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Properties of long light filaments in natural environment*

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The multiple filamentation of terawatt femtosecond (fs) laser pulses is experimentally studied in a natural environment. A more than 30-m long plasma filament with a millimeter diameter is formed by the collimated fs laser pulse freely propagating in an open atmosphere. This study provides the first quantitative experimental data about the electron density of a long range light filament in the atmosphere. The electron density of such a filament is quantitatively detected by using an electric method, showing that it is at the 10^{11}-cm^{-3} level.

Keywords: laser-plasma interactions, filamentation, propagation

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1. Introduction

During the propagation of intense fs laser pulse in air, the filamentation could take place when the self-focusing effect is saturated by the optical field ionization-induced plasma, diffraction, higher-order nonlinear effect, and other linear or nonlinear factors.[1–5] As a result of filamentation in air, a long conductive channel can be produced. Based on this phenomenon, many potential applications were proposed, such as guiding of lightning discharge,[6–9] transportation of electromagnetic energy,[10,11] laser assisted precipitation,[12,13] etc. The physical properties of light filaments over a long distance (hundred meters level and longer) are meaningful for applications based on the conductivity of a filament. However, most experiments studied the meter-scale filaments under laboratory conditions by using initial geometric focusing of fs laser pulse. Several research groups observed multiple filamentation of collimated intense femtosecond laser pulse in a range from tens of meters to kilometers.[14–20] The experimental observations showed that the diameter of such a long filament is at the millimeter level,[16–18] and the electron density was numerically estimated at 10^{11} cm^{-3} $\sim$ 10^{12} cm^{-3}.[16] Some researches confirmed the existence of free electrons in a filament by detecting the electromagnetic radiation from the filament.[19] However, there have been no reported quantitative experimental data about electron density of such long filaments in air to our knowledge.

In this paper, we study the long distance filamentation of a femtosecond laser pulse freely propagating in atmosphere in a natural environment. Diagnosis of the filament is performed over a 30-meter propagation distance. The electron density inside the filament, detected by an electric method is at a 10^{11}-cm^{-3} level.

2. Experimental setup

The experiment was carried out in a meteorological observatory in the Tianshan Mountains of the Xinjiang Uygur Autonomous Region, China. The local altitude is about 2000 meters. The light source was a 2-TW Ti: sapphire laser system at a 40-fs pulse duration and 10-Hz repetition rate. The initial width of the laser beam was about 10 mm, and the beam pattern was recorded by photo paper as shown in Fig. 1(a). When the collimated laser beam was launched into the sky, a bright channel was observed as shown in Fig. 1(b).

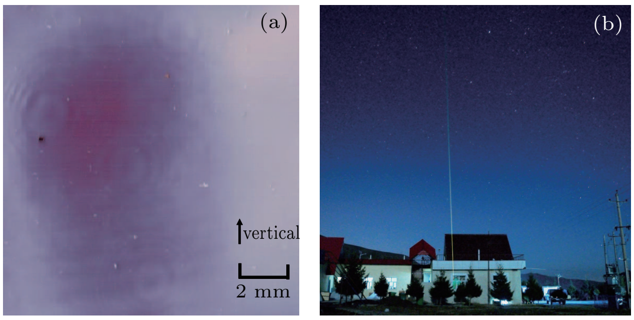

Fig. 1. (color online) (a) Initial beam pattern of the TW fs pulse, and (b) long distance filamentation of TW fs laser pulse in atmosphere.

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The pulse energy used for detecting the electron density inside filaments was 55 mJ. The laser pulse was reflected from the laser room to the courtyard wall of the observatory by several mirrors. The optical path of the laser pulse from the compressor to the last mirror was about 10 meters. The total propagation distance of the laser pulse was about 53 meters. When the laser pulse was compressed to the best condition of about 40-fs pulse duration, the strong thin multi-filaments were formed at about a 3-m propagation distance. These thin filaments could damage any optical elements. Therefore, in order to protect the mirrors, we applied some negative chirps to the laser pulse to extend the start position of filamentation to an over 20-m distance. The intensity distributions of laser beam at different propagation distances were recorded by light-sensitive photo paper and it was vertically placed along the horizontal propagate direction. The electron density of the filament was detected by an electric method,[21–28] the setup is presented in Fig. 2. A direct current voltage of 2000 V was applied to two plane copper electrodes through a 50-Ω divider resister. The distance between the two electrodes was 13 mm. There was a 2-mm diameter hole on one of the electrodes on the side of the laser pulse. When the filament passed through the hole and contacted another electrode, then the transient current should be triggered in the circuit if the ionization in the filament exists, and the electron density in the filament can be estimated from the voltage signal on the 50-Ω divider resister. It should be noted that the 2-kV applied voltage is still much lower than the breakdown voltage of the air gap, which is about 30 kV in the experiment. Therefore, the external voltage could not affect the ionization process.[24,26]

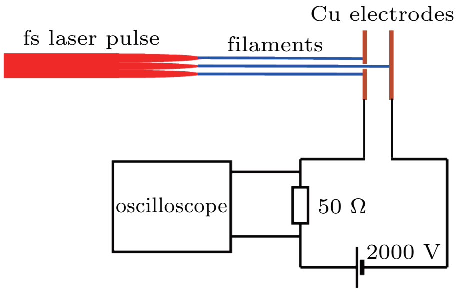

Fig. 2. (color online) Setup of electron density measurement.

3. Results and discussion

Figure 3 shows the beam patterns of laser pulse, recorded by photo paper at different propagation distances. We can clearly see that the laser pulse split into 2–3 filaments after a 23-meter propagation distance. The multi-filaments seem to appear along a line from up-left to down-right, the distribution of multi filaments is related to the asymmetry of the near field beam pattern. As the initial beam pattern is recorded by photo paper shown in Fig. 1(a), it can be seen that the multi-filament structure is basically consistent with the intensity distribution of the laser beam. From the spots in beam pattern we can estimate the diameter of filaments at about 1 mm. When the filament is formed at tens of meters away from the laser system, its diameter will be expanded to the mm level due to the air turbulence. This viewpoint has been verified by earlier experiments[16–18] and explained by simulation.[29] The farthest observation distance was only 53 meters because the space was limited; however, the beam pattern at a 53-meter distance indicates that the filaments are still robust. This indicates that the filament could extend to a further distance.

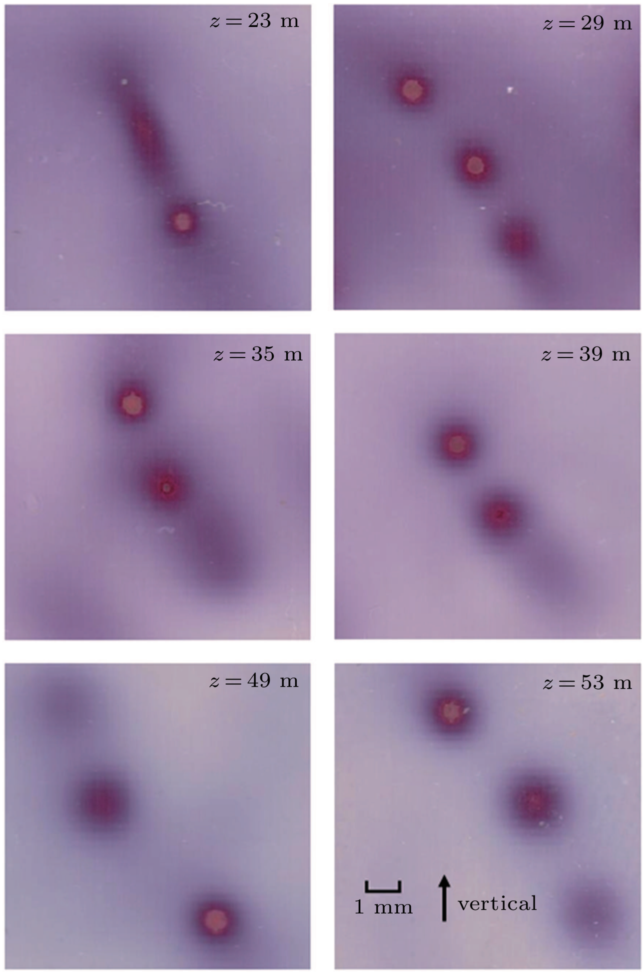

Fig. 3. (color online) Filament structure of laser beam at different propagation distances.

It should be noted that the orientations of filaments randomly drift from shot to shot due to the wind and air turbulence.[29–31] With the increase of the propagation distance, the drift area of multi-filaments becomes larger and larger. Figures 4(a) and 4(b) show the images of photo papers, obtained by continuous irradiation during 10 seconds (100 shots) at start position of filamentation (23 m) and at the farthest observation distance (53 m) respectively. At a start position of filamentation, all of the multi-filaments were distributed in an area of 6 mm in size as shown in Fig. 4(a), but at the 53-m distance, the drift area of the multi-filaments expanded to more than 10 mm in size as shown in Fig. 4(b). Due to the drift of filaments, the electric signal can be detected only when one of the multiple filaments accidentally passes through the hole at the front electrode.

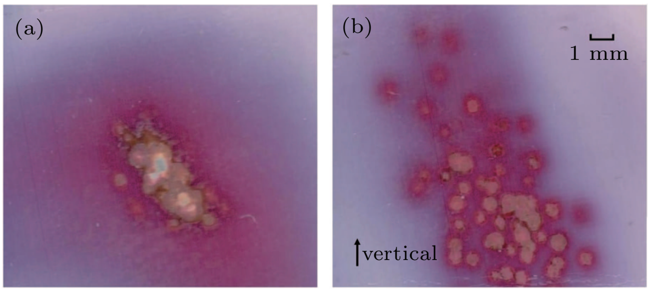

Fig. 4. (color online) Marks on photo papers burned by 10-s irradiation (100 shots) of laser pulse at (a) 23-m and (b) 53-m distances.

When the diameter of the filament is about 1 mm, it can easily pass through the 2-mm hole on the front electrode without being blocked if there is no drift of its position. The plane electrode is larger than the whole beam pattern, and the distance between filaments is always longer than 2 mm, in which condition, only one of the filaments is allowed to pass through the front electrode. The filament may be partially blocked by this hole, in this case the electric signal could be weakened, and therefore the electric signal is also changed shot by shot. Figure 5 shows the strongest electric signals at different propagation distances. The strongest signal could be obtained when most of the filament passes through the hole, and its edge contacts with the electrode. In this case the contact resistance between filament and electrode is negligibly low in comparison with that of the filament whose electric resistance value per unit length (cm) is 1 MΩ/cm. It can be observed that the peak signal intensity varies at a level of tens mV. The fluctuation of signal after the main peak is induced by the self-oscillation of the circuit.

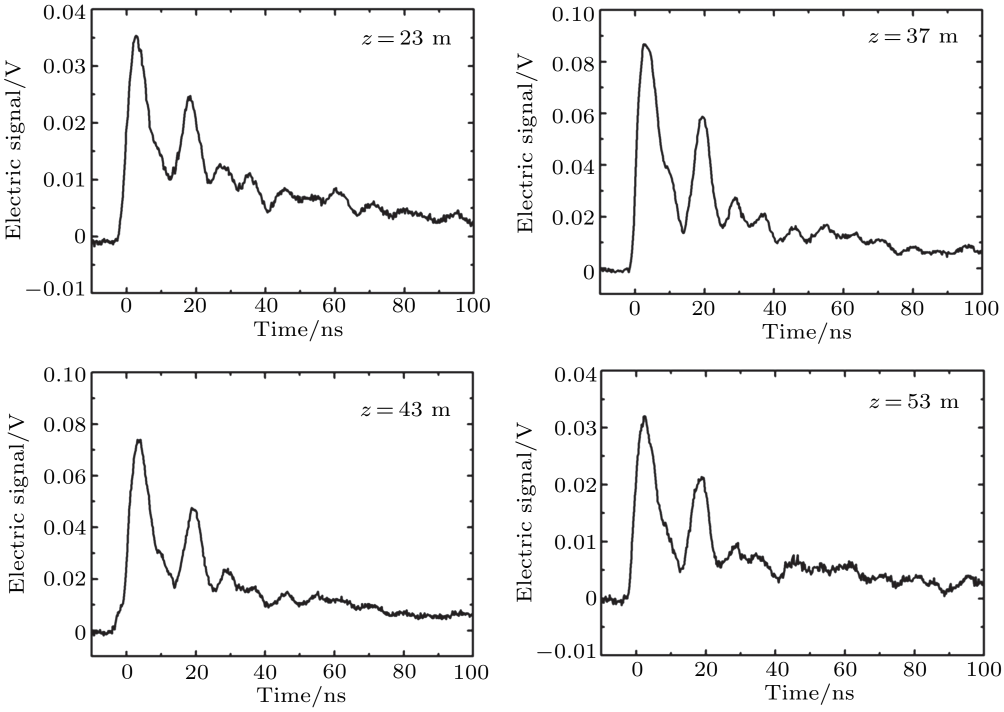

Fig. 5. The strongest electric signals of filament at different propagation distances.

The resistance of the plasma channel between the two electrodes can be calculated from the electric signal by Ohm's law. Furthermore, we can estimate the electron density of the plasma channel from the formula for electrical conductivity of plasma:[26]

$$\sigma = \frac{e^2 n_e}{m_e \nu_m} = \frac{l}{R\pi r^2}, \tag{1}$$

where e is the elementary charge, n_e is the electron density, m_e is the electron mass, $\nu_m = 1 \times 10^{12}$/s is the collisional frequency for electrons in laboratory conditions,[26] and R, l, and r are the resistance, length, and radius of the plasma column, respectively. In the short plasma column, the electron density is assumed to be uniform for simplicity. For the filament of millimeter diameter, its resistance is far greater than the divider resistance, contact resistance, and inner resistance of HV generator, so the resistance of the plasma channel is approximately equal to the total resistance of the circuit. Therefore, the electron density can be easily calculated according to formula (1). Figure 6 shows the peak electric signal intensity (left vertical axis) and electron density (right vertical axis) along the plasma channel length direction. The experimental results of electron density in the filament accord well with the theoretical estimation in the earlier work.[16] The deduced electron density inside this freely propagated filament is at a 10^{11}-cm^{-3} level, much lower than that of the filament produced by prefocused laser pulse (10^{15} cm^{-3} $\sim$ 10^{16} cm^{-3}). It is also worthwhile noting that the electron density detected by the electric method is undervalued by comparing with that by the newly proposed electromagnetic induction (EMI) method.[32]

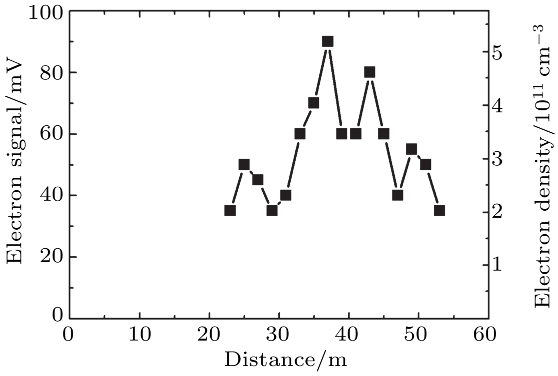

Fig. 6. Peak electric signal (left vertical axis) and electron density (right vertical axis) of filament versus propagation distance.

4. Conclusions

In this work, the light filament with more than 30 m in length has been produced by freely propagating femtosecond laser pulses. The multi-filament structure and the drift of filament are recorded by photo paper. The electron density of such a long filament has been quantitatively measured by using the electric method, showing that it is at a 10^{11}-cm^{-3} level. This electron density of freely propagating filament is much lower than that of the filament produced by pre-focused laser pulse (10^{15} cm^{-3} $\sim$ 10^{16} cm^{-3}), but the advantage of freely propagating filaments is that their length can be extended to the kilometer level,[15,17,19] which is necessary for massive applications such as lighting control[6] and remote transport of electromagnetic energy.[10] The electron density and lifetime of a long range filament can be increased by a fs laser pulse sequence.[28] However, a lot of research work still needs to be performed to make the long-range filament applicable.

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References

[1] Braun A, Korn G, Liu X, Du D, Squier J and Mourou G 1995 *Opt. Lett.* **20** 73
[2] Chin S L, Hosseini S A, Liu W, Luo Q, Théberge F, Aközbek N, Becker A, Kandidov V P, Kosareva O G and Schroeder H 2005 *Can. J. Phys.* **83** 863
[3] Berge L, Skupin S, Nuter R, Kasparian J and Wolf J P 2007 *Rep. Prog. Phys.* **70** 1633
[4] Béjot P, Kasparian J, Henin S, Loriot V, Vieillard T, Hertz E, Faucher O, Lavorel B and Wolf J P 2010 *Phys. Rev. Lett.* **104** 103903
[5] Li S Y, Guo F M, Yang Y J and Jin M X 2015 *Chin. Phys. B* **24** 104205
[6] Ball L M 1974 *Appl. Opt.* **13** 2292
[7] Rodriguez M, Sauerbrey R, Wille H, Wöste L, Fujii T, André Y B, Mysyrowicz A, Klingbeil L, Rethmeier K, Kalkner W, Kasparian J, Salmon E, Yu J and Wolf J P 2002 *Opt. Lett.* **27** 772
[8] Kasparian J, Ackermann R, André Y B, Méchain G, Méjean G, Prade B, Rohwetter P, Salmon E, Stelmaszczyk K, Yu J, Mysyrowicz A, Sauerbrey R, Wöste L and Wolf J P 2008 *Opt. Express* **16** 5757
[9] Zhang Z, Lu X, Liang W X, Hao Z Q, Zhou M L, Wang Z H and Zhang J 2009 *Chin. Phys. B* **18** 1136
[10] Châteauneuf M, Payeur S, Dubois J and Kieffer J C 2008 *Appl. Phys. Lett.* **92** 091104
[11] Bogatov N A, Kuznetsov A I, Smirnov A I and Stepanov A N 2009 *Quantum Electron.* **39** 985
[12] Rohwetter P, Kasparian J, Stelmaszczyk K, Hao Z, Henin S, Lascoux N, Nakaema W M, Petit Y, Queisser M, Salamé R, Salmon E, Wöste L and Wolf J P 2010 *Nat. Photon.* **4** 451
[13] Ju J J, Liu J S, Wang C, Sun H Y, Wang W T, Ge X C, Li C, Chin S L, Li R X and Xu Z Z 2012 *Opt. Lett.* **37** 1214
[14] Bergé L, Skupin S, Lederer F, Méjean G, Yu J, Kasparian J, Salmon E, Wolf J P, Rodriguez M, Wöste L, Bourayou R and Sauerbrey R 2004 *Phys. Rev. Lett.* **92** 225002
[15] Rodriguez M, Bourayou R, Mejean G, Kasparian J, Yu J, Salmon E, Scholz A, Stecklum B, Eisloffel J, Laux U, Hatzes A P, Sauerbrey R, Woste L and Wolf J P 2004 *Phys. Rev. E* **69** 036607
[16] Mechain G, Couairon A, Andre Y B, D'Amico C, Franco M, Prade B, Tzortzakis S, Mysyrowicz A and Sauerbrey R 2004 *Appl. Phys. B* **79** 379
[17] Mechain G, D'Amico C, Andre Y B, Tzortzakis S, Franco M, Prade B, Mysyrowicz A, Couairon A, Salmon E and Sauerbrey R 2005 *Opt. Commun.* **247** 171
[18] Hao Z Q, Zhang J, Zhang Z, Yuan X H, Zheng Z Y, Lu X, Jin Z, Wang Z H, Zhong J Y and Liu Y Q 2006 *Phys. Rev. E* **74** 066402
[19] Dur, M, Houard A, Prade B, Mysyrowicz A, Durécu A, Moreau, Fleury D, Vasseur O, Borchert H, Diener K, Schmitt R, Théberge F, Chateauneuf M, Daigle J F and Dubois J 2013 *Opt. Express* **21** 26836
[20] Apeksimov D V, Geints Y E, Zemlyanov A A, Kabanov A M, Matvienko G G, Oshlakov V K 2015 *Quantum Electron.* **45** 408
[21] Tzortzakis S, Prade B, Franco M and Mysyrowicz A 2000 *Opt. Commun.* **181** 123
[22] Hao Z Q, Zhang J, Li Y T, Lu X, Yuan X H, Zheng Z Y, Wang Z H, Ling W J and Wei Z Y 2005 *Appl. Phys. B* **80** 627
[23] Liu X L, Lu X, Ma J L, Feng L B, Ge X L, Zheng Y, Li Y T, Chen L M, Dong Q L, Wang W M, Wang Z H, Teng H, Wei Z Y and Zhang J 2012 *Opt. Express* **20** 5968
[24] Tzortzakis S, Franco M A, Andre Y B, Chiron A, Lamouroux B, Prade B S and Mysyrowicz A 1999 *Phys. Rev. E* **60** R3505
[25] Schillinger H and Sauerbrey R 1999 *Appl. Phys. B* **68** 753
[26] Ladouceur H D, Baronavski A P, Lohrmann D, Grounds P W and Girardi P G 2001 *Opt. Commun.* **189** 107
[27] Abdollahpour D, Suntsov S, Papazoglou D G and Tzortzakis S 2011 *Opt. Express* **19** 16866
[28] Lu X, Chen S Y, Ma J L, Hou L, Liao G Q, Wang J G, Han Y J, Liu X L, Teng H, Han H N, Li Y T, Chen L M, Wei Z Y and Zhang J 2015 *Sci. Rep.* **5** 15515
[29] Kandidov V P, Kosareva O G, Tamarov M P, Brodeur A and Chin S L 1999 *Quantum Electron.* **29** 911
[30] Chin S L, Talebpour A, Yang J, Petit S, Kandidov V P, Kosareva O G and Tamarov M P 2002 *Appl. Phys. B* **74** 67
[31] Ma Y Y, Lu X, Xi T T, Gong Q H and Zhang J 2008 *Opt. Express* **16** 8332
[32] Chen S Y, Liu X L, Lu X, Ma J L, Wang J G, Zhu B J, Chen L M and Li Y T 2017 *Opt. Express* **25** 32514