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We report on a longitudinally resolved measurement of plasma density along femtosecond laser filament in air via terahertz (THz) spectroscopy. By applying a needlelike high-voltage direct current (DC) electric field on the laser filament and scanning it along filament, the longitudinal evolution of amplified THz emission has been demonstrated. The peak frequency of the DC electric field biased THz emission is proportional to the plasma density inside the laser filament. This latter phenomenon was used to characterize the plasma density. Longitudinal distribution of plasma density of \( \sim 10^{15} \text{ cm}^{-3} \) along laser filament has been experimentally recorded. The technique demonstrated is very simple and helpful for understanding the THz generation process through laser filamentation. © 2014 AIP Publishing LLC.

When an intense femtosecond laser pulse propagates in an optically transparent medium, for example, in air, a phenomenon called “filamentation” happens. Femtosecond laser filamentation begins with self-focusing, which is dominated by optical Kerr response of the medium. The laser intensity keeps increasing because of self-focusing through laser propagation. Once the pulse peak power is higher than a critical value, namely, critical power for self-focusing, the self-focusing will overcome natural linear diffraction and collapse resulting in tunnel/multiphoton ionization of air molecules. The self-generated plasma is the dominant contribution responsible for pulse de-focusing. As a consequence, a plasma channel, referred to as a laser filament, is formed. Femtosecond laser filamentation has initiated many prospective applications in different fields such as remote sensing, triggering and guiding high voltage discharge with potential application on lighting control, few-cycle pulse compression, rain and snow precipitation, long range electromagnetic pulse generations from radio frequency, THz to third harmonic including higher order harmonic generation.

THz generation in an air filament recently attracts much attention. The most important reason is that THz emission can be generated close to a remote target by controlling the remote onset of the filament via controlling the initial laser parameters. THz radiation up to \( \mu \)J per pulse level has been demonstrated locally and even at a distance of few tens meters away. Remote THz generation minimizes the importance of propagation issues of linear diffraction and the strong attenuation due to water vapor absorption. It also has been reported that the terahertz energy radiated from a Ti:sapphire laser-induced filament can be enhanced by several orders of magnitude by applying a metal plate based transverse external direct current (DC) electric field to a filament in air. The polarization of this enhanced terahertz signal was found to be relatively collinear with the external DC field. This newly generated linearly polarized THz source originating from the DC-biased filament has been well interpreted by Houard et al. in Ref. 18 and Chen et al. in Ref. 19. The external electric field separates the electrons and atoms in the plasma filament, which results in a transverse current responsible for THz emission with polarization parallel to the direction of the applied external electric field. This peak frequency of THz emission corresponds to the plasma frequency which reads as

\[
\omega_{pe} = \sqrt{\varepsilon_0 e^2 n_e / m_e}\]

where \( n_e \) is the number density of electrons, \( e \) is the electric charge, \( m_e \) is the effective mass of the electron, and \( \varepsilon_0 \) is the permittivity of free space. This peak frequency is independent of the applied external electric field strength. Even more recently, by applying a helical electrical field along a plasma region, Lu and Zhang could generate an elliptically polarized THz wave. As it is well known, THz emission from a laser filament can be viewed as a coherent superposition of many plasma dot sources. The plasma density along the laser filament is not uniform and very sensitive to laser parameters although the laser intensity is clamped inside it. Understanding the behavior of THz emission and measuring the plasma density along a laser filament are still challenging issues.

In this work, a DC electric field from the tip of a needle was designed and applied on the laser filament in air. By scanning the sharp needle head along the laser filament, longitudinal evolution of THz emission has been recorded. The THz emission was enhanced. The peak frequency of the THz emission was used to characterize the plasma density. A longitudinally resolved measurement of plasma density along the femtosecond laser filament in air has been experimentally demonstrated.

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The experimental setup is illustrated in Fig. 1(a). A Ti:sapphire laser beam with a diameter of ~10 mm (intensity, 1/e2) was focused by a 50 cm focal length plano-convex lens. A laser filament with a length of around 5 cm was created in air. The fluorescence image of laser filament was taken by a charge-coupled device (CCD) camera from the side as shown in Fig. 1(b). A pair of needlelike electrodes was made of copper wire with a diameter of 2.2 mm. Then the head was cut by a cutter and polished with a sand paper. The diameter of the head was 0.8 mm. The pair of electrodes was perpendicularly applied across the laser filament (Fig. 1(a)). They could be moved along the laser filament. In the experiment, the voltage applied to the needlelike electrodes could be varied from 0 kV to 5 kV. The distance between the two tips of the electrodes was set as ~5 mm with laser filament in the middle. There was no discharge with/without laser filament when 5 kV was applying across the electrodes. The polarity of the external DC field could be reversed by switching the two electrodes. The terahertz pulse generated from the laser filament was collected in the forward direction through a 0.5-mm-thick Si filter and focused by a pair of 2-in. off-axis parabolic mirrors and measured coherently in the time domain through electro-optic (EO) sampling in a 0.5 mm ZnTe crystal.

The position of the geometrical focus was defined as “0” in Fig. 1(b). The position before the geometrical focus towards the lens is defined positive. Femtosecond laser pulses propagated from the left to the right. The THz waveform from the 800 nm laser filament without DC field was recorded as the black solid line shown in Fig. 2(a). This THz radiation was rather weak. When a 5 kV needlelike DC field was applied on the filament, for instance, at a position of 14.5 mm before the geometrical focus, a much stronger (around 5 times) THz radiation was generated as compared to the radiation from the 800 nm laser filament only. The measured waveform is shown in Fig. 2(a) as the red dashed line. Fig. 2(b) depicts the Fourier transformed THz spectra from Fig. 2(a). The peak frequency of THz radiation with DC field is 0.27 THz in Fig. 2(b).

The needlelike electrodes allow us to investigate the longitudinal behavior of amplified THz emission along laser filament because only those electrons at where the tip electrodes are will see the DC field effect. By scanning the needlelike DC field along the laser filament, the waveforms of the emitted THz pulses were recorded at each position. Fig. 3(a) depicts the THz waveform as a function of DC field position along the laser filament. Note that the waveforms in Fig. 3(a) have been automatically shifted in the Y-axis for clarity. The peak to peak (pk-pk) amplitude of the THz waveform as a function of the longitudinal position of the laser filament is plotted in Fig. 3(b). THz radiation becomes stronger as the needlelike electrodes move along laser propagation direction and reaches a maximum value before reaching geometrical focus and then decreases. Note that in the EO sampling detection system, the THz radiation is collimated with an off axis parabola and focused on a ZnTe crystal with a second parabola. Such imaging system works well for a point source, but in the case of the filament, the THz source is elongated and probably larger than the focal zone of the parabola. For this reason, the response of the EO sampling detector may not be constant along the filament position and should be lower on the leading and trailing edges of the filament. As a consequence, the measured THz peak-to-peak amplitude on the edges of the filament in Fig. 3(b) should be slightly smaller than the absolute values. It does not influence the plasma frequency for the plasma density calibration if the THz waveform keeps constant except for the change of the amplitude. Similar behavior of the fluorescence along laser filament is also shown in Fig. 3(b) for comparison. It is retrieved from the CCD image of the filament induced fluorescence. The discrepancy between THz signal and fluorescence signal on the edges of the filament may be due to the different generation mechanism and the different response of the detection systems.

Houard et al. in Ref. 18 and Chen et al. in Ref. 19 have reported that the averaged peak frequency of THz spectrum in the DC bias corresponds to the plasma frequency when the plate electrodes were applied. This peak frequency is

![FIG. 1. (a) Schematic setup for needlelike DC biased THz generation. The DC field was perpendicularly applied along the laser filament. (b) The image of laser filament in air taken by a CCD camera from the side. The red dashed line indicates the position of the geometrical focus of the lens, which is defined as ”0.” The position before the geometrical focus is positive. The laser propagates from left to right.](image1)

![FIG. 2. (a) The waveforms of THz electric field without DC field (black solid line) and when needlelike DC field was applied at 14.5 mm before geometrical focus (red dashed line). (b) The Fourier transformed THz spectra from (a).](image2)
independent of the intensity of the applied external electric field. Thus, by using the DC biased THz spectroscopy, the averaged plasma frequency over the whole filament could be measured. This allows us to achieve the measurement of the longitudinal distribution of the plasma density along laser filament. For example, the peak frequency of THz radiation is 0.27 THz in Fig. 2(b). The plasma density at the position was deduced to be around $8.7 \times 10^{15}$ cm$^{-3}$ according to Eq. (1). The longitudinally resolved plasma density along the laser filament is shown in Fig. 4(a). The measured plasma density is around $10^{15}$ cm$^{-3}$ under our experimental condition. The plasma density is lower at the leading and tailing parts of the laser filament and reaches a maximum before the geometrical focus, as in reasonable agreement with Refs. 23–25. The sharp increase of laser intensity at the tailing edge of laser filament has been predicted in Argon$^{23}$ and has been observed in air.$^{24,25}$ These could be due to the generation of short pulse at the position of 14.5 mm.

We could deduce from the above results that the sharper the electrodes are, the higher the longitudinal resolution would be. Since the amplitude of the THz radiation is proportional to the external DC field strength as shown in Fig. 4(b), a stronger DC field from a sharper point before a natural discharge occurs can improve the signal-to-noise ratio of the THz radiation. As a consequence, a better measurement precision could be achieved.

In summary, a pair of needlelike electrodes were designed and used to enhance the THz radiation from femtosecond laser filament in air. The longitudinal evolution of strong THz radiation along the laser filament has been investigated. Longitudinally resolved measurement of plasma density at around $10^{15}$ cm$^{-3}$ along a laser filament has been experimentally demonstrated using the enhanced THz spectroscopy.

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