Terahertz emission from a dc-biased two-color femtosecond laser-induced filament in air

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The generation of terahertz (THz) emission from a dc-biased two-color femtosecond laser-induced filament in air was systematically investigated. A polarization analysis demonstrated that the THz emission could be the sum of two components: one generated by two-color laser-induced filamentation and the second induced by the external dc electric field. The first component is mostly from four-wave mixing process and a transient transverse electric current under the action of the external dc field could be responsible for the second THz emission. © *2010 American Institute of Physics*. [doi:10.1063/1.3441004]

Two-color filamentation in air induced by a femtosecond Ti:sapphire laser pulse [fundamental wave (FW)] and its second harmonic wave (SHW) has been demonstrated as an efficient technique to generate an intense terahertz (THz) emission.[1–5] Several techniques based on the two-color laser-induced filamentation such as the control of multiple air plasmas,[6,7] pump beam size,[8] and pump pulse chirp[9] have been used to amplify the THz emission. For the physical mechanism of the generation of the THz pulse, two theoretical models have been reported. The first is the microscopic polarization model,[5] which has been suggested to interpret the underlying dynamic, attributing the THz emission to the free-electron drifting current driven by the combined field of the FW and its SHW. We call this photocurrent model. The second model frequently used to explain the THz emission is the four-wave mixing[4] based on the third order nonlinearity. Zhang *et al.*[10] have shown that the THz emission is mostly due to four wave mixing (4 WM) by fitting their experimental observation with the 4 WM model. It also has been reported that the THz energy radiated from a single-color (only the FW) laser-induced filament can be enhanced by several orders of magnitude by applying a transverse external dc electric field to a filament in air.[11–13] The polarization of this enhanced THz signal was found to be relatively collinear with the external dc field. The total THz emission from a dc-biased single-color laser-induced filament could be decomposed as two independent processes: THz generation by filament which is elliptically polarized and THz induced by the externally applied electric field which corresponds to a linearly polarized THz source.[13]

In this work, the THz emission from a dc-biased two-color femtosecond laser-induced filament in air was investigated systematically. By analyzing the polarization of THz emission from a dc-biased two-color laser-induced filament with electro-optic sampling (EOS) technique (sensitive to frequency below 4 THz),[14] we found that the total THz emission can be decomposed into two components, one generated by the two-color filamentation and the other induced by the external dc field. This result indicates that 4 WM is essentially the dominant process generating the strong THz signal.

The experimental setup is illustrated in Fig. 1. A 1 kHz, 800 nm, 1.7 mJ, and 50 fs (slightly negatively chirped) Ti-sapphire laser beam was focused by a 20 cm focal length planoconvex lens. The focused pump pulse (FW) passed through a 0.1 mm thick type-I barium borate (BBO) crystal to produce the SHW. The two-color laser-induced filament with a length of around 1 cm was sandwiched between two parallel 8×8 cm^2 copper plates separated by a 1 cm gap. The filament direction was along the central part parallel to one side of the plates. In the experiment, the voltage applied to the plates could be varied from 0 to 5 kV. The polarity of the external dc field could be reversed by switching the two electrodes. The vertical direction was defined as the Y-axis in the laboratory coordinates. The THz pulse was collected through a 0.5 mm thick Si filter and focused by a pair of off-axis parabolic mirrors and measured coherently in the time domain through EOS in a 0.5 mm ZnTe crystal.

The THz generation efficiency of the two-color scheme using a lens followed by a β-BBO crystal depends strongly on the angle α between the optic axis and the FW's polarization direction.[2] In the absence of any external dc field, the optimized two-color scheme ($\alpha\approx 55°$) (Ref. 10) can generate THz electric fields around 10 to 20 times larger than what can be obtained with a single color (FW) 5 kV/cm biased filament in the actual experimental conditions. Thus, in order to clearly demonstrate the effect of an external dc field on the THz emission from a two-color filament, a relatively weak

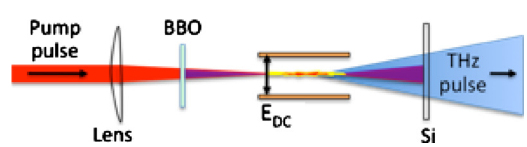

FIG. 1. (Color online) Schematic diagram of the experimental setup. The fundamental laser pulse is focused by a lens through a BBO crystal, generating a second harmonic pulse. Through a dc-biased two-color filament in air, the THz pulse transmits through a Si filter and is detected coherently via EOS.

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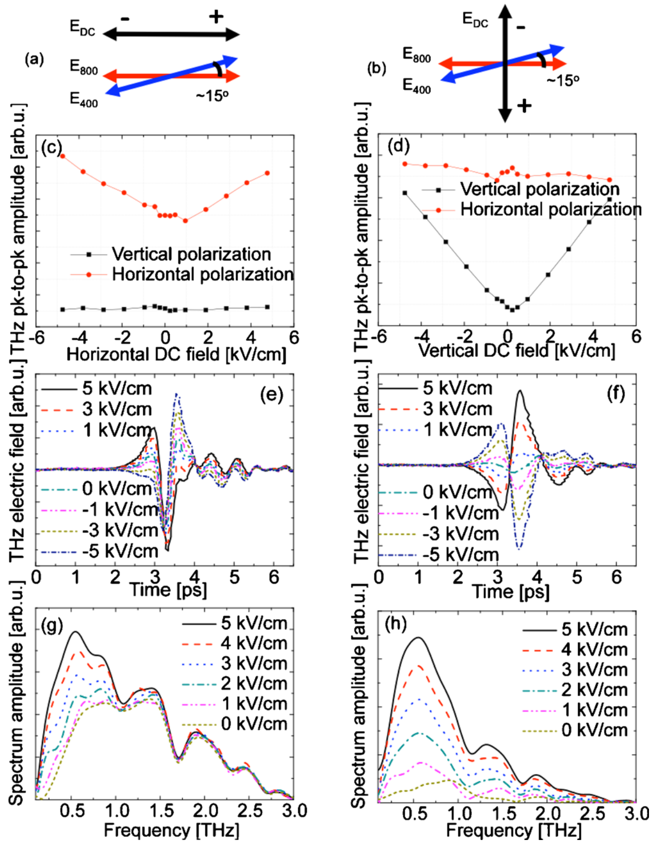

FIG. 2. (Color online) THz peak-to-peak amplitude [(c) and (d)], waveform [(e) and (f)] and frequency spectra [(g) and (h)] from a two-color laser-induced filament in air with horizontal (a) and vertical (b) external dc field. The THz waveforms and frequency spectra are for the components polarized along to the direction of external dc field.

THz signal from the bichromatic excitation is desirable. This was experimentally achieved by rotating the crystal to $\alpha \approx 15°$, where the THz efficiency is roughly 10% of the optimum.[10] Under this condition, the polarization of the FW was horizontally oriented (X-axis). The polarization of the SHW was around 15° from the polarization direction of the FW. The pulse energy of SHW was around 1 μJ. The amplitude of THz electric field was still more than one order higher than that without BBO crystal (FW filament only). Note that THz signal from a rectification process in the BBO crystal was measured by inserting a Teflon filter between the BBO crystal and the filament. It was negligibly weak.

THz pulses were characterized using the EOS technique with the external dc field parallel [Fig. 2(a)] and perpendicular [Fig. 2(b)] to the FW polarization direction, respectively. THz peak–to-peak amplitudes as a function of the external dc field are shown in Figs. 2(c) and 2(d). The external dc field could amplify only one THz component whose polarization is parallel to the direction of the external dc field. The higher the external dc field is, the stronger the THz emission is. The orthogonal THz component is not influenced by the dc field. The THz electric fields parallel to the dc field are depicted in Figs. 2(e) and 2(f). The THz waveform can be modulated by controlling the external dc field. The corresponding Fourier spectra of THz emission are shown in Figs. 2(g) and 2(h). It is clear that the peak frequencies stay at around 0.54 THz when increasing the external dc field for both cases. The dips in the THz spectra at 1.1 and 1.7 THz are due to the water vapor absorption in air.

The polarization trajectories[13,14] of THz emission from a two-color laser-induced filament with a vertical (Y direction) external dc field varying from 0 to 5 kV/cm are shown in Fig. 3. Without external dc field, a linear THz polarization trajectory is observed in Fig. 3(a). When applying the external dc field vertically, the THz polarization trajectory expands in the Y direction with the increase in the applied electric field, see Figs. 3(b)–3(d). Using the analysis technique reported in Ref. 13, the THz electric field waveform obtained without external dc field was subtracted from the corresponding ones obtained with external dc field. The recomposed THz polarization trajectories are linear as shown in Figs. 3(e)–3(g) and they are oriented along the external dc field direction. The orientation difference between the linear polarization trajectory and the Y-axis could be due to imperfect alignment between the external dc field and the Y-axis. When the dc field was horizontally oriented [as in Fig. 2(a)], the orientation of the linear THz polarization trajectories due to the dc field still stays parallel to the orientation of the dc field.

This linearly polarized THz source due to external dc field from a two-color laser-induced filament in air is similar to what has been observed from a dc-biased single-color laser-induced filament.[13] The generation mechanism of the THz field parallel to the dc field direction is different from

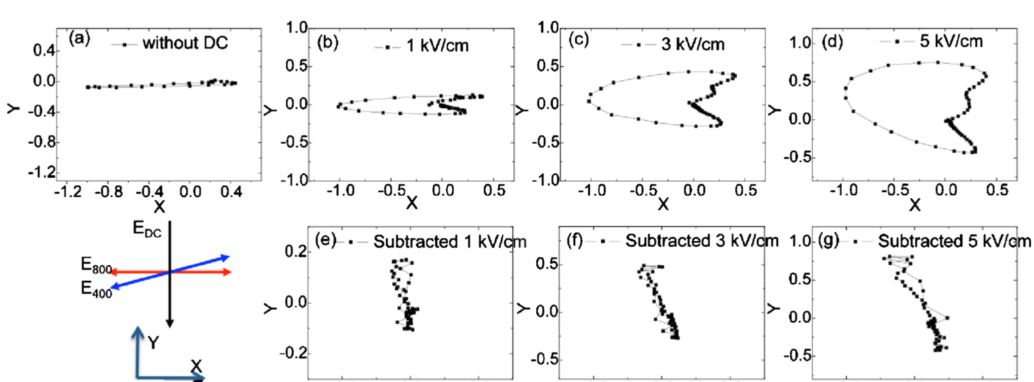

FIG. 3. (Color online) Polarization trajectories of THz emission from a two-color laser-induced filament with a dc field along the Y axis of (a) 0, (b) 1, (c) 3, and (d) 5 kV/cm. THz polarizations in (e)–(g) were obtained by subtracting the waveform without dc field (a) from (b)–(d), respectively. Each solid square corresponds to the measured THz amplitudes in two orthogonal directions at one specified time delay (Ref. 14); two successive solid squares are separated by 33 fs.

the THz emission from two-color filamentation. The former could be well interpreted by the transient transverse electric current under the action of the external dc field.[11,13] The net electric current is directed along the direction of the external dc field and is responsible for the THz emission at the plasma frequency ($\omega_{pe}=\sqrt{e^2 n_e/m_e\varepsilon_0}$) with its polarization parallel to the dc field. Here, n_e is the number density of electrons, e is the electric charge, m_e is the effective mass of the electron, and ε_0 is the permittivity of free space. In this model,[11] the THz polarization is parallel to the current direction, which agrees well with experimental evidence. As shown in Figs. 2(g) and 2(h), the peak frequency is 0.54 THz in the present of external dc fields and it corresponds to a plasma density of around 3.6×10^{15} cm^{-3}. The peak frequency without dc field is around 0.9 THz. These two different peak frequencies indicate two different generation processes for the THz source induced by external dc field and the one from only bichromatic excitation. The polarization analysis in Fig. 3 also reconfirms the claim. However, depending of the external dc field polarity, the THz component parallel to the dc field was slightly asymmetric in Fig. 2(c) and a minimum was observed around +1 kV/cm. This small decrease in the THz amplitude, as compared to the case without dc field, could be attributed to partial destructive interference between the two THz sources, one from the original field when the dc field is zero and the other from the dc-field generated THz field. On the other hand, if the photocurrent[5] did partly contribute to the THz generation from the two-color pump pulses, the external dc field with positive polarity could cancel the free-electron drift at +1 kV/cm, and thus slightly decreases the total THz amplitude by leaving alone the contribution from the four-wave mixing. Finally, since the THz emission from the electric current induced by an external dc field is mainly independent of the THz emission generated by bichromatic excitation, we could reasonably conclude that THz emission from the two-color filamentation is mostly due to the four-wave mixing process. The dominant tensor under our detuned conditions without external dc field is $\chi^{(3)}_{xxxx}$ leading to the linear THz polarization along the X-axis. Moreover, the polarity of the generated THz field in the presence of the dc bias is independent of dc field polarity in Fig. 2(e), which could indicate the generation mechanism for the dc biased two-color air filament is fundamentally different from a biased emitter type THz source. It could be due to the strong initial emission from two-color filamentation, which still leaves a question to be answered.

In conclusion, we demonstrated a systematic investigation on the THz emission from a two-color femtosecond laser-induced filament in air with an external dc field. The total THz emission could be interpreted as a sum of two contributions: a linearly polarized THz component induced by an external dc field with polarization parallel to the direction of the dc field and an emission from the two-color laser-induced filamentation. The total THz waveform could be amplified and modulated by an external dc field. The present results demonstrate intense THz generation and also help to understand the THz generation mechanism from a two-color laser-induced filament in air.

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