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Influence of cutting off position of plasma filament formed by two-color femtosecond laser on terahertz generation*

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Femtosecond laser filamentation is a method of generating terahertz, which has wide application in terahertz sub-wavelength resolution imaging. In this paper, the plasma filament formed by femtosecond laser focusing was terminated with an alumina ceramics at different positions and the influence of the cutting off position of the plasma filament on the terahertz wave was studied. The results showed that the terahertz amplitude increases as the position approaches the end of the filament gradually. The stability of amplitude and peak frequency of the terahertz generated by the filament formed by two-color femtosecond laser via a lens with a longer focal length is lower than that through a lens with a shorter focal length, especially the terahertz amplitude at the end of the filament. The study will be helpful for future researchers in the field of THz sub-wavelength imaging utilizing femtosecond laser filament.

Keywords: terahertz, laser filament

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1. Introduction

Femtosecond laser filamentation could produce some nonlinear phenomena such as supercontinuum spectra,[1,2] conical radiation,[3,4] high order harmonic emissions,[5,6] and terahertz (THz) emissions.[7,8] Cook and Hochstrasser first introduced the THz radiation generated by femtosecond laser plasma filament in the air.[9] With application of this plasma-based THz generation technique, the THz radiations with super-broadband spectrum up to 75 THz[10] and electric field as high as 400 kV/cm[11] have been obtained. The aforesaid technique has interested many researchers in the past decade.[12–15] It has been studied in terms of the length of the plasma filament[16] formed by two-color laser, the divergence angle,[17,18] the beam diameter[19] of THz produced by femtosecond laser filament, and the relationship between the divergence angle of the terahertz radiation and the convergence conditions of the optical beam.[20]

Two-color femtosecond laser could form plasma via a focal lens, which can be used as transmission of waveguide.[21] THz wave is limited in the waveguide, thus one THz spot with sub-wavelength diameter is obtained, with which the THz sub-wavelength imaging[22] becomes possible. But the intensity of the plasma light field is up to 10^{14}–10^{16} W/cm^2, which could destroy many imaging objects. Thus an attenuation chip, e.g., alumina ceramics, one non-polar electrolyte material and high transmissivity in THz frequency band, is needed to be set in front of the object to protect it, yet the effect of cutting off plasma filament in different positions on producing THz remains unclear.

In this paper, the plasma filament formed by two-color femtosecond laser was cut off by alumina ceramics in different positions where the amplitude of every THz time-domain waveform was measured. Combining fast fourier transformation (FFT), the THz frequency-domain spectrum of each time-domain waveform was calculated and then the peak frequency in the spectrum was extracted. Furthermore, we calculated and compared the coefficient of variance (CV) of THz amplitude and peak frequency in different positions of plasma filament focused by two lenses with different focal lengths, 400 mm and 1000 mm respectively. The results showed that the stability of THz amplitude and peak frequency change clearly as selecting different focal lenses and cutting off plasma filament in various locations. Hence, the experiment will be useful for the study in THz sub-wavelength resolution imaging and the measuring method will probably be a new way to measure the length of the plasma filament.

2. Experimental system

2.1. System structure

The systematic diagram in Fig. 1 covers the whole process of the research. One laser beam with pulse width 35 fs, repetition frequency 1 kHz, energy 4 mJ/pulse, and central

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wavelength 800 nm from Ti: sapphire, was split into pump pulse and probe pulse by a half wave plate and a cubic beam splitter. The pump pulse passed through a delay stage and was focused by a L1 lens in the air. Then, the focused pump pulse passed through a 100 μm-thick BBO crystal and produced the two-color laser, THz emission was generated simultaneously. The alumina ceramics was applied to terminate the plasma filament. The ceramics was fixed on an electric stage to move step by step along the laser direction. THz wave travelled through lenses L2 and L3 collection-collimation-focusing via the ceramics and finally focused on a ⟨110⟩ oriented ZnTe crystal (1 mm) together with the probe beam reflected by a Si plate. The THz was detected by the typical electric-optic sampling method.

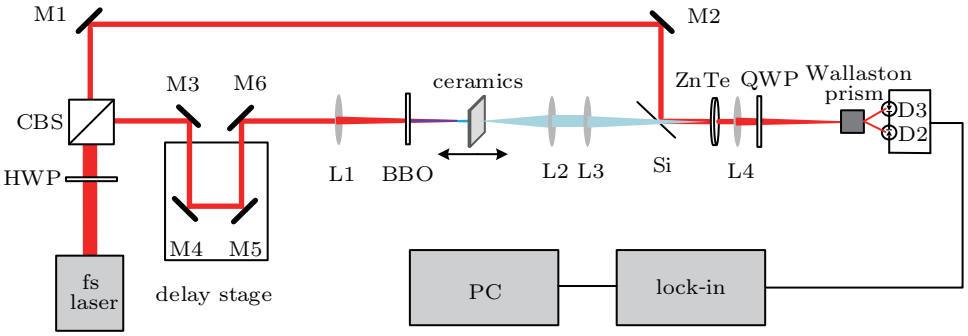


Fig. 1. (color online) Measurement systematic diagram. M1–M6 are reflector lenses, L1 is a common focusing lens, and L2 and L3 are THz focusing lenses, which have a high transmissivity around the THz wavelength.

2.2. System stability

The THz waveforms are measured repeatedly in the same experimental state to test the system stability. Figure 2(a) shows the THz time-domain waveforms measured 30 times. Because of the slight fluctuations of the femtosecond laser power, there are some tiny differences among these waveforms. The peak-to-peak values for the 30 repetitions are shown in Fig. 2(b). By calculating the CV, the system stability is 1.35%.

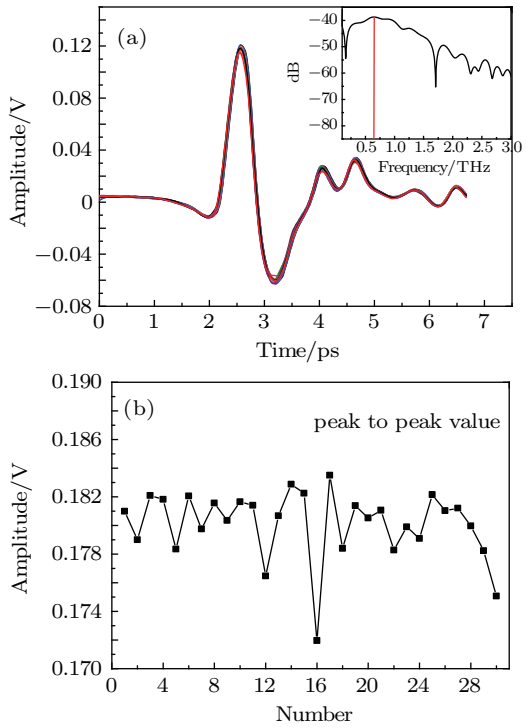


Fig. 2. (color online) System stability. (a) The THz time-domain waveforms of 30 repetitions, the inset is the THz frequency-domain spectrum, peak frequency 0.64 THz. (b) The peak to peak value of each THz time-domain waveform in (a).

3. Results

3.1. THz amplitude and peak frequency at each cutting off position

The white line in Fig. 3(a) formed by femtosecond laser via BBO crystal is the plasma filament image taken by a CCD camera. Figure 3(b) is the diagram of moving alumina ceramics (the white plate) to cut off the plasma filament (the violet line) at varying positions. The alumina ceramics fixed on the electric stage moves by steps of 0.5 mm from i, one end of the filament, to ii until iii, the other end of the filament.

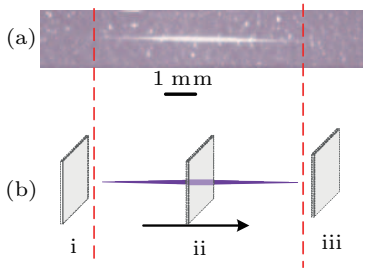


Fig. 3. (color online) (a) Plasma filament image, (b) experimental diagram of cutting off plasma filament with alumina ceramics.

The amplitude and peak frequency of the THz waveform obtained at every position are shown in Fig. 4. The inset in Fig. 4(a) is the plasma filament formed by the two-color femtosecond laser through a focusing lens ($f = 400$ mm). The plasma could not be generated as the alumina ceramics blocks the two-color laser, thus THz wave is hardly detected at the position of i. However, the THz amplitude and the length of plasma increase slowly when the alumina ceramics gradually moves to ii. It should be mentioned that a surge in peak frequency appears at $z = 66$ mm (the absolute position of the

electric stage), afterwards, the peak frequency tends to a constant value (0.64 THz). And it can be followed that the THz radiation starts at this filament position. When the alumina ceramics moves to $z = 75$ mm, the THz amplitude begin to stabilize as the plasma disappears at iii. Therefore, this position could be identified as the termination of the plasma filament. The plasma filament via another lens ($f = 1000$ mm) is shown in Fig. 4(b), the changing trends of THz amplitude and peak frequency in every truncation position are similar to those in Fig. 4(a). The peak frequency rises sharply at $z = 72.5$ mm and the THz amplitude stops increasing at $z = 93.5$ mm.

The reason for an obvious variation of the peak frequency at $z = 78$ mm in Fig. 4(b) is that the filament plasma focused by the 1000 mm focusing lens is finer, which causes the higher energy density. As a result, the bombardment of the alumina ceramics by the plasma filament is severe, the thickness of the ceramics at the cutting off position changes a lot, which delays the time of THz wave passing through the ceramics. Because the frequency-domain spectrum is obtained from FFT and the frequency is related to time in the frequency-domain spectrum, thus the differences of time THz wave passing through ceramics cause the obvious changes of frequency.

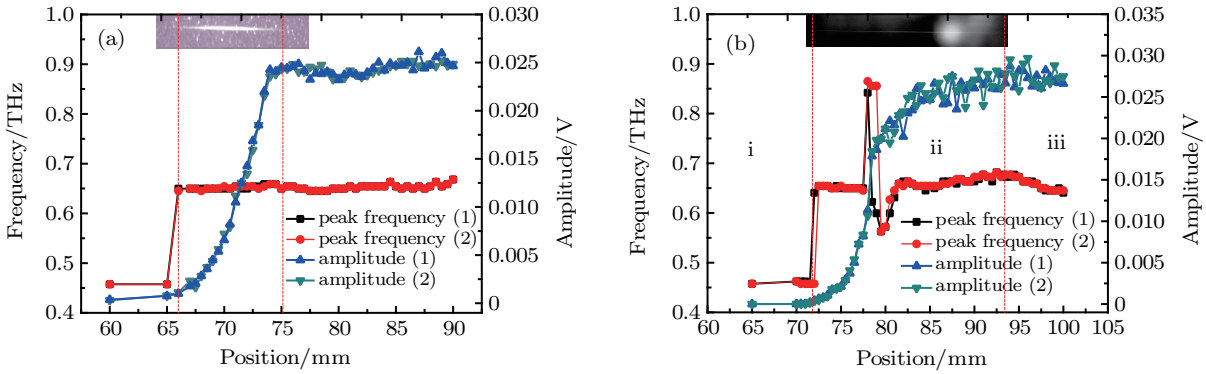


Fig. 4. (color online) THz wave amplitude and peak frequency for two repetitions at different terminated positions. (a) The THz amplitude and peak frequency are measured from the filament plasma formed by a lens with focal length 400 mm, (b) the lens focal length 1000 mm.

3.2. The stability of THz amplitude and peak frequency

Figure 5 illustrates the stability of THz amplitude and peak frequency. It is obvious that the amplitude stability of THz wave at the end of plasma filament (position iii) focused by the lens of $f = 400$ mm is better than that of the lens of $f = 1000$ mm. The THz peak frequencies (positions ii and iii) obtained from the lenses of $f = 400$ mm and $f = 1000$ mm are illustrated in Figs. 5(c) and 5(d), respectively.

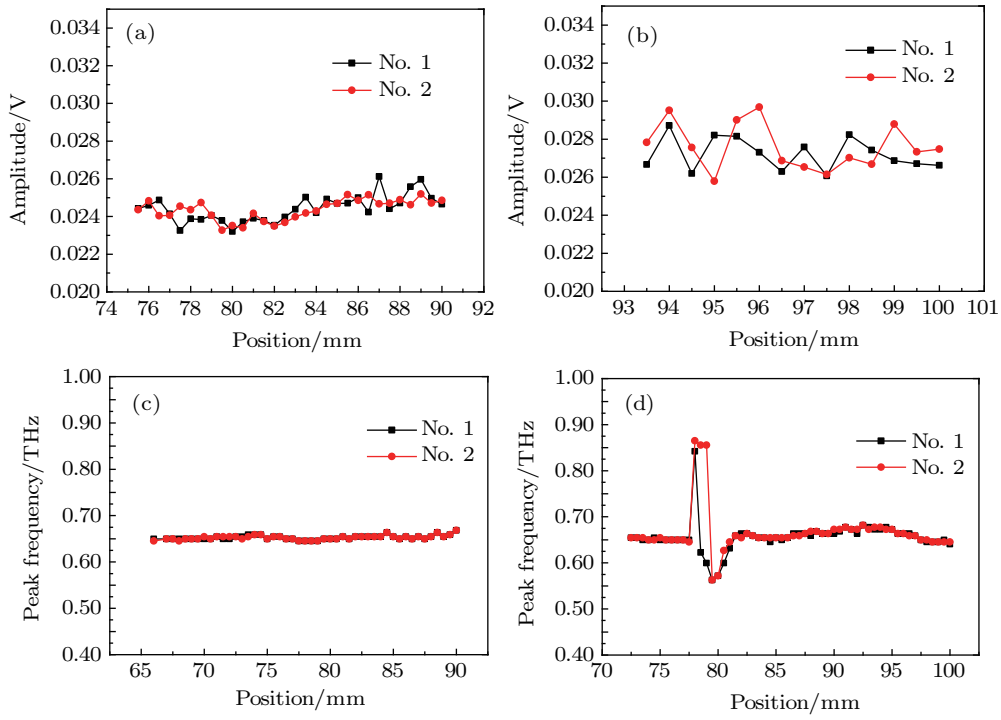


Fig. 5. (color online) Two repetitions of THz amplitude and peak frequency at each cutting off position: (a) and (c) experimental results with the lens of $f = 400$ mm, (b) and (d) experiment results with the lens of $f = 1000$ mm.

Table 1. The CV of amplitude and peak frequency.

	Lens focal length/mm	Sample standard deviation	Average	Coefficient of variation
Amplitude	400	0.00055	0.02437	0.02261
	1000	0.00114	0.02670	0.04264
Peak frequency	400	0.00475	0.65252	0.00728
	1000	0.03933	0.66294	0.05933

The CV shown in Table 1 further demonstrates the stability in terms of amplitude and peak frequency of the THz wave generated by plasma filament focused by 400 mm lens and 1000 mm lens respectively. The THz amplitude is measured at the end of the plasma filament (position iii in Fig. 5) and the peak frequency is obtained at positions ii and iii. The stability of amplitude and peak frequency of the terahertz generated by filament via 400 mm lens is higher than that of through 1000 mm lens.

The results show that the shorter focal lens is more suitable to apply in THz sub-wavelength imaging based on femtosecond laser filament because of its higher filament stability. On the other hand, the cutting off position should be situated at the end of the filament, like position ii in Fig. 4(a).

4. Conclusion

The alumina ceramics is moved along the laser direction to cut off the plasma filament produced by two-color femtosecond laser and the THz wave amplitude and peak frequency at each truncating position are obtained. The higher THz amplitude can be obtained when the plasma filament is terminated at the end due to the sufficient four-wave mixing rectification. And the THz amplitude tends to become saturated at the end of the filament. The stability of THz amplitude at the end of the plasma filament focused by a lens with shorter focal length is higher than that of a longer focal length lens. The experimental findings will have a wide range of applications in plasma filament formed by femtosecond laser especially in THz sub-wavelength resolution imaging.

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