Coherent and incoherent radial THz radiation emission from femtosecond filaments in air

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Abstract: We show that the THz radiation emitted in the radial direction by a femtosecond filament created in air is linearly polarized and coherent. By applying an electric field along the filament axis this THz radiation is strongly enhanced and becomes incoherent and not polarized.

OCIS codes: (190.5530) Pulse propagation and solitons, (350.5400) Plasmas, (350.7420) Waves

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1. Introduction

An intense femtosecond laser pulse propagating in air undergoes filamentation. During filamentation, a long low density plasma column is produced. It has been predicted that this plasma column should emit THz radiation in a direction perpendicular to the filament axis [1]. This prediction has been verified experimentally [2, 3], although the physical model underlying this prediction has been disputed [4-8]. Besides the original interpretation in terms of longitudinal plasma oscillations induced by radiative pressure [1], other models assign the THz emission to a Cerenkov-like process arising from the ionization front driven by the ponderomotive force of the laser pulse [4], or to the energy relaxation by inelastic scattering of the produced free electrons [8]. Important information allowing to distinguish among these

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processes, particularly the last one, can be obtained from the polarization and coherence properties of the THz emission.

In this manuscript, we study the polarization and coherence properties of the radial THz radiation from a filament in air. We also measure the THz emission when a voltage is applied to the plasma column. A considerable increase of the emission is observed in this last case. This increase is accompanied by a drastic change in the polarization and the loss of coherence of the emission, indicating a new mechanism for its origin. We discuss a possible origin of this incoherent emission.

2. Experimental set-up and polarization of the radial THz emission

The experimental set up is shown in Fig. 1. Two different lasers were used in the experiment. The first is a laboratory CPA [9] laser chain delivering 120 fs long optical pulses at 800 nm with a maximum energy per pulse of 10 mJ, at a repetition rate of 10 Hz. In this case a single femtosecond filament is created by focusing the laser beam in air with a 2 m-focal lens. The second laser is the Teramobile [10], delivering 100 fs long pulses at 10 Hz with an energy per pulse of 200 mJ. The Teramobile laser pulse is focused with a telescope, the focal length of which can be varied from 10 m up to infinity. For these experiments we set the telescope focal length at 18 m. In this case approximately 40 filaments are produced in a bundle of ~ 8 mm diameter.

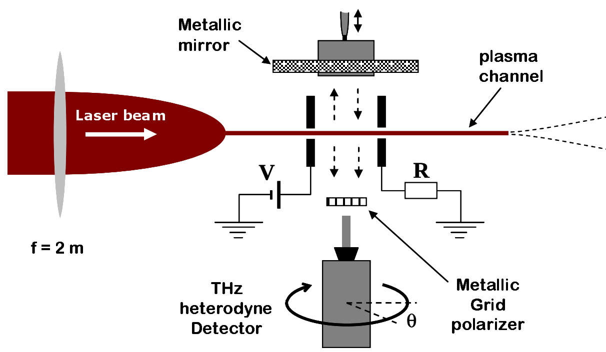

Fig. 1. Experimental Set-up. See the text for a detailed description.

The THz radiation emitted by the plasma filament is detected by means of a heterodyne detector placed perpendicularly to the filament direction. The local frequency of the heterodyne detector is 91 GHz . The detected frequencies are comprised between 88 and 94 GHz with a rejection filter at 91 GHz, to avoid feedback resonances. A waveguide in front of the detector channels the THz radiation to the detector. To perform a measurement of the polarization of the THz emission, we use a linear polarizer consisting of a specially designed metallic grid in front of the heterodyne waveguide. Using the unpolarized emission from a cw thermal source as a test, we first observed that a rotation of the waveguide and detector with respect to the grid polarizer yields a Malus law. This indicates that the waveguide plus detector system acts as a linear polarizer along the polarization axis of the detection. We then oriented the ensemble either parallel or perpendicular to the filament axis.

The result is shown in Fig. 2 for a single filament. We find the THz component to be linearly polarized along the filament axis. Figure 2 clearly shows that the component of the THz electric field perpendicular to the filament direction is zero (continuous line in the Fig. 2). We also verified that the THz signal is independent of the polarization direction of the laser beam producing the filament. The same polarization properties were found with multi-filament configuration using the Teramobile laser beam.

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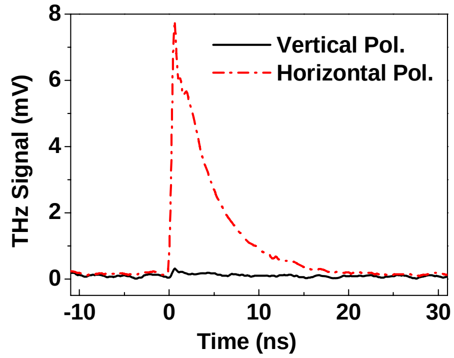

Fig. 2. Polarization properties of the THz field in absence of applied electric field. The graph shows both perpendicular (solid line) and parallel (dotted line) components of the THz field (the time axis represents the response of our detection system).

3. Study of the coherence properties of the radial THz signal

In order to monitor the coherence of the emission, we measured the interference between the THz emitted from one side of the filament and that emitted from the opposite side, after reflection on a movable perpendicular mirror (see set-up in Figs. 1 and 5(a)). We expect, for a coherent source, to observe an interference pattern with a period of one-half wavelength (λ / 2). In the present experiment, the frequencies detected by the heterodyne system are comprised between 88 and 94 GHz (91 ± 3 GHz). We expect therefore an interference pattern with a period of 1.65 ± 0.05 mm. Results are shown in Fig. 3(a). By moving the metallic mirror we get an interference pattern with a period of λ / 2 (1.6 ± 0.2 mm) as expected, with a good contrast as shown in Fig. 3(a). The visibility of the fringe pattern is better than 0.5. The coherence length of the detector is 5cm. The mirror is placed at 20cm from the filament and is moved back over 1cm. The length that gives the delay between the waves emitted from the two opposite sides is therefore 42cm, almost one order of magnitude longer than the detector coherence length. We conclude therefore that the fringes we observe are a proof of the coherence (first order) of the emitted radiation.

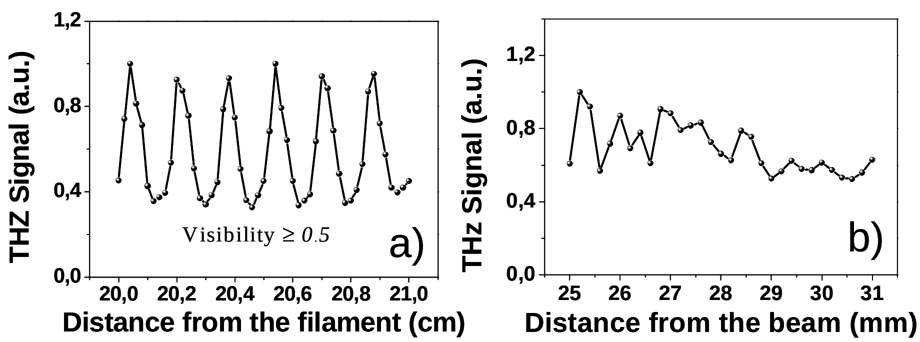

Fig. 3. Coherence properties of the THz radiation in the case of a single filament (a) and in the case of the multi-filamentation with the Teramobile laser beam (b). The x axis indicates the distance between the filament and the reflecting mirror.

Repeating the same experiment with the Teramobile laser, we notice the absence of fringes, as shown in Fig. 3(b). This can be understood simply by noting that the signal is the sum from many filaments which are not located at the same distance from the detector and/or reflecting mirror. The superposition of phase shifted emissions washes out the fringe pattern even if each individual filament emits coherent THz radiation. Nevertheless, the linear polarized nature of the emission subsists, because the emission from each individual filament remains polarized.

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4. Radial THz emission in presence of a DC longitudinal electric field

In a second experiment, we applied an electric potential difference V (see Figs. 1 and 5(a)) to a portion of the filament by means of two copper electrodes separated by 4 cm and placed along the midsection of the filament. Each electrode has a 2 mm-diameter hole in its center to let the filament pass through. The current I_R flowing through an external resistor R of 10 Ω could be measured when the electric circuit was short-circuited by the plasma channel. With a distance of 4 cm between the electrodes the applied static voltage could be varied from V=0 kV up to about V=120 kV before having a spontaneous electric discharge in air starting at the edges of the electrodes.

Results are shown in Fig. 4(a). The THz radiation energy increases quadratically as a function of the applied DC voltage. With an applied electric field of 3 kV/cm we find a THz signal larger than for an un-charged filament by more than one order of magnitude. A plot of the maximum current signal as a function of the DC voltage applied between the electrodes gives a linear dependence, as shown in Fig. 4(b).

A study of the polarization pattern of the emission in the presence of the DC field, using the same procedure as described above, shows that it is unpolarized. Both perpendicular and parallel components of the signal have the same order of magnitude, as shown in Fig. 5(b).

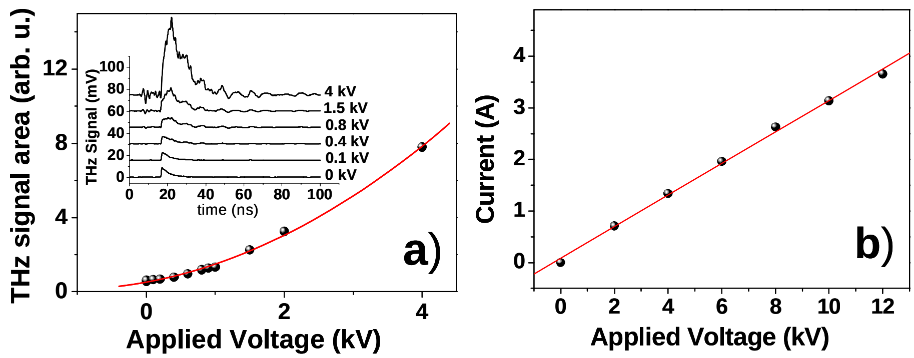

Fig. 4. Evolution of the horizontal component of the THz signal (a) and the peaks of the current signal (b) with the applied voltage. In the graph of the Fig. 4(a) the area of the THz signals in the inset is plotted as function of the applied voltage, the experimental data are well fitted by a quadratic law (continuous line).

Performing the interference experiment with a single filament, we found that the interference fringes disappear in presence of the applied potential difference, indicating the presence of an incoherent radiation. This result is shown in Fig. 5(c). We have verified that the peculiar geometry of our source (thin string) cannot induce polarization or/and interference effects by repeating the experiment with a 200 μm thick heated metallic wire. No polarization or obvious interference was found from this source.

5. Explanation of the results by means of a phenomenological model

We have considered several mechanisms for the new THz signal. Löffler, *et al*. [11] have previously observed an intense THz emission in the presence of an electric field by strongly focusing an intense femtosecond laser pulse in air. In the experiment of Löffler, *et al*., the external electric field was parallel to the laser field in contrast to our experiments. They attribute the THz emission to the tunneling regime of ionization, when the laser intensity reaches 10^{15} W/cm². In our case, the THz radiation is emitted by a plasma channel created by filamentation. The laser intensity in the filament is well known to be clamped to a maximum value of about 5×10^{13} W/cm² [12]. At such intensities, the ionization mechanism can still be adequately described by a multi-photon perturbation regime. Therefore we conclude that tunneling ionization we observe is not responsible for the enhanced THz emission.

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Both the polarization and interference experiments indicate the onset of a new emission mechanism by the electrically charged filament. Moreover, the THz signal in presence of the DC electric field appears with a delay of about 2ns with respect to the signal without electric field. It can be clearly seen from the graph of Fig. 6. When a weak potential difference is applied between the two electrodes, we can distinguish two peaks on the signal. The first peak, around zero, does not depend on the electric field intensity and keeps its polarization direction. The second peak depends on the electric field intensity and is not polarized.

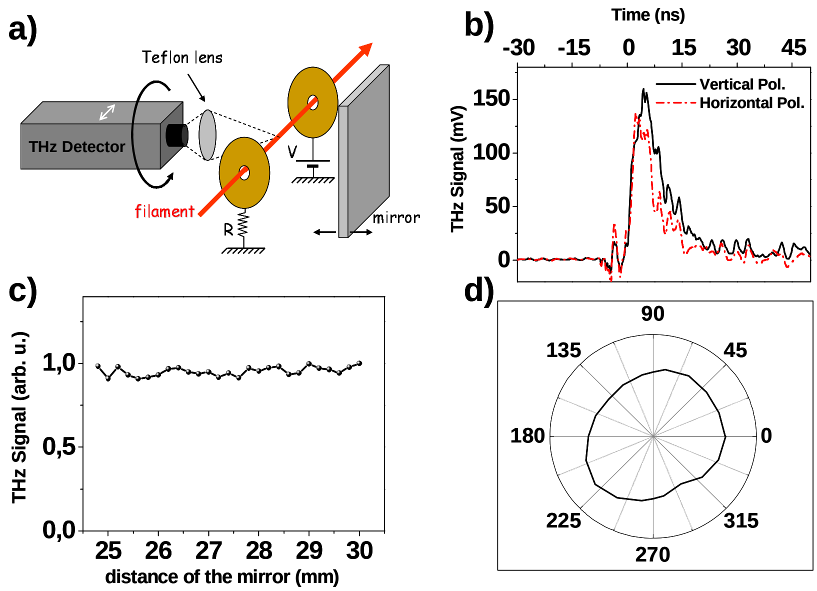

Fig. 5. Polarization properties of the THz field in presence of applied electric field. a) Scheme of the polarization and coherence experiment. Figure 5(b) shows both perpendicular (solid line) and parallel (dotted line) components of the THz field. Figure 5(c) shows the absence of interference of the THz radiation emitted by a charged filament. Figure 5(d) shows the complete polarization diagram of the THz radiation emitted by a single charged filament.

The most likely explanation is based on Joule heating of the charged plasma column, generating a thin hot air wire. This mechanism was investigated by our group in 2001 [13]. Using time-resolved diffractometry technique [14], we showed that the Joule heating of a thin air column and its subsequent expansion is responsible for the initiation of guided discharges by filaments. We estimate the increase of the temperature of the air column as follows. The maximum dissipated energy in the air column is given by $\Delta E_J \approx \Delta P_J \cdot \tau$, where τ is the lifetime of the plasma, which is of the order of 1 ns [14] and $\Delta P_J = V \cdot I$, where I is the current flowing in the circuit. From the graph in the Fig. 4(b) we obtain $\Delta E_J \approx \Delta P_J \cdot \tau \approx 3 \cdot 10^4 W \times 10^{-9} s = 30\ \mu J$. Finally, we have $\Delta T = \Delta E_J / (M \cdot C_p) \approx 100\ K$ where $C_p \approx 1\ J \cdot g^{-1} \cdot K^{-1}$ is the specific heat capacity of the air and $M \approx 1.6 \cdot 10^{-7} g$ where $M = \rho(\pi r_f^2 L)$ is the mass of the heated air column where $\rho = 10^{-3} g \cdot cm^{-3}$ is the air density, $r_f = 50 \mu m$ the filament radius and $L = 4cm$ the distance between the two electrodes. This calculation is made assuming a constant air pressure and is in agreement with the increase of the temperature of the air column extracted from the analysis of time-resolved diffractometry in Ref. [14]. We therefore attribute the increase of THz emission with applied electric field, as well as the unpolarized and incoherent character of this new THz emission to the same heating process with the subsequent black body radiation from the heated air column.

Under such a hypothesis we can estimate the total power emitted in space by the heated air in the 100 GHz range. According to Wien's law the maximum emission frequency for a

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black-body at 400 K is around 23.6 THz. Therefore, at the detection frequency of 91 GHZ, the Black-body law is well approximated by the Rayleigh-Jeans law. We can then calculate the total power emitted in total space by the filament by using the following formula:

$$\Delta P = \frac{4\pi^2 RL}{c^2}\nu_c^2 k_B \Delta T \Delta \nu \,. \tag{2}$$

This formula represents the Rayleigh-Jeans law integrated over the emitting surface $2\pi r_f L$ of the filament and multiplied by the detected frequency range $\Delta\nu = 6GHz$. ΔT is the variation of temperature responsible for the emission and $\nu_c = 91\ GHz$. The coefficient $k_B = 1.38\times10^{-23} J\cdot K^{-1}$ is the Boltzmann's constant. For an increasing of temperature of $\Delta T = 100K$ we can estimate from Eq. (2) that the total power emitted by the 10 kV charged filament in the 6 GHz range around 91 GHz is about $\Delta P = 60\,pW$.

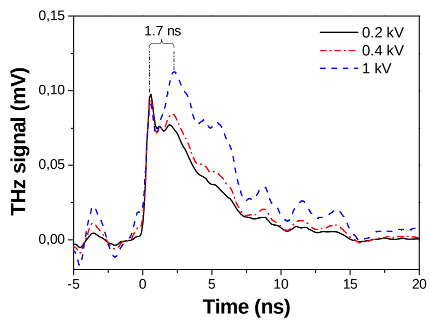

Fig. 6. Signal of the radial THz emission from the filament in presence of a weak electric field applied along the filament. The second peak of the signal increases as the electric field increases. The first peak does not depend on the applied electric field. The delay between the two peaks for weak applied electric fields is about 2ns.

Finally, returning to the THz emission in the absence of electric field, we note that its coherence properties are consistent with the Cherenkov mechanism proposed by Sprangle, *et al*. [4] but is not consistent with the mechanism proposed in Ref. [8]. We can estimate that the total power emitted in the absence of applied field is one order of magnitude less than the power from the thermal emission in the presence of an external field. Therefore we estimate the total power emitted by the un-charged filament to be about 6 pW, in agreement with the model of Ref. [4]. As pointed out by Sprangle, *et al*. [4], the emitted pulse duration should be of the order of 50 ps and have a spectrum extending over several THz.

6. Conclusion

In conclusion, we have shown that the radial THz emission from a single plasma filament in air is linearly polarized along the filament axis and is coherent. When the filament is electrically charged, an order of magnitude increase of the signal is observed. This is accompanied by a loss of coherence and a depolarization, showing that it corresponds to the appearance of a new emission mechanism. We interpret the new emission as due to the blackbody radiation of a thin air column left after the plasma has recombined.

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