THz Radiation from Air Plasma Produced with Aperture-limited Two-color Lasers

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Abstract: Terahertz (THz) radiation from air-plasma produced with two-color femtosecond laser pulses has been measured with controlled pump laser energy by an aperture before the laser focusing lens. It is found that the THz amplitude first increases with the laser energy. With the further increase of the laser energy over 320 μJ, the THz amplitude begins to decrease. This is attributed to the phase-shift between the fundamental pump pulse and its second harmonic along the laser filament, which depends upon the air-plasma length and the corresponding plasma density.

Keywords: Terahertz radiation, Air-plasma, Aperture, Two-color lasers

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1. Introduction

The interaction of two-color femtosecond laser pulses with air-plasma has been used to generate strong terahertz (THz) radiation[1-3]. Several theoretical models such as four-wave mixing[1,3-4], optical ionization current[5-6] and transition-Cherenkov radiation[7], were proposed to explain the generation of THz radiation. Among these models, the plasma parameters especially plasma density, are supposed to have important effects on the THz radiation. For example, Chen et al. have simulated the THz radiation based on the particle-in-cell (PIC) approach with field ionization included in the code[6], which indicates that the plasma density has affected the THz radiation both in the spectrum and intensity. Peng et al. observed that the THz radiation could be optimized by introducing an optical aperture [8]. The change of the aperture diameter brought both changes of the laser power and the size of focus spot, subsequently the plasma density accordingly. In this letter, we report experimental observation of the dependence of THz emission on the incident laser energy by introducing an aperture far before the focus lens. Compare with previous experiments[8,9], a relatively long pulse duration around 140fs was used in our experiment.

2. Experimental Results and Analysis

The experiment scheme for THz wave generation and detection is shown in Fig. 1. A non-collinear typical electric-optical sampling method was used to detect the THz wave in our experiment. A convex lens focused the fundamental laser pulse and its second harmonic from a type-I BBO crystal with a thickness of 100 *μm* into ambient air and formed a laser air plasma filament. A couple of off-axis parabolic mirrors were used to collimate and focus the produced THz wave. The focal lengthen of both OAP mirrors was 100 *mm*. A 1mm-thick silicon wafer was inserted between two OAP mirrors to block the residual light while the THz wave could pass through it with a little attenuation. The probe laser beam and the THz wave overlapped in the 1mm-thick zinc telluride crystal simultaneously. The time delay between them was controlled by a stage. Our Ti:sapphire laser system is able to provide 140 *fs* laser pulses at the central wavelength 800 *nm* and a repetition rate of 1 *kHz*, with the maximum pulse energy of 600 *μJ* in the experiment. Fig. 2 is a typical THz waveform in time and its corresponding frequency spectrum obtained with pump energy 540 *μJ*.

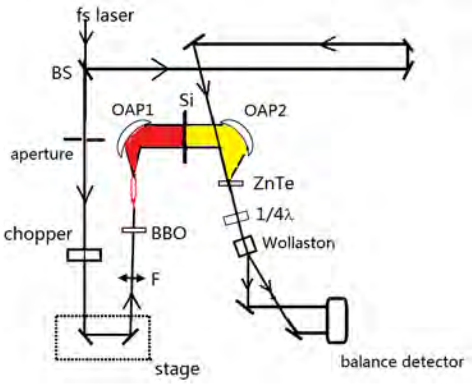

Fig. 1 Experimental setup for THz wave generation and detection.

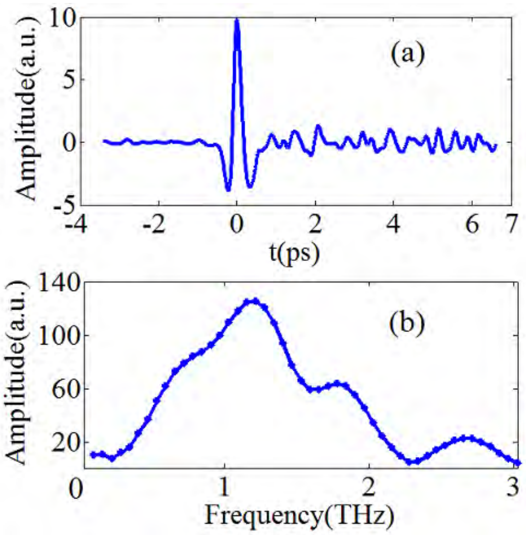

Fig. 2 THz radiation from air-plasma produced by two-color laser pulses. (a) Time waveform; (b) Frequency spectrum.

An aperture was used to change the pump laser energy. It was found that the THz wave amplitude first increases with the pump energy until around 320 *μJ*. With the further increase of the pump energy by increasing the aperture diameter, the THz wave amplitude appears to decrease, as shown in Fig. 3. Around the pump energy of 320 *μJ*, the corresponding THz amplitude is about 1.5 times as that without an aperture (with pump energy around 540 μJ). Note that this is quite similar to that observed with laser pulses at a shorter duration and higher energy [8]. Because the focused laser spots have the similar diameter size for different pump energy, the focused laser intensity should be proportional to the laser energy. Therefore different pump energy corresponds to different plasma densities and plasma length since the ionization rate is related with laser intensity. This suggests that there may be an optimized plasma density and length to radiate THz waves.

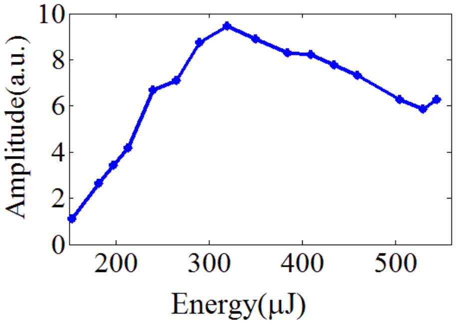

Fig. 3 The THz field amplitude as a function of pump pulse energy, which is controlled by changing the aperture diameter.

On the other hand, even though at different pump laser energy the strength of THz emission is different, their frequency spectra appear quite similar. Figure 4 shows the spectra of the THz waves at the incident laser energy 350 μJ and 540 μJ, respectively, controlled with different aperture diameters. Since it is usually believed that the THz frequency is proportional to plasma density, this result suggests that the average plasma densities in the filaments may be similar in the two cases, though their distributions are different. The theory model proposed by Liu et al.[9] helps to explain our observation shown in Figs. 3 and 4. It has been suggested that due to the different dispersion inside the filaments and the Gouy phase shift, the phase difference $\Delta\phi$ between the fundamental and its second harmonic of the incident laser pulse changes along the filaments. The local THz amplitude is proportional to $a_{\omega}a_{2\omega}f(\Delta\phi)$, where a_{ω} and $a_{2\omega}$ are the amplitudes of the fundamental laser pulse and its second harmonic, respectively, $f(\Delta\phi)$ represents a function depending upon the phase difference. Thus the local THz emission, which co-moves with the laser pulse, also changes both in phase and amplitude along the laser filaments. As a result, the accumulated THz amplitude does not show to scale with the laser energy monotonically, even though the air plasma is longer with higher laser power. Simple one-dimensional model has shown that when the phase difference between the incident fundamental and second harmonic pulses change, the resulting THz amplitude also changes [10].

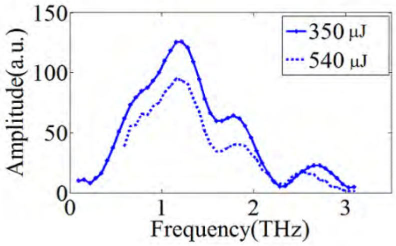

Fig. 4 Frequency spectra of THz waves produced with pump laser energy 350μJ and 540μJ, respectively.

3. Conclusion

In conclusion, THz pulses radiated from two-color laser interaction with air plasma have been measured with the pump laser energy controlled by an aperture, adding before the focusing lens. With proper energy or a proper diameter of the aperture added before the focusing lens, the THz radiation amplitude as high as nearly 1.5 times stronger than that without the aperture has been detected in our experiment. We attribute this due to the energy-dependent phase shift between the fundamental pump laser and its second harmonic, which is dependent upon the laser filament length and plasma density.

Acknowledgements

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