

Strong Enhancement of Terahertz Radiation from Laser Filaments in Air by a Static Electric Field

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We observe a 3 order of magnitude enhancement of the terahertz energy radiated by a femtosecond pulse undergoing filamentation in air in the presence of a static electric field. Measurements of terahertz pulse duration, spectrum, polarization, and radiation pattern elucidate the physical processes responsible for this radiation. A theoretical model explains the results and predicts another 3 orders of magnitude enhancement with a terawatt laser pulse.

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The ionization front produced by an intense femtosecond laser pulse propagating in air is the source of a terahertz (THz) radiation emitted in a narrow cone in the forward direction [1,2]. The radiation is produced by the longitudinal oscillations of the plasma left in the wake of the moving ionization front. These plasma oscillations are excited by the ponderomotive force of the laser pulse and are heavily damped by electron collisions on a picosecond time scale. The radiation is emitted by a dipolelike structure moving at the speed of light; it is therefore similar to the Cherenkov emission created by a pair of opposite charges. Because of the simplicity in its implementation, this THz source is suitable for many applications. It requires no optical element or crystal in the path of the femtosecond laser which would be prone to damage or induce dispersion, and is therefore easily scalable to higher laser intensities. In contrast to other methods such as four wave mixing of femtosecond pulses at frequencies ω and 2ω , there is no phase sensitive adjustment or precise alignment between pulses. Another attractive feature is the fact that such a source can be placed in the proximity of distant targets, solving thereby the long-standing problem posed by the strong attenuation of THz radiation in air due to water vapor. Displacing the onset of ionization is easily achieved by either imposing a negative linear chirp to the femtosecond laser pulse or by enlarging the beam diameter [3,4].

In this Letter, we show that the THz radiation from the laser filament is highly sensitive to the presence of a transverse electric field. We demonstrate an enhancement of its intensity by 3 orders of magnitude and show how a further enhancement by at least another 3 orders of magnitude should be easily obtained. This enhanced source maintains all advantages discussed above since the static field can also be placed in front of the sample. The THz pulse we have obtained in the laboratory with a 2 mJ femtosecond pulse is already sufficiently intense to allow its complete characterization by nonlinear mixing in air

with an infrared source [5]. We present an analytical model explaining all observed features.

A commercial Ti:sapphire chirped pulse amplified laser chain, delivering 50 fs duration pulses at 800 nm, with a maximum energy of 10 mJ per pulse operating at a repetition rate of 100 Hz, or a similar system operating at 1 kHz was used. The laser beam was focused in air by a convex lens to form a plasma filament with a typical length of 5 cm. A static electric field (also referred to as a dc bias) was applied to the ionized region along direction X (perpendicular to the filament axis Z) by placing two copper plane electrodes across the filament; see Fig. 1(a). The electrode length was 5 cm and the maximum applied field was 10 kV/cm. To characterize the THz radiation emerging from the region between the electrodes, several detectors were used. A bolometric detector cooled to 4 K in conjunction with a bandpass filter centered at 1.3 THz (bandwidth ~ 1 THz) measured the THz pulse energy (see [6] for details). The angular radiation pattern was measured with a heterodyne detector sensitive to the

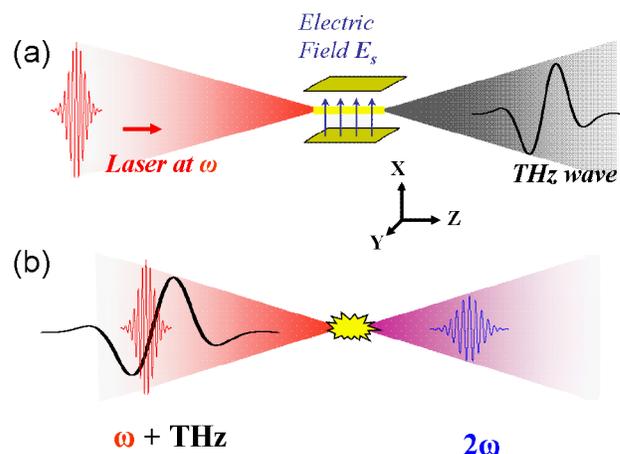


FIG. 1 (color online). Experimental method for THz generation (a) and for THz detection (b).

0.1 THz component of the spectrum [2]. The THz waveform was fully characterized by mixing in ionized air the THz signal with a short laser pulse at 800 nm to generate an optical signal at 400 nm, using the technique pioneered by Dai *et al.* [5] [see Fig. 1(b)].

Figure 2 shows the angular patterns of THz radiation measured in the plane Z-X, with the detector sensitive to the X component of the polarization. In the absence of static field, we observe the typical conical shape of the THz emission from the longitudinal current excited by the laser pulse ponderomotive force reported in [2], Fig. 2(a). With increase of the electric field, the energy of THz signal increases, while its peak gradually converges to the filament axis. A change of the dc field polarity reverses the observed pattern with respect to the plane Z-Y (see insets in Fig. 2). We also measured the angular pattern as a function of the filament length, which was varied by changing the focal length of the lens, Fig. 3(a). The influence of the external field on the total energy of THz signal in the range 0.5–2 THz measured with a bolometer is shown in Fig. 3(b). A quadratic dependence is observed, with no sign of saturation up to the highest applied field of 6 kV/cm. This means that the amplitude of the THz signal

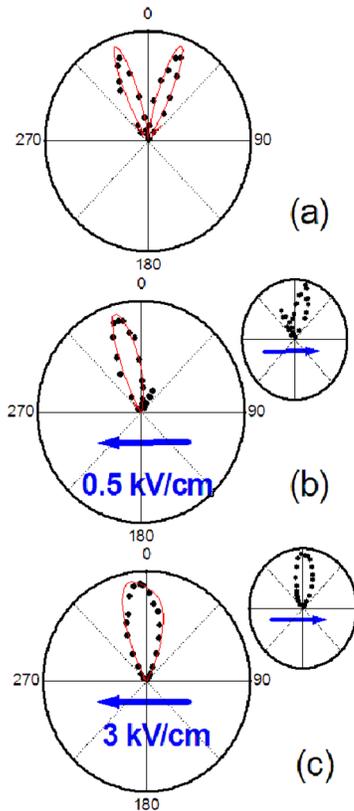


FIG. 2 (color online). Angular dependence of the THz emission generated in a filament in the presence of a dc field $|E_s| = 0$ (a), 0.5 (b), and 3 kV/cm (c). Measurements were made at 0.1 THz with a focusing lens $F = 1000$ mm generating a 2 cm plasma filament. Red continuous curves: fit using Eq. (5) with a laser intensity $I_L \approx 9 \times 10^{13}$ W/cm².

is directly proportional to the static electric field. In another experiment, we obtained a factor of 10^3 enhancement with a 2.5 mJ laser pulse energy and a dc field of 5 kV.

The polarization of the THz signal was measured by rotating a grid polarizer in front of the bolometer around Z axis. The THz emission was found to be linearly polarized in the plane X-Z containing the external electric field, but did not depend on the laser polarization. This excludes a four wave mixing or difference frequency generation between the laser field and the static field as the origin of the THz enhancement, as suggested in Ref. [7]. Since the THz field generated by the ponderomotive current is radially polarized [1], the polarization and directionality of the signal in the present experiment indicate a direct THz emission from the transverse current excited in the plasma column by the external electric field.

The THz temporal waveform has been characterized by the technique shown in Fig. 1(b) using a kilohertz laser system. Part of the initial pulse at the wavelength of 800 nm was mixed with the THz pulse emerging from the filament, yielding a signal at the second harmonic frequency, 400 nm. By measuring the harmonic signal as a function of the delay between the THz and the ultrashort infrared pulse, one determines the waveform of the THz field, giving access to the pulse duration and spectrum. This detection method presents the advantage over classical electro-optics sensors to have a better time response since it avoids phonon absorption and dispersion of crystals in the THz range [8]. An example of such a signal is shown in Fig. 4(a). The THz pulse is short, essentially a single cycle. Its spectrum, obtained by a Fourier transform, is shown in Fig. 4(b).

We model this laser-created filament as a plasma channel of a cylindrical shape, with a homogeneous electron density n_e and a radius ρ_c . The static external electric field E_s is directed along the X axis perpendicularly to the channel axis Z. Electrons in the channel feel the electric field E_s at the moment they are detached from atoms by the

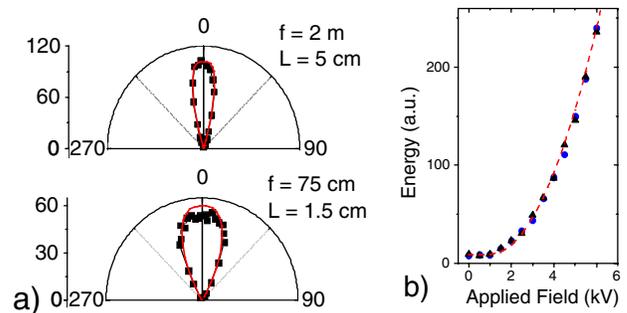


FIG. 3 (color online). (a) Angular dependence of THz emission in the presence of a static field $E_s = 5$ kV/cm for the filament lengths 1.5 and 5 cm. Red curves are fits using Eq. (2) with the corresponding plasma lengths. (b) Energy of the THz radiation in the range 1–2.5 THz measured as a function of the dc electric field for a 2 cm plasma. The input IR pulse has energy of 1.4 mJ and a pulse duration of 50 fs.

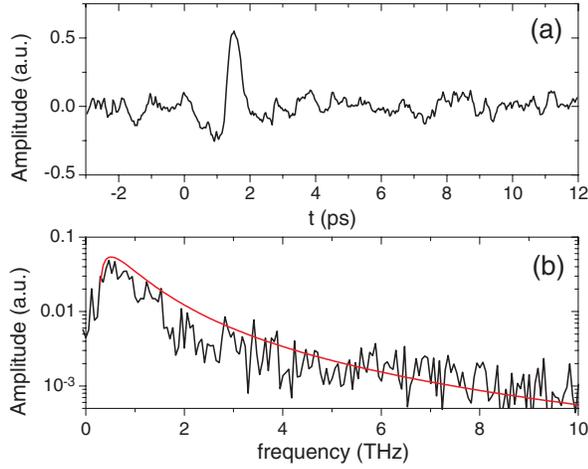


FIG. 4 (color online). (a) THz field measured by induced second harmonic generation. (b) Corresponding spectrum in the range 0.1–10 THz obtained by a Fourier transform. The red continuous curve is calculated using Eq. (3) with $\omega_{pe} = 1.9 \times 10^{12} \text{ rad s}^{-1}$ and $\nu_e = 5 \times 10^{12} \text{ rad s}^{-1}$.

ac electric field of the laser pulse. Therefore the electron motion at different positions z in the channel is similar but occurs with time delay z/c , which depends on the distance of a particular cross section from the channel head. That is, the electron motion depends on the coordinates in the channel cross section, x , y , and the local time $\tau = t - z/c$.

The plasma in the channel being a good conductor, the electrons start moving under the action of the external electric field, accumulate charge at the channel edge, and eventually screen completely the electric field in the plasma. However, there is a transient process of redistribution of charges, and the temporal behavior of the electric current depends on the relation between three parameters: the duration of the ionization process t_{ion} , the electron collision time t_{col} , and the period of plasma oscillations t_{pl} . For the experimental set of parameters of the laser filament in air at normal pressure, the electron density in the channel is 10^{16} – 10^{17} cm^{-3} , the channel radius 30–50 μm , and the laser pulse duration is about 50 fs. Then the plasma period is approximately 1–0.5 ps, the collision time is of the same order 1–0.3 ps, both of them longer than the ionization time. One can therefore consider a plasma response to an instantaneous ionization. The electric current is directed along the direction of the external electric field and it exhibits oscillations at the plasma frequency decaying in a few electron collision times.

The temporal behavior of the electric current $j_x(\tau)$ is qualitatively similar to that in the wakefield created by the laser ponderomotive force considered in Ref. [2],

$$j_x(\tau) = j_0 \sin(\omega_p \tau) e^{-\nu_e \tau/2}. \quad (1)$$

Here $\omega_p = (\omega_{pe}^2 - \nu_e^2/4)^{1/2}$ is the frequency of the damped plasma oscillation, $\omega_{pe} = (e^2 n_e / m_e \epsilon_0)^{1/2}$ is the plasma frequency, and ν_e is the electron collision fre-

quency. There are two major differences from the wake plasma current discussed in Ref. [2]: first, the current is directed along the external electric field perpendicularly to the channel axis and located inside the circle of the radius ρ_0 , and second, its amplitude, $j_0 = \epsilon_0 E_s \omega_{pe}^2 / \omega_p$, is proportional to the external field E_s .

The spectrum of the emitted energy in the solid angle $d\Omega$ is given by

$$\frac{d^2 W}{d\omega d\Omega} = \frac{|j_\omega|^2}{4\pi\epsilon_0 c} \frac{\rho_0^4 \cos^2 \theta}{(1 - \cos \theta)^2} \sin^2 \left(\frac{L\omega}{2c} (1 - \cos \theta) \right). \quad (2)$$

The maximum of the emission is directed along the filament axis, $\theta = 0$, and the filament length L defines the angular width of the emission cone, $\Delta\theta = 4\pi c/L\omega$. Moreover, in difference from the longitudinal current, the total emitted energy is proportional to the channel length L . As shown in Fig. 3(a), the measurements at 0.1 THz are in good agreement with this expression. We observe a linear increase of the radiated energy, and a reduction of the angular width, while increasing the plasma length.

The spectrum of the electromagnetic emission is defined by the current Fourier component:

$$j_\omega = \frac{\epsilon_0 E_s \omega_{pe}^2}{\omega^2 - \omega_{pe}^2 + i\nu_e \omega} = \epsilon_0 E_s g_\omega(\omega). \quad (3)$$

It has a maximum at the plasma frequency and the line-width is proportional to the electron collision frequency. The spectrum obtained from the waveform measurement is in good agreement with this formula [see Fig. 4(b)]. Let us consider also the waveform of the emission at the distance $r \gg L$ from the source:

$$E(r, t) = E_s \frac{\rho_0^2 \omega_p}{rc\theta^2} \sin \left(\frac{L\omega_p}{4c} \theta^2 \right) \cos \omega_p \left(t - \frac{r}{c} \right) e^{-\nu_e t/2}. \quad (4)$$

This is a typical damped oscillation at the plasma frequency. The on-axis amplitude is proportional to the filament length and the plasma density, and the cone opening is a few degrees for the present parameters.

The analysis of the far field THz emission provides a method for measuring the ponderomotive potential (or the laser intensity in the filament). For a low dc field, the THz field generated by the ponderomotive force E^1 is comparable with the one induced by the static transverse field E^2 . By observing the far field angular pattern resulting from their superposition, one can estimate the relative strength of the two fields, and deduce the ponderomotive potential of the laser pulse responsible for the transition Cherenkov emission. The Fourier components of the two radiation electric fields at the distance r from the filament within the emission cone read

$$E_{\omega}^1(r) = \frac{U_p \omega_{pe} g \omega \rho_0^2 \sin(\theta)}{e c^2 r \theta^2} \sin\left(\frac{L\omega}{4c} \theta^2\right)$$

$$E_{\omega}^2(r) = \frac{E_s g \omega \rho_0^2}{r \epsilon_0 c \theta^2} \sin\left(\frac{L\omega}{4c} \theta^2\right), \quad (5)$$

where $U_p = e^2 I_L / (2m_e \epsilon_0 c \omega_0^2)$ is the ponderomotive potential proportional to the laser pulse intensity [2]. We compared the calculated pattern at $\omega = 0.1$ THz with the measurements presented in Figs. 2(b) and 2(c). The best fit is obtained for $U_p = 5.4$ eV, corresponding to a laser intensity inside the filament $I_L = 9 \times 10^{13}$ W cm⁻².

The model predicts also a correct dependence of the emitted energy on the dc field. Indeed, the total emitted energy reads

$$W \approx \frac{\pi^2}{8} \epsilon_0 E_s^2 \rho_0^4 L \frac{\omega_{pe}^3}{c^2 \nu_e}. \quad (6)$$

It is proportional to the square of the filament cross section, to the square of the dc electric field strength, to the filament length, and to the plasma density in the channel in the power 3/2.

Löffler *et al.* were the first to report a large enhancement of the THz emitted by ionized air in presence of a static field [9]. Our model of THz emission in a certain sense is similar to the current surge idea they suggested. The emission is produced by an electric current propagating in the wake of the laser pulse. However, the important difference is the predicted coherent and nonlocal nature of the emission, which defines its good directivity and a relatively high radiated energy. There is also very close similarity with the electromagnetic emission from double filament structure [10]. The qualitative features are very similar since the current source has the same direction; the main difference is that the electric field generated by bifilamentation depends on the distance between the filaments, which is not well known. The geometry with external electric field offers better defined conditions and consequently a more unambiguous comparison with a theoretical model.

The model reproduces all observed results. This is true for the radiation pattern for different field strengths (as shown by red curves in Fig. 2) and for different plasma column lengths (Fig. 3(b)). The model also predicts the correct dependence of the THz intensity as a function of the dc electric field [see Fig. 3(b)]. The total emitted energy, measured with the bolometric detector and the bandpass filter (see Ref. [6] for the calibration method), is estimated to be 0.05 nJ for $E_s = 5$ kV/cm, laser energy 2.4 mJ, and $L = 2$ cm, while Eq. (6) for the same parameters gives 0.08 nJ. There are clear possibilities for improvement of the THz emission efficiency. First, one can apply a higher dc electric field. A voltage of 20 kV, still well below the threshold for spontaneous sparking discharge, will lead to a factor of 16 enhancement. Increasing the distance over which the electric field is applied to $L = 20$ cm can bring another factor of 10. Another improvement by 1 or 2 orders

of magnitude can be achieved with the use of a more powerful femtosecond laser. Above the threshold of ~ 10 GW, the IR femtosecond pulse generates N filaments, which all act as a source of THz emission. (Here, $N \sim P/P_{cr}$ and $P_{cr} = 5$ GW is the critical power for filamentation [4].) In the experiment without static field, we observed a factor of 40 enhancement of the THz signal by using a pulse energy of 200 mJ from the teramobile instead 10 mJ [2]. Furthermore, since the THz radiation emitted by each individual filament is coherent, by phase sensitive control of the filament pattern one should obtain a THz intensity scaling like N^2 . Altogether, one can expect an increase of the THz intensity by at least 10^3 , bringing the pulse energy content to hundreds of nJ for a pulse duration of 1 ps.

One can also notice that, according to the theoretical model, the same enhancement of the THz generation should be observed if the static field is replaced by a THz or a microwave pulse of the same electric field (several kV/cm). Indeed, if the period of the applied field is much longer than the time during which ionization occurs ($t_{ion} \approx 50$ fs), this field is seen as static by the ionization front. Thus, by selecting a microwave pulse which is not absorbed by air and focusing it on the filament, one should be able to remotely enhance the THz emission of the plasma string.

In conclusion, it is demonstrated experimentally that the THz emission from a femtosecond laser filament in air can be greatly enhanced when an electric field is applied in the ionized air region. A theoretical model has been developed, which explains well all observed features. From far field THz measurements, most of the intrinsic characteristics of the plasma column can be deduced or alternatively the (remote) local electric field can be measured if the plasma properties are known.

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