

## Conical Forward THz Emission from Femtosecond-Laser-Beam Filamentation in Air

C. D'Amico, A. Houard, M. Franco, B. Prade, and A. Mysyrowicz\*

*Laboratoire d'Optique Appliquée, ENSTA, Ecole Polytechnique, CNRS UMR 7639, Palaiseau, 91761 France*

A. Couairon

*Centre de Physique Théorique, CNRS, Ecole Polytechnique, F-91128 Palaiseau, France*

V. T. Tikhonchuk

*Centre Lasers Intenses et Applications, Université Bordeaux I, CEA, CNRS, UMR 5107, Talence, 33405 France*

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We attribute a strong forward directed THz emission from femtosecond laser filaments in air to a transition-Cherenkov emission from the plasma space charge moving behind the ionization front at light velocity. Distant targets can be easily irradiated by this new source of THz radiation.

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For a long time, the THz region ( $10^{11}$ – $10^{13}$  Hz, wavelengths from 30  $\mu\text{m}$  to 3 mm) has remained the last unexplored bastion between visible and long wavelength electromagnetic radiation, due to the lack of efficient emitters and receptors. However, this situation changed dramatically during the last decade, and THz radiation rapidly became an important research tool for atoms, molecules, semiconductors, high-temperature superconductors, biomedical tissues, organic chemical materials, cellular structures, etc. Numerous applications of THz radiation have been proposed in areas such as biomedical diagnostics, tomographic imaging, security screening, and chemical identification [1].

Most of the advances are tied to the use of nonlinear optical techniques to produce THz radiation. So far, the most established nonlinear technique has been optical field rectification, which achieves frequency down conversion of laser pulses [2]. The optical rectification of a femtosecond pulse (duration  $\sim 100$  fs) leads to a coherent pulse in the desired frequency range, since the Fourier transform of the rectified pulse envelope yields a carrier frequency  $\delta\nu \approx 1/\delta\tau \approx 10^{13}$  Hz. Optical rectification was achieved first via the second order polarizability  $P_i(\omega) = \chi_{ijk}^{(2)}(\omega, \omega + \omega', -\omega')E_j(\omega + \omega')E_k^*(\omega')$  induced in a nonlinear medium lacking inversion symmetry, where  $\omega$  and  $\omega'$  are the THz and optical frequencies, respectively. ZnTe has proved to be a particularly suitable material because of its good transparency window in the THz region and because of the accidental phase matching between the phase velocities of THz radiation and 800 nm, the central wavelength of femtosecond laser pulses based on the well developed Ti:sapphire technology.

Optical rectification has also been achieved via a third order nonlinear process. By mixing two femtosecond laser pulses at frequencies  $\omega$  and  $2\omega$  with a proper phase relation, the inversion symmetry of the medium seen by the total field is effectively broken and optical rectification of

the pulse envelope becomes possible even in a centrosymmetric Kerr medium [3]. This technique, described by the third order nonlinear susceptibility  $\chi_{ijkl}^{(3)}(\omega, 2\omega' + \omega, -\omega', -\omega')$ , is particularly attractive because normal air or other common gases can be used as a rectifying medium. Very recently, THz production in air via a third order optical rectification process was shown to be strongly enhanced by the presence of a plasma generated by one of the incident laser pulses [4]. THz signals with field strength greater than 400 kV/cm have been reported in air [5]. Still, the production of THz radiation by optical rectification in air remains a difficult task requiring precise alignments. Another major challenge to overcome before the THz frequency domain becomes widely used for applications is the transfer of THz radiation over long distances  $l \gg 1$  m. The peak intensity of short THz pulses is attenuating rapidly during propagation because of air group velocity dispersion, beam diffraction, and absorption by water vapor. Most THz experiments so far are performed over small distances in the laboratory under controlled air conditions to avoid humidity.

In this Letter, we report generation of THz emission in air by a mechanism different from optical rectification, which offers the advantage of extreme simplicity. This emission is in the form of a strongly collimated THz beam in the forward direction, which we attribute to a combined transition-Cherenkov radiation generated by the space charge created behind the ionization front and moving in the wake of the laser pulse at light velocity. It uses normal air as the generation medium and requires a single femtosecond laser beam without precise alignment procedure. More importantly, the THz source can be easily positioned in the vicinity of a distant target, possibly kilometers away, thereby solving the problem of transporting THz radiation in air. In terms of effective irradiance of a distant target, this new THz source surpasses other THz sources by orders of magnitude. We have developed a

theoretical model which reproduces well the observed characteristics of the THz emission. It calculates the long wavelength radiation emitted by a dipole source moving with the light velocity in the wake of the intense femto-second pulse. The dipolelike charge distribution which is oriented along the propagation axis results from a combination of the ionization process and the ponderomotive force induced by the incident laser pulse.

The key feature is filamentation of fs laser pulses in air [6]. Femtosecond filamentation occurs spontaneously when a short intense laser pulse is launched through a transparent medium with a power above a critical value  $P_{\text{cr}} = 3.72\lambda^2/8\pi n_0 n_2$ , where  $n_0$  and  $n_2$  are, respectively, the refractive index and optical Kerr constant at the laser frequency. In air, the threshold power  $P_{\text{cr}} \approx 5$  GW is easily achieved by commercially available low repetition rate Ti:sapphire lasers. Filaments are the product of a dynamic competition between several linear and nonlinear effects. For our purpose, the most important nonlinear effects are the optical Kerr effect, which tends to focus the intense beam upon itself, and the plasma defocusing action, which happens whenever the laser intensity on axis has increased sufficiently for the multiphoton ionization of air molecules to occur. In the zone of nonlinear interaction, this competition leads to a high peak intensity and a small average beam diameter  $d \sim 100 \mu\text{m}$  over a long distance when compared to the Rayleigh (diffraction) length of  $\sim 4$  cm at the wavelength of 800 nm. For this reason, the propagating pulse is often called a self-guided pulse. Filaments on a large scale are remarkably robust and largely insensitive to initial laser conditions, provided a smooth focusing geometry (focal length  $> 1$  m) is achieved. The “self-guided” pulse leaves in its wake a long thin plasma column with an initial electron density  $n_e$  of the order of  $10^{16} \text{ cm}^{-3}$ . This plasma wake is generated over a typical distance of 1 m for an input laser power slightly above the critical power. It can reach hundreds of meters at higher input powers.

It has been pointed out [7] that the plasma strings formed during filamentation should emit THz radiation in a direction perpendicular to the filament axis, because the radiation pressure excites longitudinal plasma oscillations at the plasma frequency  $\omega_{\text{pe}} = \sqrt{n_e e^2 / m_e \epsilon_0} = 10^{13} \text{ rad s}^{-1}$ . Radial THz emission has been observed experimentally [8]. Its origin has been recently reinterpreted by Sprangle *et al.* [9] as being due to the ponderomotive force of the laser pulse rather than the radiation pressure. The peak amplitude of the radial THz field is estimated to be of the order of 5 kV/cm [9]. The nature of the THz emission we report here is different. Instead of being emitted radially, it is confined to a very narrow cone in the forward direction (see the right side of Fig. 1). We have compared the forward and radial emission from filaments at a distance of 5 cm from the middle section of the filament source and found the former to be more intense by more than 2 orders

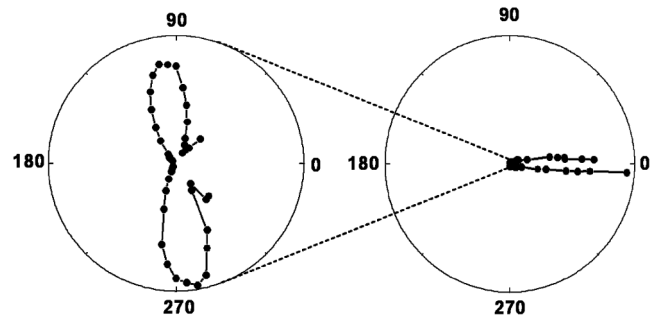


FIG. 1. Comparison between the radial (left side) and forward (right side) THz emission from a filament. Detection of the radial emission requires a reduction by 1 order of magnitude of the distance between filament and detector.

of magnitude, as shown in Fig. 1. Furthermore, the forward THz radiation displays unusual polarization properties, which are incompatible with third order optical rectification in air.

The experimental setup is shown in Fig. 2. The laser is a Ti:sapphire chirped pulse amplification system operating at 10 Hz and delivering pulses of 150 fs duration. In the experiment, the central part of the beam is selected by means of a 5 mm diameter diaphragm, yielding an energy of 4 mJ per pulse. A single filament is created by focusing the laser pulses in air with a 2 m focal lens. We detect one spectral component of the broadband THz radiation emitted by the plasma filament by means of a heterodyne detector operating either at 91 or 110 GHz. The radiation diagram of the THz emission is obtained by rotating the detector around a point on the filament axis (see Fig. 2). To measure the polarization properties of the THz forward emission, we use a linear polarizer consisting of a specially designed metallic grid in front of the heterodyne detection system which itself acts as a linear polarizer. By rotating this grid polarizer we measured the amplitude of the signal as a function of the grid polarization angle [see Fig. 3(a)]. The THz forward emission yields a squared Malus law, indicating that the signal has a linear polarization. The direction of this polarization is independent of the laser

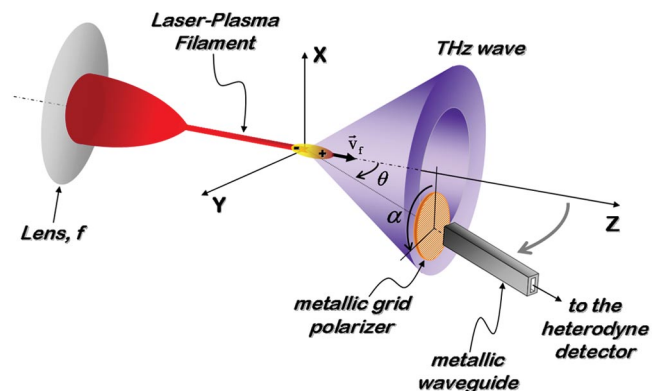


FIG. 2 (color). Experimental setup (schematic).

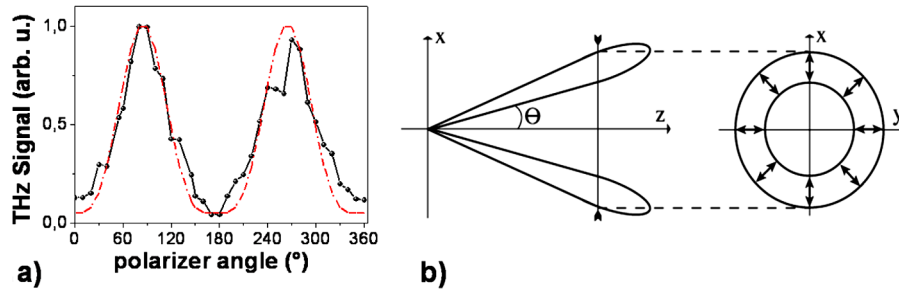


FIG. 3 (color online). Polarization of the THz forward emission measured at  $\theta = 10^\circ$  with a focal lens of 75 cm, obtained by rotating a grid linear polarizer in front of the heterodyne detector. The heterodyne detector itself acts also as a linear polarizer. The THz emission yields a squared Malus Law:  $I \propto \sin^4(\theta)$  (dotted line), indicating that the polarization of the THz signal is perpendicular to the emission cone surface. (b) Recapitulates the polarization diagram of the THz emission.

polarization. It lies in the plane defined by the laser axis  $z$  and the detection axis. The polarization properties of the THz radiation are summarized in Fig. 3(b). In Fig. 4, we show the THz radiation diagram measured for different laser focusing distances. One notices a larger opening of the radiation cone with a smaller focal distance. A narrow forward collimated THz beam is obtained with the focal lengths larger than 1 m, when the plasma channel is maintained over a length of a few tens of a centimeter.

In view of its polarization properties, the THz emission cannot be assigned to a mechanism implying the oscillation of a free electron cloud driven by the linearly polarized electric field of the laser, since one would expect the

electric vector of the THz radiation to depend on the laser polarization vector. One can therefore exclude the mechanism based on the optical rectification via a four-wave or higher order mixing process. We attribute the origin of the THz radiation to a combined “transition-Cherenkov” emission by a dipolelike electric charge oriented along the propagation axis, and moving at the light velocity behind the self-guided laser pulse in the medium. During filamentation, the laser ponderomotive force creates a dipolelike charge separation behind the ionization front [10]. This is due to the fact that the plasma formed during filamentation is weakly ionized but remains strongly collisional. According to the estimates of Ref. [9], the electron-

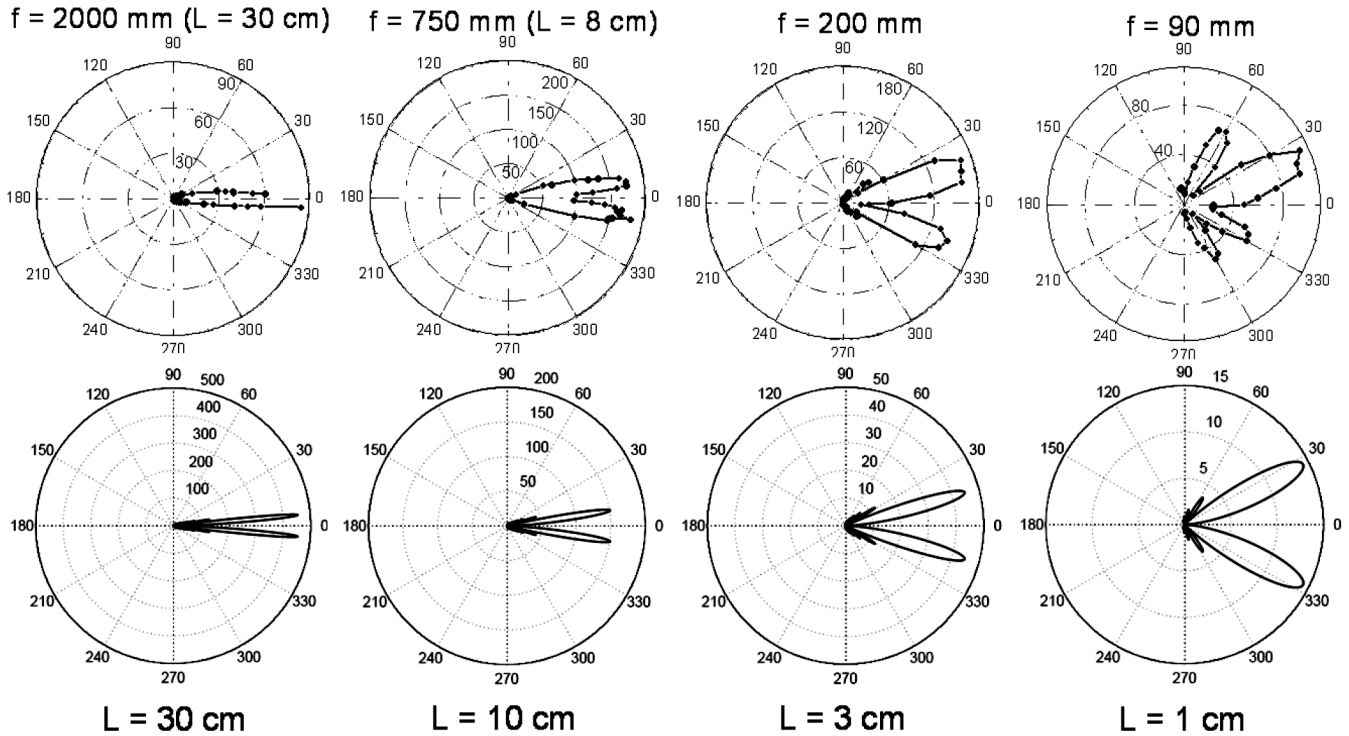


FIG. 4. Emission diagrams  $I(\theta)$  for the THz signal obtained with different focal lengths for the laser. Upper curves: experimental results. Lower curves: calculations. The filament plasma length  $L$  ( $f = 2000$  and  $f = 750$  mm) is obtained from direct measurement. Simulations yield similar values. Relative THz intensities are indicated for each diagram.

atom collision time at ambient air pressure is on the order of 0.1–0.2 ps, which is shorter than the plasma wave period. Therefore the wake field contains effectively 1–2 oscillations and looks like an electric dipole moving with the laser pulse. The dipole length  $l$  is of the order of the plasma wave damping length ( $\sim 30\text{--}100\ \mu\text{m}$ ), which is shorter than the emission wavelength,  $\lambda \approx 3\ \text{mm}$ . Because of this, the emission efficiency is smaller than the common Cherenkov emission by the factor  $(l/\lambda)^2$ .

Another important difference from the common Cherenkov emission is the fact that in our case, the emitting charges are moving with the laser pulse at the light velocity  $c$  in a medium where the refractive index  $N(\omega)$  is very close to 1. This reduces the emission efficiency, but does not suppress it completely, if one takes into account the finite length of the emission. In this respect, the mechanism of THz emission holds also some features of transition—radiation [11]. According to a recent analysis of the Cherenkov emission of electrons [12], the emitted THz field intensity is proportional to the logarithm of the medium length  $L$ , in the case of a charge moving at the light velocity in the medium, whereas it is proportional to  $L$  in the case of the common Cherenkov emission. An analysis similar to that of Ref. [12], for the wake field created by the laser pulse provides the spectral intensity of the electromagnetic emission at the frequency  $\omega$  and at the angle  $\theta$  with respect to the laser propagation axis, which reads as

$$\frac{d^2W}{d\omega d\Omega} = \frac{r_e E_l^2 \omega^2 \nu_e^2}{16\pi^2 m_e c^3 \omega_0^4 \theta^2} \sin^2(\omega L \theta^2 / 4c). \quad (1)$$

Here,  $r_e$  and  $m_e$  are the electron classical radius and mass,  $\nu_e$  is the electron collision frequency,  $E_l$  is the laser pulse energy, and  $\omega_0$  is the laser frequency. Note that the emission efficiency depends on the length of the plasma filament and on the square of the laser energy. It is also broadband since it is limited by the plasma frequency and the frequency of electron collisions to a few THz bandwidth.

The angular emission patterns for a THz field wavelength of 3 mm calculated from Eq. (1) are shown in Fig. 4 (bottom) for different medium lengths  $0.3\ \text{cm} < L < 30\ \text{cm}$ . The characteristic angle of the most intense lobe depends on  $L$  as  $\theta_{\max} = \sqrt{\lambda/L}$ . The adopted values of  $L$  correspond to the measured or calculated plasma length achieved during filamentation for the corresponding focusing geometries, as shown at the top of Fig. 4.

To test the potential of this forward THz conical emission to reach high intensities on distant targets, we have also measured the THz emission from filaments generated with the Teramobile laser [13]. In this case, the input laser power (2 TW) largely exceeds the critical power for fila-

mentation ( $\sim 5\ \text{GW}$ ). As a consequence, a bundle of approximately 40 filaments with the same energy was produced at a distance of 30 m from the laser. A THz signal in the forward direction was detected at this distance with an intensity increased by a factor 40 when compared to the single filament. This is in agreement with the proposed interpretation, as the spectral intensity of the THz emission is proportional to the sum of the filaments energy. With the Teramobile laser, we have demonstrated that the distance where filamentation occurs can be varied over several hundreds of meters by introducing a chirp to precompensate the group velocity dispersion in air [14]. Therefore, the THz source can be easily moved close to a remote target. By steering the laser beam one can achieve the THz mapping of the remote object. Filament generated THz radiation could thus find applications in biomedical imaging [1].

In conclusion, the space charge generated in the wake of the laser pulse undergoing filamentation produces an electromagnetic emission in the THz domain, which is interpreted as a transition-Cherenkov-type radiation. This is a robust phenomenon, which may find various applications due to its simplicity and flexibility.

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\*Electronic address: andre.mysyrowicz@ensta.fr

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