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The comparison study of diagnostics of light filaments in air

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Abstract Long plasma channels in air induced by femtosecond laser pulses are investigated using three different methods, including the cross-section imaging, resistivity measuring and acoustic diagnostics. These methods are based on different properties of the light filaments. A comparison of the three diagnostics shows that the imaging method is the most precise one in studying the filaments distribution and evolution, that the sonographic method is the most convenient approach to detecting long plasma channels by detecting the acoustic wave generation, and that the resistivity measurement can only be applied for giving a rough estimate. The diagnostics of filaments allow us to choose appropriate detecting methods and provide further insight into the dynamic evolution of the light filaments in air.

Keywords: plasma channels, filaments, cross-section imaging, resistivity measurement, acoustic diagnostics.

Multiple filaments generated by intense femtosecond (fs) laser pulse in air have been investigated widely since the first experimental observations by Braun *et al*.[1]. The filaments can maintain many Rayleigh distances of the laser beam about hundreds of meters[2], even several kilometers in air[3]. Many interesting phenomena have been observed during the long distance propagation of filaments, such as supercontinuum radiation[4,5], third-harmonic generation[6,7], conical emission[8−11] and other plasma-related phenomena. The filamentation is accompanied by very large spectral broadening from the UV to the mid-IR, which is used as a white-light source in the sky for atmospheric trace-gas remote sensing[12]. Furthermore, the long-range conductive plasma channels can be used to control lightning[13]. The harmonic generation can help us to develop the coherent light source with short wavelength into the ultraviolet or X-rays scope[14−16].

Up to date, the mechanism underlying the propagation of laser pulse has been well studied. The fundamental mechanism of the long-distance filaments formation is as follows. When intense fs laser pulse propagates in air, it is focused by the nonlinear Kerr self-focusing effect. When the laser intensity exceeds the ionization threshold of air, the ionization of air occurs, leading to the generation of low-density plasma which defocuses the laser. The self-focusing and defocusing processes repeat again and guide laser pulse to propagate over long-distance.

Multiple filaments form during the laser propagation in air. A single filament has a diameter of about 100 μm, and the intensity in the filament is about $6\times10^{13}-1\times10^{14}$ W/cm^2[17], corresponding electron density of $10^{16}-10^{18}$ cm^{-3}[18]. It is difficult to directly measure the intensity distribution in the channels. Some methods have been used to diagnose the plasma channels, such as shadowgraphy[19], interferometry[18], fluorescence detection[2,20], THz detection[21] and electromagnetic pulse measurement[22]. These methods have their own advantages and drawbacks. In this paper, we use three techniques to diagnose the filaments formed by intense fs laser pulse in air. They all reveal the evolution of filaments in detail. The three methods are based on the different properties of filaments. Because of the high intensity of filaments, we can image the cross-section of the laser beam using a simple experimental setup. Using the conductivity of the filaments, the resistivity measurement is used to detect the filaments. By detecting the acoustic wave radiation, the length and the gross intensity distribution in the channels as well as the electron density can be obtained. A further comparison of the three diagnostics indicates their respective advantages and drawbacks.

1 Experimental setup and results

Our laser system used is a Ti:sapphire laser system (XL-II) with an output energy up to 640 mJ in 30 fs pulses. The central wavelength is 800 nm and the repetition rate is 10 Hz. In our experiments, laser pulses are focused by an $f = 4$ m lens in air and form long plasma channels containing several filaments that can be observed directly by naked eyes. Three diagnostic techniques are used to measure the plasma channels: imaging of beam cross-section using a glass plate, resistivity measurement and acoustic detection. The experimental setup is shown in Fig. 1.

1.1 Imaging of beam cross-section

A glass plate is inserted at a 33° angle with the aim of sampling the cross section of the channels. A lens images the channels onto a charged-coupled device (CCD) camera (512×512 pixels) with a pixel size of 24 μm. The wavelength response of the CCD used in our experiments is about 200—1100 nm. A high-speed shutter is used to take single shot image of the filaments on the plate. The glass plate is placed on a translation stage, which can move in parallel with the CCD. This ensures that each laser pulse shoots a new place of the plate. The imaging system is set up on a small stage that is moved along the laser propagation axis to obtain the images at different positions. The setup is shown in Fig. 1(a). Because of the high intensity in filaments, white light emits from the glass plate when the filaments shoot the plate. By measuring the light radiation, the filaments patterns are obtained.

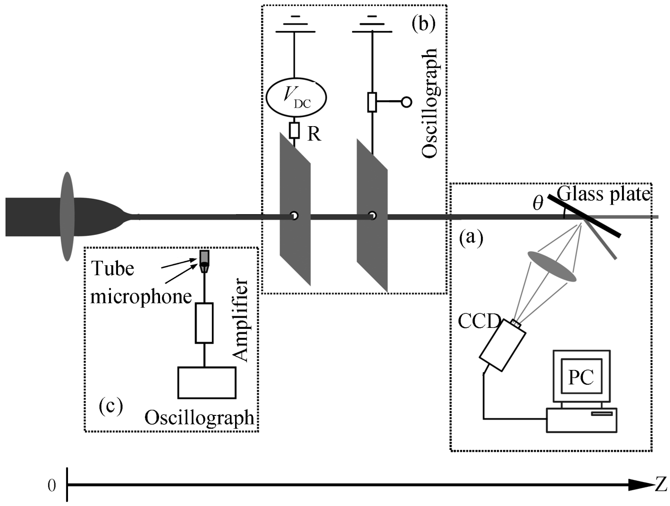

Fig. 1. The experimental setup. (a) The imaging setup; (b) resistivity measurement; (c) acoustic detection setup.

Fig. 2 shows a representative profile of filaments. We can not only study the evolution of filaments, but also get some information about filaments, such as the diameter and length of filaments. The mean diameter D of the plasma channels is the global approximation of multiple filaments

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

where D_i is the diameter of the ith filament, and n means the total number of filaments. Fig. 3 shows the mean diameter of the plasma channels for both 50 mJ and 22 mJ laser energy. The error bar of the diameter measured in our experiments includes both the standard deviation of measurements and the uncertainty in reading the filaments patterns. We can see that it is easier to form multiple filaments at a higher energy (50 mJ). The length of the plasma channels induced by 50 mJ laser pulses is about 30 cm longer than that by 22 mJ in the experiments. From the tendency of the channels diameter, we can conclude that the laser pulse undergoes filamentation, focusing-defocusing cycle and spreading out. The difference of diameter between the two cases is caused by different degrees of modulation at different laser energy. Using the imaging measurements, the spatial evolution of the filaments can be studied. The processes of filamentation, splitting and fusion of plasma filaments are observed. Therefore, the imaging technique is suitable to study the filaments evolution in detail.

1.2 Resistivity measurement

The electron density in the plasma channels is about 10^{16}—10^{18} cm^{-3}. It is conductive, just like a wire. Based on the property, the lightning control using plasma channels in air has been studied at different laboratories. On the other hand, the conductivity can be used to diagnose plasma channels. Through measuring the resistivity of the channels, the length, electron density and the evolution of the channels can be retrieved. We can optimize the condition of filamentation and its resistivity for application analysis, such as guiding a very long electrical discharge.

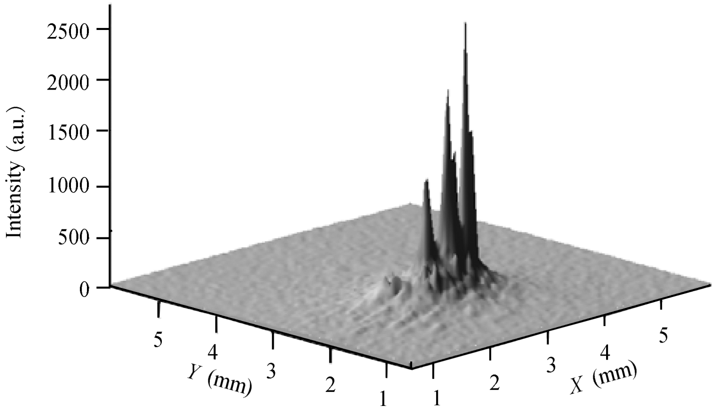

Fig. 2. A representative profile of filaments measured in experiments.

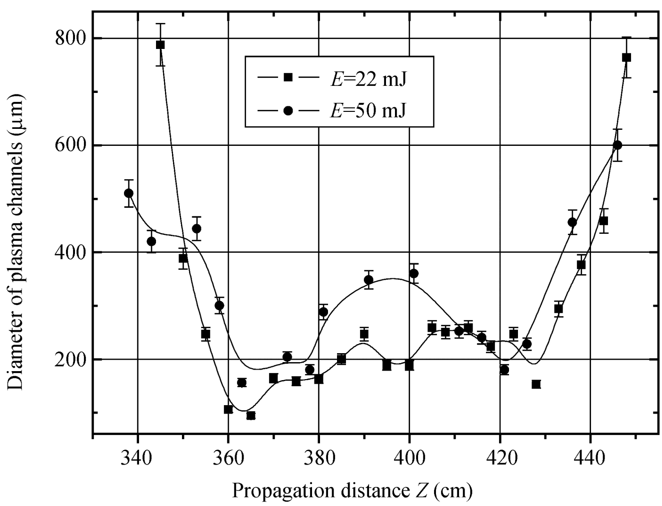

Fig. 3. The mean diameter of the plasma channels versus laser propagation distance.

Two parallel copper plates are placed on the beam axis. The plasma channels traverse through the two plates. A DC voltage of V_{DC} = 880 V is applied between both electrodes. The electrical signals are recorded by a digital oscilloscope. An R = 10 kΩ resistance is used to limit the current and the signal voltage is obtained from a 200 Ω resistance by an oscilloscope. The experimental setup is shown in Fig. 1(b). The diameter of the pinhole drilled at the plate center is 0.5 mm, and the laser energy is 50 mJ.

The resistivity evolution along the laser propagation distance is shown in Fig. 4. We can see from the Fig. 4 that the filaments form at about 350 cm, and spread beyond 440 cm, forming 90 cm length plasma channels. At Z = 403 cm, the minimal resistivity of 0.3339 Ω·cm is obtained. The error bar of the signals measured in our experiments includes both the standard deviation of measurements and the high resistivity between the ionized core of the filament and the edge of the electrodes. The detail analysis about the contact resistivity can be found in ref. [23]. The experiments show that the resistivity of the channels has relationship with the focal length of the lens. Under the condition of fixed laser energy, the longer the focus is, the lower the electron density is, and the bigger the resistivity is[23]. Furthermore, we need to choose the suitable pinhole diameter to decrease the contact resistivity. The method of the resistivity measurement is simple in principle, which can be used to estimate the plasma channels quickly. However, the error is introduced through the contact resistivity between the filaments and the copper electrodes.

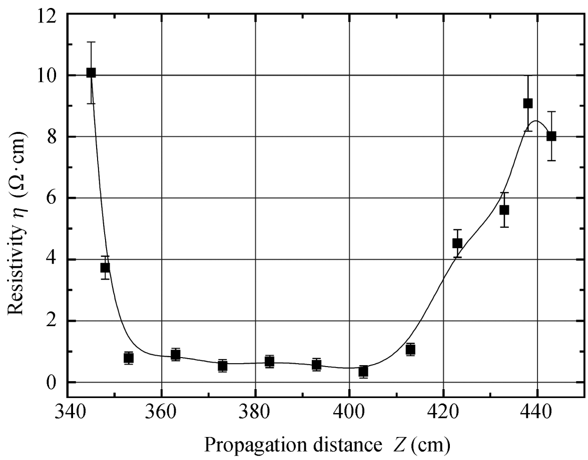

Fig. 4. The resistivity of plasma channels versus laser propagation distance.

1.3 Acoustic diagnostics

In the plasma channels, air molecules are partially ionized through the multiphoton ionization instantly by intense laser pulse. Plasma shock waves are formed and then decay to plasma sound wave subsequently, which are the sound signals we detect in the experiments. The intensity of the acoustic wave is directly proportional to the amount of laser energy absorbed in the filaments, and thus proportional to the initial free electron density. It is demonstrated that by detecting the sound signals along the channels, the length and the electron density of the channels can be obtained[24,25]. Therefore, the acoustic diagnostics method is based on the laser intensity and electron density in the filaments.

In our experiments, a microphone (bandwidth, 16—20 kHz together with its amplifier) is installed inside a shielding tube oriented perpendicularly toward the filament at a distance of 7 cm from it. The tube has a length of 3 cm and an inner diameter of 4 mm, restricting the directly measured filament to a length of 1.5 cm. A pulsed acoustic signal is detected by the microphone and recorded by a digital oscilloscope synchronized to a laser pulse using a photodiode that detects scattered light from the lens. The experimental setup is shown in Fig. 1(c). The laser energies used in our experiments are 29 mJ and 53 mJ.

The microphone output voltage as a function of the propagation distance is shown in Fig. 5. We can see changes in the sound signals by changing the distance of the microphone along the plasma channels. Higher amplitude signals represent higher free-electron density inside the plasma channels. In order to reduce the background noise, the laser pulse fluctuations and air turbulence, the signals average 100—200 laser pulses. The error bar of the signals in Fig. 5 is the standard deviation of the measurements. The rapid increase of the signal around 320 cm for 39 mJ and 280 cm for 53 mJ indicates the starting of the plasma channels, and the rapid decrease around 430 cm for 39 mJ and 436 cm for 53 mJ indicates the ending of the filaments. This indicates that the length of the channels is at least 110 cm for laser pulse energy of 39 mJ and 156 cm for the energy of 53 mJ respectively. By measuring the sound signals along the channels, the channels length and distribution of electron density along the channels can be obtained conveniently[25]. Only moving the microphone along the channels, we can measure many parameters of the plasma channels. And thus, the acoustic diagnostics method is a simple and convenient approach to detecting the plasma channels nondestructively.

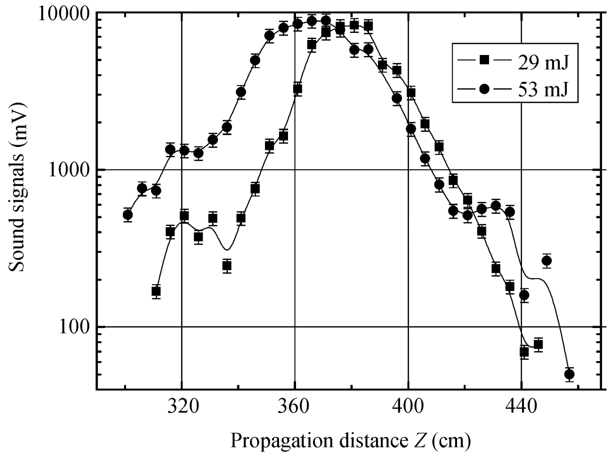

Fig. 5. The sound signals as a function of laser propagation distance.

2 Discussions and conclusions

The diagnostics of the plasma channels in air induced by intense fs laser pulses are investigated. Three techniques are used based on the different properties of the filaments. The imaging of the beam cross-section, resistivity measurement and acoustic diagnostics all reveal the detailed evolution of the filamentation, the laser intensity and the electron density along the plasma channels. However, the three diagnostic methods have their own advantages and drawbacks.

As for the method of beam cross-section imaging, it can study the filaments distribution and evolution in detail. It supplies much information such as the formation, interaction and the spreading of filaments. However, the experimental setup needs much time to adjust, to replace the glass plate, to shoot the imaging place of the glass, etc. It is not suitable to quickly diagnose laser beam.

The resistivity measurement has much larger errors due to the contact resistivity between the filaments and the electrodes. At the onset and end of the filaments, the electrode separation (about 5—10 cm) will also introduce errors. However, it can be an alternative method to diagnose the plasma channels quickly.

The acoustic diagnostics is the most simple and convenient one among the three methods. It can detect the channels quickly, and has no more instruments to adjust. It is suitable for the quick diagnosis of long distance plasma channels. However, we can see from Fig. 5 that the onset of filamentation is closer to the lens than that measured by the other two methods. The main reason is that the laser intensity before filamentation is strong enough to excite sound emission when the laser pulse encounters dust in air, which introduces some errors to microphone signal. And thus, the acoustic method need quiet and clean environment.

In conclusion, the imaging method is the most precise one to diagnose the plasma channels, and the resistivity measurement can be regarded as a method to rough estimate the plasma channels due to its contact resistivity and some other errors. The acoustic diagnostics is the most simple and convenient one due to its real time, nondestructivity and quick detecting. Although the acoustic measuring has some errors before the onset of filaments, it has great advantages over the other two methods. The study of diagnostics of light filaments in air enables us to choose appropriate method to detect the evolution of fs laser pulses. These methods can support each other and can be used to diagnose different properties of light filaments in air.

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