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Yi Liu, Aurélien Houard, Bernard Prade, André Mysyrowicz, Abdourahmane
Diaw, Vladimir Tikhonchuk

Amplification of Transition-Cherenkov Terahertz Radiation of Femtosecond Filament in Air

Yi Liu, Aurélien Houard, Bernard Prade, André Mysyrowicz[*]

Laboratoire d'Optique Appliquée, ENSTA, Ecole Polytechnique, CNRS UMR 7639,

Palaiseau, 91761, France

Vladimir T. Tikhonchuk

Centre Lasers Intenses et Applications, Université Bordeaux 1, CEA, CNRS UMR 5107,

Talence, 33405 France

Abstract: The transition-Cherenkov terahertz (THz) radiation from a femtosecond laser filament in air is enhanced by 3 orders of magnitude in the presence of a longitudinal static electric field, while the radiation pattern and the polarization remain the same. An amplified longitudinal electron current inside the filament is responsible for this amplified THz emission.

A plasma filament formed in air by femtosecond laser pulse is a promising source for electromagnetic radiation in the THz domain [1-6], due to the simplicity of alignment, availability of the effective medium, and also due to the ability to position the THz emitter in the proximity of a remote sample far away from the laser system [5, 6]. The femtosecond laser filament arises from the dynamic competition between Kerr beam self-focusing and beam defocusing by the produced air ionization. The filament characteristics such as length and position can be easily controlled by manipulating the laser pulse or the focusing conditions [7]. The forward THz radiation from a single filament was found to be radially polarized and exhibit a hollow-cone structure where the radiation intensity on the laser propagation axis is zero and the cone opening angle

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[*] Corresponding author : andre.mysyrowicz@ensta.fr

depends on the filament length [5, 6]. As to the mechanism for this THz wave, the authors proposed a transition-Cherenkov model where the electrostatic wake behind the ionization front inside the filament gives out electromagnetic emission in the THz domain. However, the conversion efficiency of the mechanism is relatively low, on the order of 10^{-9}, because of the relatively weak electric field in the wake of the ionization front [8]. Recently, it was demonstrated that by applying a transverse electric field (with respect to the filament axis), it is possible to enhance the THz emission intensity by at least 3 orders of magnitude [9].

In this paper, we follow this idea and demonstrate that the intensity of the THz emission from laser filament is enhanced by three orders of magnitude if one applies a static electric field along the filament axis. In contrast to the case with a transverse field, the angular radiation pattern and the polarization characteristics of the THz wave remain the same as those without the external electric field. We extend the transition-Cherenkov model by taking into account the electron current in filament driven by the external voltage. This model reproduces all the observed features of this amplified THz emission.

A commercial femtosecond laser system (Thales, Alpha-100) is used in this experiment. It delivers a laser pulse of 50 fs and 15 mJ at a repetition rate of 100 Hz. The IR pulses are focused by a convex lens of 1 m or 1.5 m in the ambient air and a plasma filament is formed. Two square copper electrodes with circular holes of different size on the center are mounted across the filament (Fig. 1). The sizes of holes in the first and second electrodes are 3 mm and 20 mm respectively. A larger size of second hole assures that the filament is not disturbed by electrodes and that the THz radiation produced by the filament propagates freely outside of the electrode cavity. A heterodyne THz detector sensitive for 0.1 THz component of the THz emission is used for the characterization of the THz signal [5, 6].

In the first series of measurements, a pulse of 2.3 mJ is used and the distance between two electrodes D is set to 15 mm. The radiation pattern of the THz emission from the biased filament is measured as a function of electric field strength, and the results are shown in Fig. 2(a). Note that the THz signal intensity without external field is multiplied by a factor of 200 for visibility. Two conclusions are evident. First, the THz

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intensity in the presence of electric field $E = 10$ kV/cm is enhanced by about 1,000 times. Second, the enhanced THz radiation exhibits the same radiation pattern as that without the external field. The enhanced THz emission is found to be radially polarized as in the case of a pure transition-Cherenkov radiation (data not shown) [5, 6].

The similarity of the radiation pattern and polarization properties of this enhanced THz emission with the case without the external electric field indicates that it has the same physical origin. In the case of a pure transition-Cherenkov emission, the pondermotive force of the laser pulse inside the filament creates an electrostatic in its wake. It corresponds to a charge separation in the longitudinal direction, which resembles an electric dipole moving at the velocity of light along it own axis [5, 6, 10]. The energy spectral density of the THz radiation emitted by the wake in the unit solid angle reads:

$$\frac{d^2W}{d\omega d\Omega} = \frac{|j_z(\omega)|^2}{4\pi\varepsilon_0 c} \frac{\rho_0^4 \sin^2\theta}{(1-\cos\theta)^2} \sin^2\left(\frac{L\omega}{2c}(1-\cos\theta)\right), \qquad (1)$$

where $j_z(\omega)$ is the Fourier spectrum of the electron current, L is the length of the plasma emitter, ρ_0 is the radius of the plasma column, and θ is the radiation angle with respect to the laser propagation axis z [5, 6]. The electric current has a maximum at the electron plasma frequency, $\omega_{pe} = \sqrt{e^2 n_e / m_e \varepsilon_0}$, and its amplitude is proportional to the laser ponderomotive force. The emission energy depends weakly on the filament length (as $\ln L/\lambda$), while the angle of maximum emission, $\theta_{max} = (\lambda/L)^{0.5}$, where λ is the radiation wavelength.

In the present experiment, it is reasonable to assume that the ionization process in the air is due to the focused laser pulse, and it is not influenced by the presence of external electric field, which is well below the discharge threshold. However, the external field E_e can easily exceed the wake electric field E_w created by the laser ponderomotive force. The latter was estimated to be ~ 200 V/cm under present experimental conditions [6]. Consequently, the electrons liberated by the laser field around the peak of the femtosecond pulse are accelerated by the total longitudinal electric field, $E_e + E_w$, originated from the laser ponderomotive force and the external field [5, 6, 10]. Due to the short collision time between the free electrons and neutral atoms in the filament plasma, the coherent plasma oscillations driven by the electric field are

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strongly damped in the collision time scale, which is on the order of 0.1-0.2 ps. This transient current j_z driven by the total field $E = E_e + E_w$ in the longitudinal direction is expected to radiate in the same manner as the electron current produced by the ponderomotive force, except that the emission intensity is greatly enhanced, if $E_e \gg E_w$. In other words, in equation (1) the emission intensity should be multiplied by the factor $(1 + E_e/E_w)^2$, which accounts for a coherent addition of electric currents driven by the ponderomotive force and the external field. Also the length of the plasma filament L has to be replaced by the distance D between the electrodes.

In order to verify the dependence on the filament length, we performed the measurements of radiation pattern for the distances D = 15 and 60 mm. As a result, the radiation angle θ changed from 25° in Fig. 2(a) to 17° in Fig. 2(b). According to the transition-Cherenkov model [5, 6], the angle of the most intense THz lobe depends on D as $\theta_{max} = (\lambda/D)^{0.5}$. Considering the THz wavelength λ = 300 μm at 0.1 THz, the opening angles of THz emission for D = 15 and 60 mm are 26° and 14°, correspondingly. These values agree well with the experimental observations. In this experiment, the second plane copper electrode with 20 mm hole was replaced by a spherical electrode placed 2 mm under the filament. The THz radiation was partially blocked, and therefore the THz signal amplitudes could not be compared.

The variation of the THz signal intensity is presented in Fig. 3 as a function of the applied electric field. The positive (negative) electric field denotes the situation where the voltage V was positive (negative). In the inset, the result for a low field is presented. There, the offset of the THz intensity at zero voltage corresponds to the pure transition-Cherenkov emission. For the same electric field of opposite polarity, the THz enhancements show almost no difference. Based on this observation, we come to the conclusion that the electric current driven by the external field E_e greatly exceeds the current induced by the ponderomotive force. The quadratic dependence of the THz intensity on the field E_e is consistent with equation (1) multiplied by the factor $(1 + E_e/E_w)^2$. Moreover, a hundred time enhancement of the THz signal for E_e = 2 kV/cm, provides a direct estimate of the strength of the ponderomotively driven electric field E_e = 200 V/cm, which is in agreement with the theoretical estimate in Ref. 6. A further enhancement of the THz could be achieved by applying higher electric field provided it is below the breakdown field of the air.

As a final remark, we would like to mention that the physical picture for THz emission discussed here is similar to the surface depletion field induced THz radiation in semiconductor THz emitters such as InP, and GaAs [11, 12]. The difference lies in the fact that in the laser irradiated semiconductors the electron current is created by the surface electric field, which is normal to the sample surface, while in our case it is directed along the laser axis.

In conclusion, the transition-Cherenkov THz radiation from femtosecond in air is amplified by three orders of magnitude by applying an external longitudinal electric field. The angular distribution and polarization of the amplified THz emission are observed to be the same as that of the pure transition-Cherenkov process. The amplification effect is explained by a higher electric current in the wake driven by the external electric field.

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Figure captions:

Figure 1. Schematic setup of the experiment.

Figure 2. Radiation pattern of the amplified transition-Cherenkov THz emission: (a) D =15 mm, (b) D = 60 mm. The transition-Cherenkov emission without the external electric field is multiplied by a factor of 200 for visibility. Note that (a) and (b) are not in the same scale.

Figure 3. Intensity of the amplified transition-Cherenkov THz radiation as a function of the external electric field. The inset presents another independent measurement for small electric fields. The solid lines denote a quadratic fit.

lens

THz

θ

α

V

Z

*waveguide
of the THz detector*

(a)

THz intensity (a.u.)

110
0   180
110

90
270
0

10kV/cm
5kV/cm
200*Cherenkov

(b)

THz intensity (a.u.)

65
0   180
65

90
270
0