation of laser pulses possible. The propagation of an ultraintense fs laser pulse in air first undergoes nonlinear Kerr self-focusing effect because of the intensity-dependent refractive index of air. When the focused-laser intensity reaches the ionization threshold of air, a low-density plasma is produced. This leads to defocusing of the laser pulse. The self-focusing and defocusing processes repeat and can guide the laser pulse to propagate over a distance much longer than the Rayleigh length. As a result, a long plasma channel with enhanced conductivity is formed in the track of the laser pulse. The filamentation is accompanied by very large spectral broadening from the UV to the mid-IR, corresponding to supercontinuum (SC) generation, which can be used as a white-light source for atmospheric trace-gas remote sensing [1,2]. The long-distance conductive plasma channel can also be used to control lightning [3–5].

Braun *et al.* [6] first observed that ultrashort laser pulses can be self-focused into long-distance multiple filaments (MF) in air. Since then, a large number of experimental and theoretical studies have been performed on laser filamentation in air. Many interesting phenomena have been observed during the long distance propagation of filaments, such as SC radiation [7–10], conical emission [11–13], third-harmonic generation [14–16], multiple refocusing [17], etc. The phenomena result from the complex spatiotemporal process. The dynamic energy transformation between the filaments core and the wide low-intensity energy background (also called energy reservoir) results in the multiple refocusing. The recurrence of the focusing-defocusing supports the long distance propagation of the laser pulse in air.

The traditional method for investigating MF in the laboratories is to focus the fs laser using a convex lens. MF are formed before the geometrical focus of the lens. For convenience, this type of filament shall be called prefocused-MF. However, recent experiments demonstrate that freely propagating fs laser pulses without initial focusing can form MF with very long propagation distance [18–20]. We shall call such filaments free-MF. The characteristics of such type of MF are quite different from that of the prefocused-MF. The understanding of MF is still not quite clear. In this paper, we experimentally compared the properties of the prefocused-MF and free-MF. Here, the free-MF propagation implies relatively wide beam, long-distance propagation for several hundreds of meters up to kilometers, instead of the propagation of a small-size transverse laser beam (or contracted beam) using a telescope system consisting of convex and concave lens [21]. We found that almost all the characteristics of the MF are quite different for the two cases. In particular, free-MF show unique and unexpected properties. It should be noted that we did not do all the measurements in

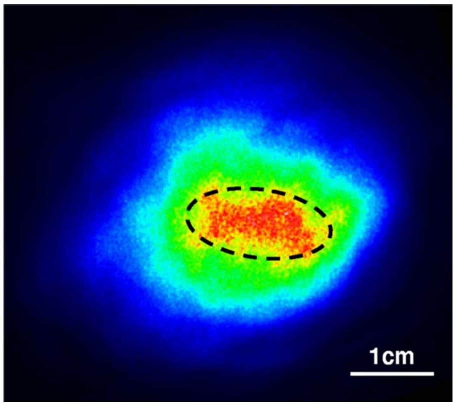

FIG. 1. (Color online) Profile of the initial laser beam recorded at the output of the compressor.

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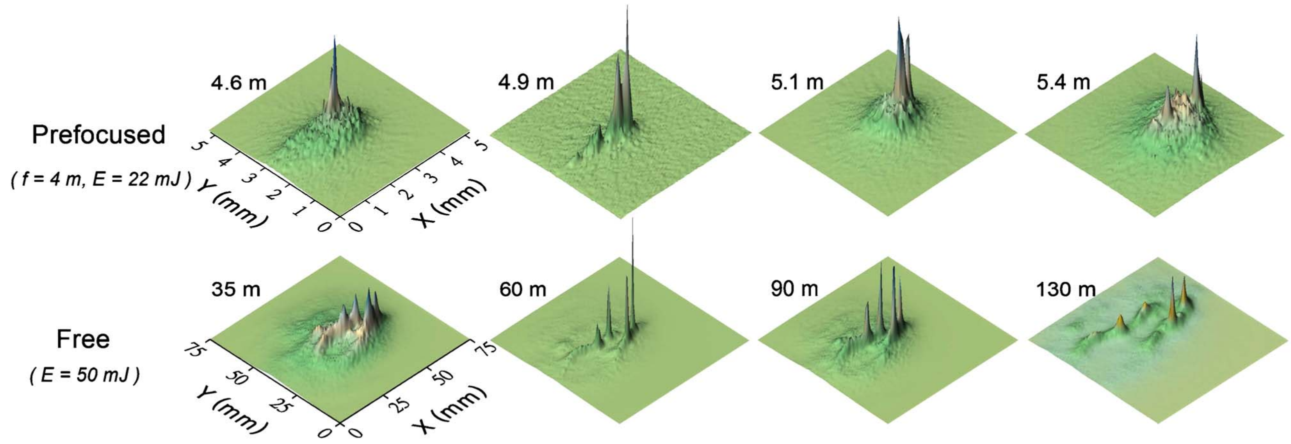

FIG. 2. (Color online) The filaments patterns as a function of propagation distance. Upper row is the case of the prefocused laser beam. Lower row is the free propagation case, and the pulse duration is 257 fs with a negative chirp. Note that they have different scales for the beam cross section.

the experiments. However, to the best of our knowledge, it is the first time to systematically explore the problem, although the value of the intensity (in the prefocused case) and the electron density were taken from existing publications.

II. EXPERIMENTAL SETUP

The laser used in our experiments is a Ti:sapphire laser system (XL-II) with an output energy up to 640 mJ in 30 fs pulse and a central wavelength of 800 nm. The repetition rate is 10 Hz. At the output of the compressor chamber, the initial laser beam diameter is about 2.5 cm (FWHM). The input beam spatial profile is almost circular, however, the center high-intensity region is elliptical with an eccentricity of $b/a=2.12$ ($a=0.82$ cm, $b=1.74$ cm; see the ellipse in Fig. 1). For investigating prefocused propagation, tens of millijoule (22 mJ in our experiments) is sufficient. Nonlinear effects such as SC generation, dynamic MF interactions, fluorescence, and acoustic radiation, are significant. The laser pulses are focused by an $f=4$ m lens with geometrical focal length about 5.05 m in air since the laser beam used has a divergence angle in our experiments. For studying free propagation, the laser system runs with less than 200 mJ of laser energy. The grating pair in the compressor chamber is adjusted so that the fs pulse has a negative chirp, favorable for long-distance propagation of the MF in air. The effect of chirp on the free-MF has been studied by our recent experiments and other studies [19,22]. The MF evolution is recorded by a charged-coupled device (CCD) camera (512×512 pixels) with a pixel size of 24 μm and from a white screen positioned in the beam path at different propagation

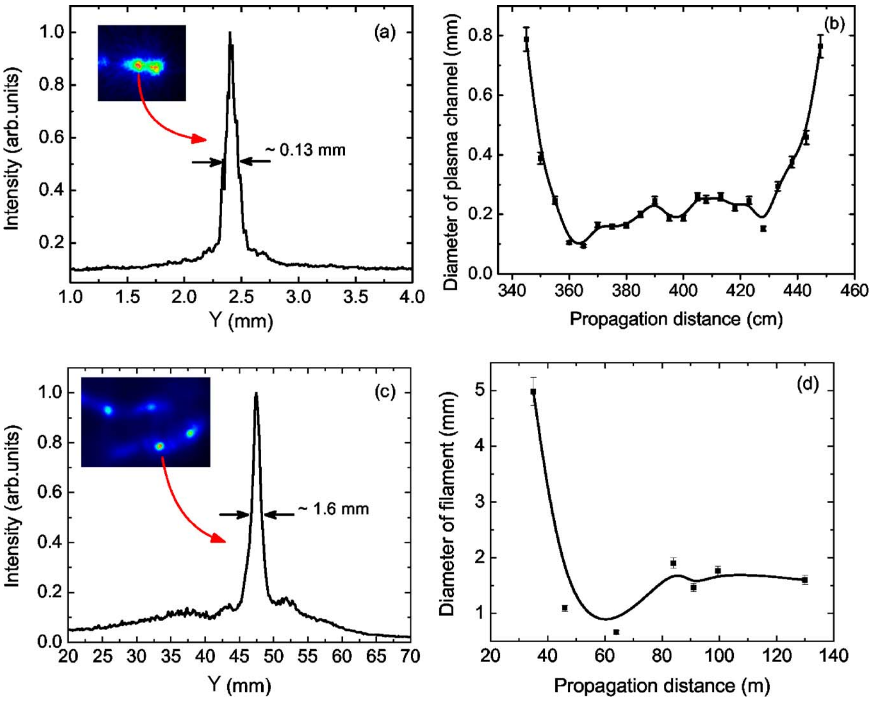

FIG. 3. (Color online) The comparison of the diameter of filaments and its evolution as a function of propagation distance. (a) and (c) The diameter of a single filament at (a) $Z=4.9$ m and (b) $Z=130$ m of propagation distance in the prefocused and free propagation case respectively (see Fig. 2). Note that (b) and (d) have different scales for the propagation distance.

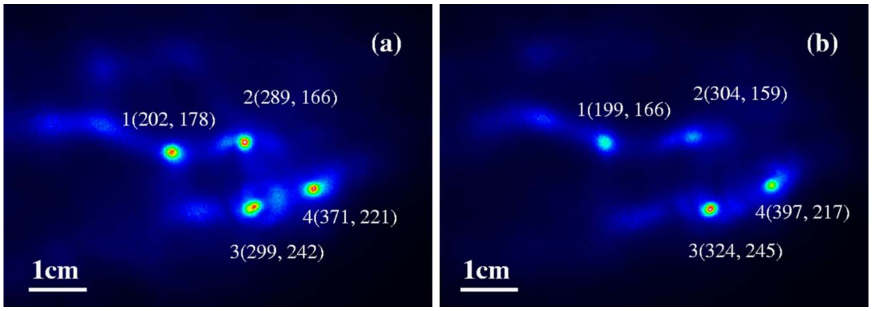

FIG. 4. (Color online) Two MF patterns formed by two laser shots. The filaments are labeled 1-4, and their positions are located with the coordinates (in units of CCD chip pixel).

distances. Acoustic and fluorescence measurements are also used in the MF diagnostics.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

Recent experimental results indicate that the free-MF have mm size diameter, and the intensity is near the ionization threshold of air, corresponding to very low density plasma generation. However, for the prefocused-MF, many experiments have shown that the typical diameter of a filament is about 100 μm and the light intensity inside is about $10^{13}-10^{14}$ W/cm^2, corresponding to an electron density of $10^{16}-10^{18}$ cm^{-3} [6,23–25]. The nonlinear effects and the interaction among the filaments are extremely strong, so that the filamentation process and its evolution are complicated. The behaviors of the prefocused-MF are thus different in many respects from that of the free-MF.

Figure 2 shows the MF patterns induced by the fs laser pulse with and without a lens, as a function of the propagation distance. The upper row shows the evolution of prefocused-MF at 22 mJ of laser energy and 30 fs of pulse duration. The focal length of the lens is 4 m. The lower row shows the evolution of the free-MF. The laser pulse duration is about 257 fs with a negative initial chirp in the free case, in order to be for the filaments long-distance propagation in air, and 50 mJ of laser energy. There are large differences in the MF and their evolution for the two cases. First, the filament diameter (FWHM) is about 0.13 mm in the prefocused case versus 1.6 mm in the free propagation case. The details are shown in the Figs. 3(a) and 3(c). Second, the separation distance of the MF is also different. In the prefocused-MF case, the filaments are close to each other. The separation is generally about 0.3 mm or double the diameter of a typical prefocused filament. However, the free filaments are distributed across the beam cross section, as shown in the lower row of Fig. 2. The separation distance of the free-MF is about 12 mm, about one order of magnitude larger than the free-filament diameter. On the other hand, in the plasma channel the beam size is only about several millimeters in the profocused-MF case, whereas it expands up to several tens of millimeters in the free propagation case. In short, the diameter of the MF, the space between them, and the corresponding energy reservoir are all different in the evolution of the two cases.

In another experiment, we studied the relationship between the filament core and the energy background and measured the laser energy in a single filament in the free case, which is about 1 mJ. (The details of these results will be reported elsewhere.) Therefore, using the measured values of the trapped energy and diameter and assuming that the pulse duration remains constant during the propagation in the channel [6], we can estimate the intensity in the filament to be about 6×10^{11} W/cm^2. Méchain *et al.* [19] have also demonstrated that the intensity of the free-MF is $10^{11}-10^{12}$ W/cm^2, which is around the ionization threshold of air. The intensity is about two orders of magnitude lower than that in the prefocused-MF condition. However, the various nonlinear effects are strongly intensity dependent. Consequently, more complicated interaction processes occur in the prefocused laser beam, including the evolution from a single filament into two or three or even more distinct filaments, and the merging of filaments [26]. On the other hand, the evolution of the free-MF does not show any obvious interaction between the MF. The number and pattern of the main MF almost do not change. The MF seems to propagate independently. However, we should note the bright "bridges" connecting the filaments and the wide low-intensity energy reservoir surrounding the MF. The filaments form and are fed by the energy reservoir. The plasma generated by the MF causes strong defocusing, such that a part of the energy of the MF is released to the energy reservoir. Self-focusing of the low-intensity energy reservoir will again return some of the energy to the MF. That is, the energy reservoir can continuously replenish the energy loss in the MF core and support the filamentation process over a very long distance. Thus, the dynamic energy interchange between the MF core and the energy reservoir results in the long-distance propagation of the free-MF in air [27,28]. Moreover, the free-MF propagation does not indicate any filament-filament interaction as in the case of the prefocused-MF. The interaction among the filaments takes place indirectly through their competing interaction with the energy reservoir. That is, some energy exchange between the filaments does occur through the bright bridges, which is the medium of nonlinear

TABLE I. The parameters of filaments formed by two laser shots (see Fig. 4).

MF No.	Intensity (arb.units) (a)	Intensity (arb.units) (b)	Excursion (mm)
1	10764	6048	1.8
2	12870	4251	2.4
3	9625	15285	3.7
4	12967	9495	3.9

TABLE II. Characteristics of multiple filaments generated by the prefocused and free propagation laser pulse. D is diameter; I is intensity; ρ is electron density; L is filament length; F-B denotes the filament-background interaction, and F-F denotes the filament-filament interaction.

	D (μm)	I (W/cm^2)	ρ (cm^{-3})	L (m)	Stability	Interactions
Prefocused-MF	10^2	10^{13-14}[a]	10^{16-18}[b]	10^{0-1}	Reproducible	F-B, F-F
Free-MF	10^3	10^{11-12}[c]	10^{11-12}[c]	10^{1-3}	(see Table I)	F-B

[a] References [6,25].

[b] References [23–25].

[c] Reference [18].

energy transformation within the laser cross section during its propagation in air [29]. As a result, the laser and the MF propagation can be hundreds of meters long.

Figures 3(b) and 3(d) show the diameter of the MF as a function of the laser propagation distance. The error bar of the diameter measured in our experiments includes both the standard deviation of measurements and the uncertainty in the reading of the filaments patterns. In the prefocused case, there are complicated interactions among filaments in our experiments as mentioned above. It is impossible to trace a single filament to study its diameter evolution. In order to reveal the evolution of the plasma channel, Fig. 3(b) shows its diameter along the channel. The diameter D is the global approximation of the main filaments

$$D = \left(\sum_{i=1}^{n} D_i^2 \right)^{1/2},$$

where D_i is the diameter of the number i filament, n means the total number of the main filaments [30]. We can conclude that the plasma channel induced by the prefocused laser beam starts at about 350 cm and terminates at about 450 cm. That is, the MF length is about 100 cm. Figure 3(d) shows the very long propagation distance of the single filament as indicated in Fig. 3(c). The free-MF start to form shortly before 40 m and propagate with mm size diameter up to 130 m. The length of the free-MF is two orders of magnitude longer than that of the prefocused-MF. Moreover, it can be much longer than 130 m which is the limit in our laboratory. The shorter length of the prefocused-MF can be attributed to the stronger interaction and larger incident angle between the filaments, as well as the laser beam dispersion caused by the lens [31,32].

The prefocused-MF are readily reproducible from shot to shot [26]. However, in the free-MF case, the MF position and their intensities, as well as the appearance of smaller filaments can vary from shot to shot, while the number of the main filaments does not change. The details are shown in Fig. 4. Figures 4(a) and 4(b) show the MF patterns formed by two laser shots at Z=130 m. The four main filaments are labeled 1–4, and their positions are located by the coordinates (in units of CCD chip pixel). A comparison is made in Table I. It is shown that the intensity and position of the MF change greatly from shot to shot. This can be attributed to the fact that each laser shot undergoes different air conditions and the laser pulse itself has some degree of variation, as have also been observed by Stelmaszczyk *et al.* [33].

Table II summarizes the characteristics of MF. The differences in the diameter, intensity, electron density, length, stability, and interaction type for the two cases are pointed out.

We have also used acoustic and fluorescence measurements to detect the MF. We can get strong sound and fluorescence signals in the prefocused-MF case [30,34–36]. However, in the free-MF case, we cannot get obvious signals from both methods. The reason could be the too low electron density inside the free-MF because of the weak ionization of the air. It seems so far there is no promising method for measuring the precise laser intensity as well as the electron density in the free-MF. Furthermore, the mechanism underlying the free-MF including their interaction and evolution also needs further studies.

IV. CONCLUSIONS

The propagation of prefocused and free fs laser pulse beams in air has been experimentally investigated. The different characteristics of the MF are studied in detail. The MF, their evolution, and the nonlinear interactions among them are quite different for the two cases. The free-MF exhibit unique characteristics including the diameter, length, and MF pattern. Furthermore, each type of MF has its own advantages. The prefocused-MF are stable from shot to shot with tiny-scaled intensity. The free-MF can deliver high energy to remote desired destinations. Thus, one can choose different laser energies, chirp conditions, and focal lengths of the lens (if any), to achieve different purposes.

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