Characterization of terahertz emission from a dc-biased filament in air

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We demonstrate that the terahertz emission from a dc-biased filament can be regarded as a sum of an elliptically polarized terahertz source (generated by a filament without external electric field) and a linearly polarized terahertz source induced by the external electric field applied to the filament. The peak frequency and linewidth of the linearly polarized terahertz source are related to the average plasma density of the filament. © *2009 American Institute of Physics*. [doi:10.1063/1.3224944]

Long-distance propagation of terahertz wave in air is highly limited by the strong absorption of terahertz by water vapor in air. Terahertz radiation from a filament seems to be one solution to this propagation problem since the onset of the filament can be manipulated by controlling the initial beam diameter and pulse duration.[1,2] Therefore, the terahertz pulses can be generated close to the remote target by the filament. It was reported by D'Amico *et al.*[3] that the terahertz emission from a filament was radially polarized. Their conclusion was based on the measurement obtained with a heterodyne detector (sensitive to 0.1 THz). Later, by using electro-optic sampling (EOS) technique (sensitive to frequency below 4 THz), it was demonstrated that the terahertz pulses in the forward direction of a filament are elliptically polarized.[4,5] The discrepancy might be explained by the fact that the EOS technique cannot detect the radially polarized terahertz because the amplitude of the electric field on the top of the terahertz conical emission is in opposite phase with the bottom of the terahertz conical emission, resulting in a zero signal at the focus inside a ZnTe crystal. The drawback of terahertz emission from a filament is that the conversion efficiency is relatively low (about 10^{-9}).[6,7] It has been proven that the terahertz energy radiated from a filament can be enhanced by several orders of magnitude by applying a transverse external electric field to the filament in air.[8–10] The polarization of this enhanced terahertz signal was found to be collinear relatively to the external electric field.[9]

In this work, by analyzing the polarization of terahertz emission from a dc-biased filament with EOS method, we found that the original elliptically polarized terahertz source from a single filament is not affected by applying an external electric field to the filament. Therefore, the terahertz radiation from a dc-biased filament can be regarded as a sum of elliptically polarized terahertz emission (from a single filament) and linearly polarized terahertz emission (induced by applying an external electric field to the filament). Only the second one can be amplified by the increase in the external electric field.

In our experiment, a 1 kHz, 800 nm, 50 fs (slightly negatively chirped) Ti-sapphire laser beam was focused by a convex lens with 50 cm focal length, creating a 4-cm-length filament in air. The terahertz radiation from the filament was collected by a parabolic mirror in the forward direction of the filament and measured by the EOS method, which was detailed in previous literature.[5] The thickness of the ZnTe crystal is 0.5 mm. The filament was sandwiched by two parallel copper plates separated by a 1 cm gap. The size of each copper plate was 8×8 cm^2 and the filament direction was along the central part parallel to one side of the plates. The voltage applied to the plates could be varied from 0 to 5 kV. The external electric field was vertically oriented, defined as Y axis in the laboratory coordinate.

Figure 1 shows the polarizations of terahertz emission from a filament with an external electric field varying from 0 to 5 kV/cm. The pump energy was 1.6 mJ, vertically polarized. The terahertz polarizations were obtained by composing the terahertz electric fields measured in two orthogonal directions by EOS.[5] Without external electric field, an elliptical terahertz polarization trajectory was observed in Fig. 1(a). It could originate from the nonlinear birefringence of neutral molecules induced in the filament.[4,5] In the presence of the external electric field, the terahertz emission changed its polarization trajectory with the increase in the applied electric field, Figs. 1(b)–1(d). When the terahertz electric fields obtained with external electric field were subtracted by the corresponding ones obtained without external electric field [Fig. 1(a)], the recomposed terahertz polarization trajectories were surprisingly uniform: linearly polarized along the orientation of the external electric field, as shown in Figs. 1(e)–1(g). Note that the ratio of the intensity corresponding to the width and length of the terahertz ellipses $|E^{\mathrm{THz}}_{\min}/E^{\mathrm{THz}}_{\max}|^2$ is around 1:400 for all voltages. The imperfect dc field distribution and the fringe effect at the periphery of the copper plates could have contributed to the residual ellipticity. We could thus claim that in the ideal case, the dc field would generate a linearly polarized terahertz field parallel to the external field. The difference of 2° between the linear polarization trajectory and the Y axis is due to imperfect alignment between the external electric field and the Y axis of the terahertz component defined by the orientation of the wire

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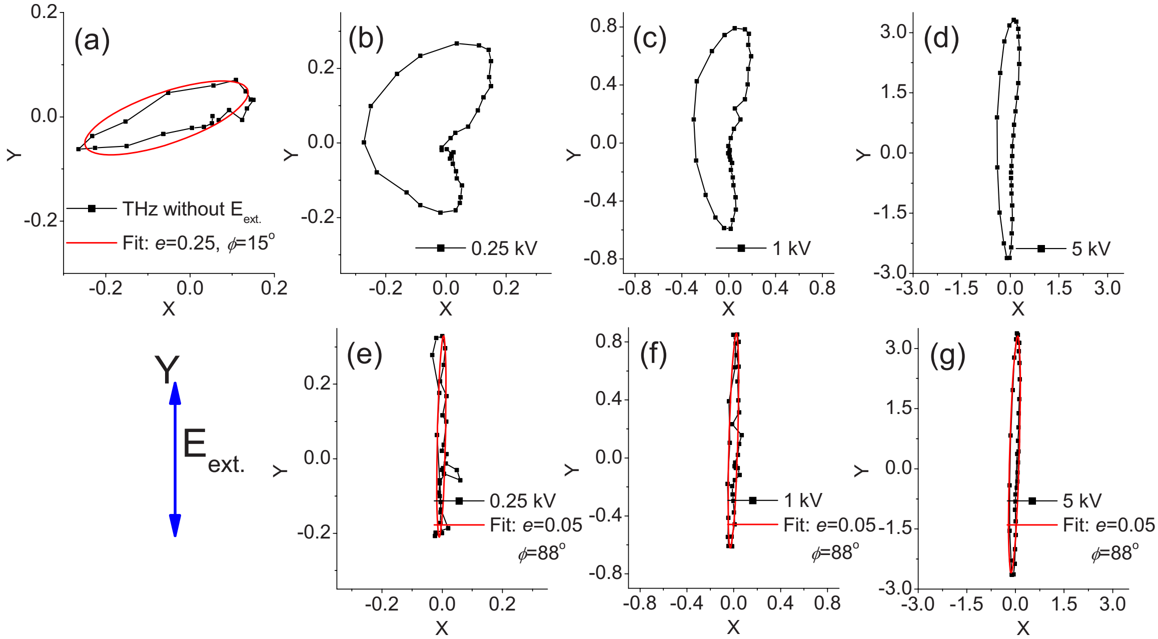

FIG. 1. (Color online) Polarization of terahertz emission from a filament with a dc field of (a) 0, (b) 0.25, (c) 1, and (d) 5 kV/cm. Terahertz polarizations in [(e)–(g)] were obtained at 0.25, 1, and 5 kV/cm by subtracting the waveforms without dc field, respectively.

grid. When the pump polarization was rotated by 90°, the terahertz polarization ellipse from the filament without external electric field rotated accordingly.[5] However, the orientation and the profile of the linear terahertz polarization trajectory stayed parallel to the orientation of the external electric field (Y axis). This linearly polarized terahertz source originating from the dc-biased filament has been well interpreted by Houard *et al.* in Ref. 9. The external electric field separates the electrons and atoms in the plasma filament, which results in a transverse current responsible for terahertz emission with polarization parallel to the direction of the applied external electric field.

Figure 2(a) shows a linear dependence of the terahertz amplitude along the Y axis as a function of the external electric field. This relation obeys the prediction of the model in Ref. 9: the total emitted terahertz energy $W \propto E_s^2$, where E_s is the external electric field. Thus the amplitude of the terahertz signal is proportional to the external electric field. An offset at zero bias corresponds to the terahertz signal obtained without dc bias. We observed that the terahertz signal along the Y axis increased by 50 times with an external electric field of 5 kV/cm. Figure 2(b) presents the Fourier spectra of the terahertz emission from the filament with external electric field varying from 0 to 5 kV/cm. The corresponding terahertz waveforms are shown in Figs. 2(c)–2(f). The spectrum shifts to low frequencies in the presence of the external electric field, i.e., the temporal shape of an optical cycle is getting longer [Figs. 2(c)–2(e)] than that without external electric field [Fig. 2(f)]. This corroborates that the elliptically polarized terahertz (from filament only) and the linearly polarized terahertz (induced by external electric field) are generated independently. Consequently, one can obtain the electric field of the linear source by subtracting that of the elliptical one from the total electric field. The peak frequencies of the Fourier spectra stay at 0.39 THz with the increase in the dc bias, as shown in Fig. 2(b). This maximum corresponds to the plasma frequency ($\omega_{pe}=\sqrt{e^2 n_e / m_e \varepsilon_0}$), which is independent of the intensity of the applied external electric field.[9] The estimated averaged plasma density is around 1.9×10^{15} cm^{-3}.

Figure 3 shows the variation of the peak-to-peak ampli-

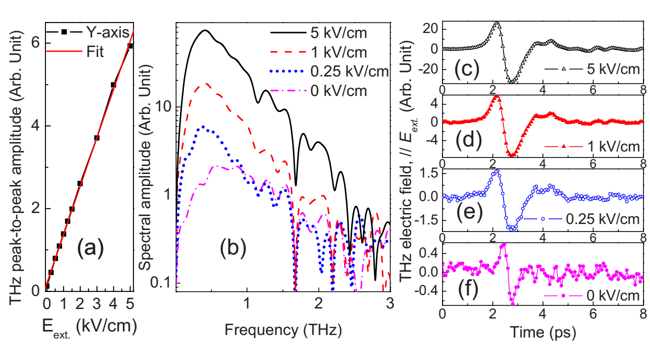

FIG. 2. (Color online) (a) Peak-to-peak amplitude of terahertz Y component as a function of external electric field. (b) Terahertz spectral amplitudes obtained by Fourier transforms with E_{ext} of 0 kV/cm (dashed-dot line), 0.25 kV/cm (dot line), 1 kV/cm (dashed line), and 5 kV/cm (solid line). Terahertz waveforms (Y axis) obtained with E_{ext} of (c) 5, (d) 1, (e) 0.25, and (f) 0 kV/cm. The pump was 1.6 mJ.

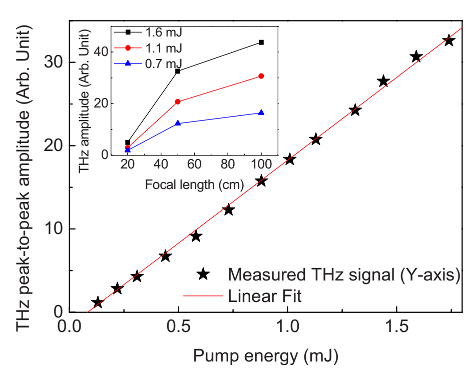

FIG. 3. (Color online) Peak-to-peak amplitude of the terahertz signal (Y axis) as a function of the pump energy with $E_{ext}=5$ kV/cm: experimental data (pentagons) and a linear fit (line), with 50 cm focal length lens. Inset: comparison of terahertz amplitudes (Y axis) from a dc-biased (5 kV/cm) filament formed by three focal length lens (20, 50, and 100 cm) when the pump energy is 0.7 mJ (triangles), 1.1 mJ (circles), and 1.6 mJ (squares).

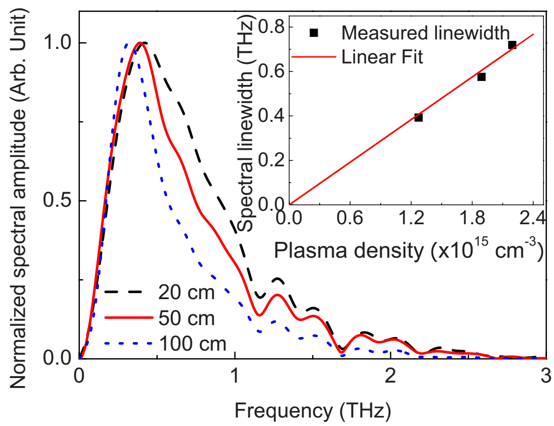

FIG. 4. (Color online) Normalized spectral amplitudes for linearly polarized terahertz emission from dc-biased filaments with 20 cm (dashed line), 50 cm (solid line), and 100 cm (dot line) focal length lens. $E_{ext}=5$ kV/cm. The pump is 1.6 mJ. Inset: linear dependence between linewidth and plasma density.

tude (Y axis) of the terahertz emission from a dc-biased filament ($E_{ext}=5$ kV/cm) as a function of the pump energy. A linear fitting indicates a threshold around 80 μJ which corresponds to the threshold intensity at which significant ionization occurs. Above this threshold, the amplitude increases linearly with the pump energy. Such linear increase is most probably due to the linear increase in the total plasma during the filamentation in air when the laser pulse is focused by a 50 cm focal length lens.[11] The observed maximum terahertz amplitude is estimated to be around 277 V/cm.[12] We also measured the terahertz amplitude (Y axis, $E_{ext}=5$ kV/cm) as a function of focal lengths of various lenses (filament length) (inset of Fig. 3). At the pump energy of 1.6 mJ, the typical filament lengths are 1, 4, and 10 cm for the lenses with focal length of 20, 50, and 100 cm, respectively. The inset shows that an enhancement at least by a factor of 8 as the filament length increases from 1 cm to 10 cm with the same pump energy. According to the dependence of the terahertz spectral energy on the plasma length,[9] for small emission angles (almost forwardly directly terahertz radiation), terahertz amplitude should grow linearly with the filament length. Due to the limited length of our copper plates and collection efficiency of the parabolic mirror for long filament, the growth of the measured terahertz amplitude is slower than the linear one as seen in the inset of Fig. 3.

Figure 4 presents the spectral amplitudes of the (linearly polarized) terahertz emission from dc-biased (Y axis, $E_{ext}=5$ kV/cm) filaments with varied focal conditions. We observed the peak frequency shifts from 0.42 THz (20 cm lens) to 0.32 THz (100 cm lens). The calculated plasma densities are 2.2×10^{15} and 1.3×10^{15} cm^{-3}, respectively. The spectral linewidths are 0.7 THz (20 cm), 0.6 THz (50 cm), and 0.4 THz (100 cm). A wider linewidth belongs to a shorter focal length lens (20 cm: dashed line in Fig. 4) which produces a higher plasma density. The inset of Fig. 4 shows a linear dependence of the spectral linewidth as a function of the calculated plasma density for three focal length lenses. This matches well the theoretical model in Ref. 9 that the linewidth is proportional to the electron collision frequency, i.e., proportional to the plasma density.

We note that the plasma density derived from the spectral maxima of terahertz radiation is found to be lower than that obtained through "local" fluorescence intensity measurement from the side of the filament.[13] The reason is that the latter depends straightforwardly on the local number of electrons thus reflecting the peak density in the filament, or the density averaged over comparatively smaller detection volume.[14] In the present case, the terahertz emission from the whole filament was measured and represented an overall average plasma density. We neglect the effect of the absorption of the ZnTe crystal and the Teflon plate because their absorption curves are around flat below 1 THz.[15,16] The spectral amplitude above 1 THz is still much lower than the peak amplitude even the absorption is taken into account.

In conclusion, we demonstrated that the total electric field of the terahertz emission from a dc-biased filament can be regarded as a sum of the one from an elliptically polarized terahertz source (generated by filament without external electric field) and the other one from a linearly polarized terahertz source (induced by applying an external electric field to the filament). Due to their independent origins, the two terahertz sources have different peak frequency. The linearly polarized terahertz source is polarized along the orientation of the external electric field. It can be amplified by increasing either the applied external electric field, the pump energy, or the filament length. We also proved the possibility of controlling the peak frequency and linewidth of the linearly polarized terahertz emission by manipulating the plasma density in the filament.

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