Terahertz Radiation Source in Air Based on Bifilamentation of Femtosecond Laser Pulses

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New THz source in air based on bi-filamentation

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A new terahertz source in air based on the bi-filamentation of femtosecond laser pulses is reported. This THz radiation is one order of magnitude more intense than the transition-Cherenkov THz emission from femtosecond laser filaments reported recently and shows different angular and polarization properties. We attribute it to the emission from a bimodal transmission line created by two plasma filaments.

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THz spectroscopy is rapidly emerging as a new domain with rich implications in both fundamental and applied sciences. However, up to now a major obstacle for its use has been the strong attenuation (100 dB/km) that THz radiation experiences while propagating in air, due to the presence of water vapor. Recently, a method of generating THz was demonstrated which provides a solution to this problem [1]. It was shown that a femtosecond laser pulse undergoing filamentation emits a strong THz pulse confined in a narrow cone oriented along the forward direction. By simple manipulation on the laser pulse undergoing filamentation, it is possible to place the filament formation, hence the THz radiation source, in the immediate proximity of a remote sample. Therefore in terms of effective irradiance at long distance, this method easily surpasses other known THz sources in spite of the fact the overall efficiency of the transition-Cherenkov emission is relatively low. A first demonstration showed the production of THz at a distance of 30 meters from the laser. Another advantage of this method is its extreme simplicity: filamentation being a self-action does not require any precise alignment.

The physical origin of the THz radiation was attributed to a transition-Cherenkov emission process from the electron current pulse propagating in the wake of laser pulse along the plasma filament. A short laser pulse undergoing filamentation forms a plasma channel in its wake due to the interplay between the Kerr-like focusing in air and defocusing on plasma electrons. The generated plasma is weakly ionized (typically, about 0.1% of the oxygen molecules in air are ionized) yet it is strongly collisional, since the gas pressure is atmospheric. The ponderomotive force of the laser pulse produces in plasma an electron current oscillating at a frequency around 1

THz (the density of free electrons produced by filamentation is ~ 3×10^{16} cm^{-3}). These longitudinal plasma oscillations are strongly damped (relaxation time ~ 300 fs). Therefore, this current pulse can be assimilated to a dipole oriented along the propagation axis and moving at the speed of light. For a finite length of filament, the moving dipole emits a radially polarized, broadband electromagnetic radiation due to the Cherenkov-like effect in a cone of the aperture determined by the ratio of the filament length to the emission wavelength. Excellent agreement is found between the measured radiation pattern at around 100 GHz and the predictions from the theoretical model.

In this letter we present new results where a similar forward oriented THz emission is produced in air. However its physical origin is different, which is manifested in higher intensity and different angular distribution and polarization. It is obtained by sending a sequence of two femtosecond IR laser pulses separated by less than 5 ns, forming two overlapping filaments in air. The first and second pulses individually produce the transition-Cherenkov THz emission described above. However, surprisingly, the magnitude of the THz radiation from the double pulse is larger by more than one order of magnitude (see Fig. 1). The radiation pattern is also different: the maximum of radiation intensity is on the propagation axis (see Fig. 2), and its polarization is strictly linear, instead of being radially polarized. However, the polarization direction does not depend upon the polarization directions of either laser pulses.

The laser used in our experiments was the Teramobile system, which provides 150-fs pulse at 790 nm with as much as 300 mJ of energy per pulse [2], or a 100 Hz Ti : Sapphire laser delivering 50 fs pulses at 800 nm with a maximum energy of 15 mJ per pulse. In the experiments, the output femtosecond pulse was split into two pulses by a Mach-Zehnder interferometer so that the time delay between the two pulses could be continuously adjusted. After the interferometer, the collinearly propagating pulses were focused by the same convex lens to form two spatially overlapping filaments. (see inset in Fig. 1). The filament length depends on the focusing conditions. It was varied from 5 to 50 cm in the present experiment.

The forward THz radiation was reflected by a centrally pierced metallic mirror positioned at the end of filament. The mirror collected the THz radiation while transmitting the filament core through the central hole with a diameter of 1 cm. The reflected THz radiation was focused by a Teflon lens and detected with a heterodyne detector, which is sensitive to the 91 GHz frequency component. In this way, the entire forward THz radiation at this wavelength was collected except the leakage of the THz though the hole on the mirror center.

The amplitude of the THz signal obtained with the pulse sequence is shown in Fig. 1 as a function of the time delay between the two IR pulses in the case of focal length f = 2m. The THz signals produced individually by each of the two pulses are also shown. With both pulses, an enhancement of the THz radiation by more than one order of magnitude is observed for time delays shorter than 1 ns. With larger time delays, the enhanced THz emission decreases gradually, and it becomes equal to the sum of the individual THz signals for delays exceeding 4.6 ns.

To measure the angular pattern of the emission, the pierced mirror was removed and a waveguide for the THz radiation was used instead of the Teflon lens [1]. The angular distribution of this THz emission was measured by rotating the detector in the horizontal plane around a point on the filament axis. In Fig. 2, the THz radiation patterns from single and double IR pulse filaments are presented. We notice that the maximum radiation intensity obtained with two pulses lies along the propagation axis, in contrast to the single pulse case.

We also measured the polarization properties of this new THz emission. Inside the THz detector, a rectangular waveguide acts as a linear polarizer. Correspondingly, the polarization of the THz wave can be measured by rotating the detector around its axis. The THz signal yields a Malus' law, which indicates that the THz radiation is linearly polarized. The polarization direction of the THz radiation was found to be independent on the polarization directions of both IR pulses. However, we observed that the polarization direction changed day by day and was very sensitive to the alignment of the two IR pulses. This feature will be discussed later in detail.

These three observations indicate that the physical origin of the THz radiation generated by the double pulse is different from the transition-Cherenkov mechanism. We have explored several possibilities to elucidate its origin:

1) THz emission from the second IR pulse amplified by the plasma formed by the first pulse

Since the enhancement of THz radiation is observed for time delays of up to a few ns between the two pulses, it obviously points out to a retarded effect connected to the presence of a plasma produced by the first pulse. It is therefore conceivable that the plasma left by the first pulse acts as an amplifying medium for the transition-Cherenkov THz produced by the second pulse. Amplification could be due for instance to a Raman gain or an induced emission from inverted population of excited vibrational-rotational states of air molecules. In order to check this hypothesis, we have repeated the double pulse experiment in a noble gas (Xe) and found a similarly greatly enhanced emission. We can therefore exclude the Raman or inversion mechanisms, which do not occur in a monoatomic gas.

2) THz generation in a stratified plasma

It has been predicted that a short laser pulse propagating in a periodically varying (stratified) plasma can generate electromagnetic radiation in the THz domain [3], if the modulation period is of the order of a few hundred microns. However, such a modulation cannot be created spontaneously in the time between two pulses. The plasma oscillations created by the first pulse are decaying in a time scale less than 1 ps, and they cannot induce any specific large-scale plasma motion. Moreover, the plasma column is expected to be fairly homogeneous along the filament because of the strong clamping effect upon the pulse intensity [4]. Therefore, this undulator effect is not likely at the origin of the THz emission in our experiments.

3) Geometric effect

The fact that the direction of the polarization of the THz signal is sensitive to the alignment of the interferometer generating the two laser pulses gave us a clue to the origin of the THz emission. Namely that it should correspond to the geometry of two plasma filaments. To verify this hypothesis, we have done the following experiments. First, we have produced two perfectly collinear laser pulses. This was done by manipulating the optical spectrum inside the compressor of the CPA laser system, such that two exactly collinear pulses separated by 80 fs are produced at the output as a single beam. With such a sequence of two pulses, two perfectly overlapping plasma columns are produced but no nonlinear enhancement of the THz generation was observed. Second, resorting again to the Mach-Zehnder interferometer, we have analyzed more closely the superposition pattern of the filament tracks produced by both pulses. This was performed by introducing a glass plate in the middle part of the laser filament and examining *post mortem* the produced permanent damage. We observed an elongated damage pattern corresponding to two partially overlapping filaments. The elongated axis of the pattern was always aligned along the THz polarization direction. Two typical results are shown in Fig. 3. The distance between the centers of two filaments is of the order of 100 μm.

Having identified the crucial parameter in the experiment, we now discuss the physical origin and characteristics of the enhanced forward directed THz emission. In the case of a single pulse the amplitude of the plasma wave excited by the ponderomotive force of a short laser pulse ($\omega_{pe}\tau_L < \pi$) can be estimated as $E_p \simeq \omega_{pe}^2 U_p \tau_L / ec$, where ω_{pe} is the plasma frequency, U_p is the laser pulse ponderomotive potential, and τ_L is the laser pulse duration. This current has only the axial component since the plasma filament is axially symmetric and is independent upon the laser pulse polarization. It has a length of the order of the damping length $c / \nu_e \simeq 100\ \mu m$, where ν_e is the electron collision frequency, and it propagates with the light velocity c along the filament of length l. Such a current cannot generate an electromagnetic emission exactly in the axial direction. The optimum emission angle depends on the ratio of the radiation wavelength λ to the filament length: $\theta \simeq \sqrt{\lambda / l}$.

Things look different in the case of two pulses. The first plasma filament stays intact (the plasma recombination time is a few ns), and another filament is created by the second laser pulse beside it. This arrangement of two parallel plasma columns can be assimilated to a transmission line, which supports two types of waves: the longitudinal plasma wave, propagating in each wire independently, and an electromagnetic TM mode with the electric field in the plane of the two wires (the components E_x and E_z) and the magnetic field directed perpendicular to this plane (the component B_y). This mode propagates with the light velocity and the coupling between the wires is achieved by the mutual conductance C and inductance L (par unit length of the line). In our case the current I, created by the laser pulse ponderomotive force in the second filament, induces the tension V between the wires according to the Faraday law, $\partial V / \partial z = -L \partial I / \partial t$. This tension is related to the linear density of electric charge, $Q = CV$. Moreover, the charge conservation implies the continuity equation, $\partial Q / \partial t = -\partial I / \partial z$. Combining these two equations one finds the telegrapher's equation:

$$\frac{\partial^2 V}{\partial t^2} = \frac{1}{CL} \frac{\partial^2 V}{\partial z^2}.$$

It is well-known in electrodynamics (see, for example, [5]) that the product $CL = 1/c^2$ for any transmission line, and $L = (\mu_0 / 4\pi)\left[1 + 4\ln(d/a)\right]$, where d is the distance between the wires and a is the wire radius. This equation describes an electromagnetic pulse propagating with the light velocity along the line. Having in mind that the electric current is driven by the laser pulse ponderomotive force, $I \simeq \varepsilon_0 \omega E_p \pi a^2$, the estimate for the tension amplitude reads: $V \simeq cLI \simeq a^2 E_p \omega / c$.

This wave is, however, confined within the line, because the main electric current is propagating in the axial direction. To explain the axially directed electromagnetic emission one has to account for the perpendicular current between the wires, $j_x \simeq \sigma V / d$, where $\sigma = e^2 n_e / m_e(\nu_e - i\omega)$ is the plasma conductivity. This current exists only if the filaments are not completely separated and there is some plasma between them, that is, $d \sim a$.

Having these estimates in hand, one can easily describe the general characteristics of the electromagnetic emission from the bi-filament. First, it is confined within a cone of angle $\theta \simeq \sqrt{\lambda / l}$ with the maximum along the laser beam propagation direction. In contrast to the emission of a longitudinal current from a single filament, which is proportional to $\ln(l/\lambda)$, the emission intensity from a pair of filaments is linearly proportional to the length l[6]. For the parameters of experiment (l = 20 cm and λ = 3 mm) it gives a factor of ten for the intensity enhancement. Second, the polarization is linear, lying in the plane of plasma filaments. The spectrum attains its maximum at the plasma frequency (~ 1 THz) and it extends towards longer wavelengths decreasing as $1/\lambda^2$. The maximum delay between two laser pulses is explained by the lifetime of the first plasma filament. The recombination time is of the order of 3 – 4 ns in air. Finally, the total emitted energy depends on the filament lengths and dimensions. The maximum energy which can be emitted, is limited by the total energy of the plasma wave: $W_{\max} \simeq \varepsilon_0 E_p^2 a^2 l$. It increases as the square of laser pulse intensity and duration.

In conclusion, we observed a new THz radiation based on bi-filamentation of two femtosecond pulses in air. This THz radiation is found to be one order of magnitude more intense than our recently reported transition-Cherenkov THz radiation from the plasma filaments. Moreover, this THz wave is radiated in a small angle confined in the direction of the laser propagation and it is linearly polarized. We confirmed that the polarization plane of the THz was determined by the relative position of the two filaments, which actually provides an extremely simple method to control the THz polarization. The physical origin and the basic characteristics of the process are explained with a simple model of a transmission line formed by a pair of neighbouring plasma filaments. Like the transition-Cherenkov mechanism of the THz emission from laser-created filaments, it is a simple and flexible method of generation of electromagnetic radiation in the THz domain to illuminate a remote target. This new THz source should be beneficial for applications such as the THz tomography.

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FIGURE CAPTIONS

Fig. 1. Amplitude of the THz signal as a function of the time delay between the two IR pulses. The signal generated by the first and the second pulse individually is also shown. The grey, white, and black bars denote the THz signal produced by the pulse sequence, the first pulse, and the second pulse, respectively. Inset: the schematic setup of the experiments, L: convex lens, D: heterodyne terahertz detector, M: metallic mirror with a 1-cm-hole on the center.

Fig. 2. (a): angular distribution of THz radiation from single IR pulse filament , (b): angular distribution of the THz from the bi-filamentation. Both figures are not to the same scale.

Fig. 3. THz polarization and damage pattern of the bi-filament on a glass plate. The solid line in (a) and (b) are fitted by Malus' law.

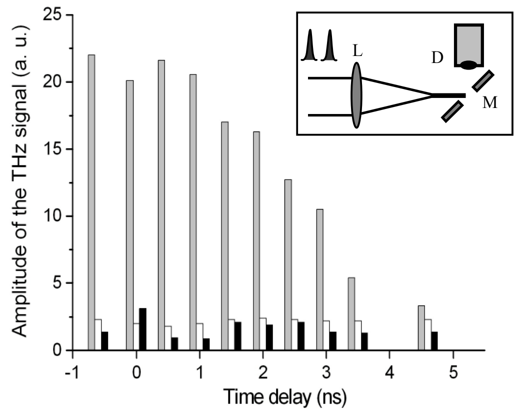
Amplitude of the THz signal (a. u.)
Time delay (ns)
25
20
15
10
5
0
-1
0
1
2
3
4
5
L
D
M

FIG. 1

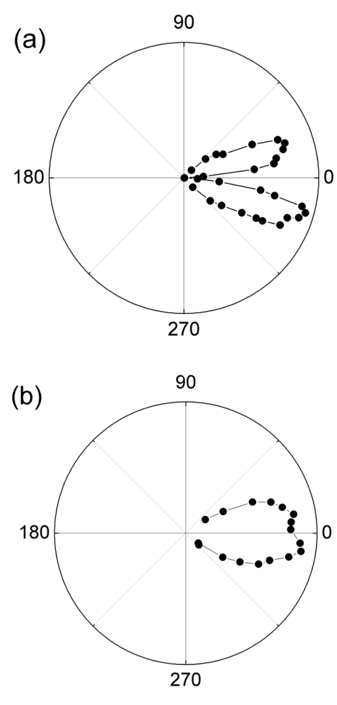
(a)
90
180
0
270
(b)
90
180
0
270

FIG. 2

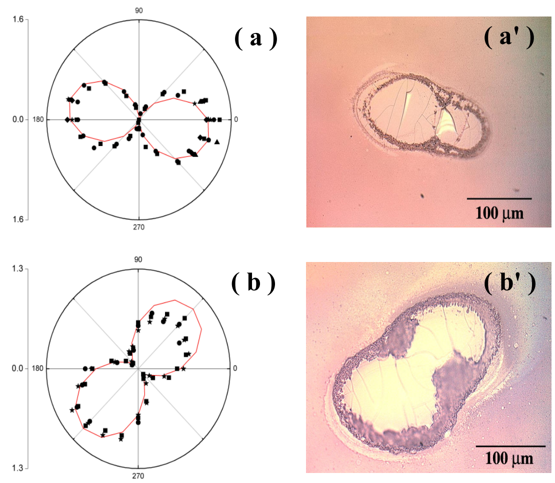

FIG. 3