Terahertz pulse emission optimization from tailored femtosecond laser pulse filamentation in air

J.-M. Manceau,[1] A. Averchi,[2,5] F. Bonaretti,[2,5] D. Faccio,[2,5] P. Di Trapani,[2,3,5] A. Couairon,[4,5] and S. Tzortzakis[1,*]

[1]*Institute of Electronic Structure and Laser (IESL), Foundation for Research and Technology (FORTH)—Hellas, P.O. Box 1527, 71110 Heraklion, Greece*

[2]*Department of Physics and Mathematics and CNISM, University of Insubria, Via Valleggio 11, IT-22100 Como, Italy*

[3]*Department of Quantum Electronics, Vilnius University, Sauletekio Avenue 9, Building 3, LT-10222 Vilnius, Lithuania*

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

[5]*Virtual Institute for Nonlinear Optics, Centro di Cultura Scientifica Alessandro Volta, Villa Olmo, Via Simone Cantoni 1, 22100 Como, Italy*

**Corresponding author: stzortz@iesl.forth.gr*

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We study the generation of intense terahertz pulses produced by two-color laser pulse filamentation in air. We tailor the filamentation process and the produced plasma strings and study how the generated terahertz field is modified. An important terahertz pulse shortening is found for plasma strings with uniform electron density. © 2009 Optical Society of America

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Emission of broadband and intense terahertz radiation pulses from two-color femtosecond laser filament induced plasma strings in gases is lately becoming a technique of great interest [1]. This can easily be understood as it is, with tilted-pulse-front optical rectification in stochiometric $LiNbO_3$ (LN) crystals [2], and difference-frequency mixing of parametrically amplified femtosecond pulses [3], the technique producing the most powerful terahertz pulses on tabletop systems, with energies reaching the regime of microjoules per pulse.

The increase in the terahertz pulse peak power as well as its temporal shaping is a subject of intense study in view of promising applications in nonlinear terahertz optics. For instance, coherent emission of terahertz radiation from an n-type GaAs layer pumped by intense terahertz pulses has been demonstrated [4]. A series of nonlinear effects, including polariton harmonic generation in LN [2], as well as a terahertz-induced Pockels effect in an electro-optic crystal, has been reported [5]. Moreover, a recent study on terahertz pulse shaping showed the possibility to create single and mutlicycle terahertz pulses, which consequently offers the possibility to shape the spectral profile [6].

In this Letter we demonstrate the possibility of optimizing the emitted terahertz radiation by tailoring the spatial distribution of the electron density in the plasma string generated by the filament. We show a considerable terahertz pulse shortening when the plasma string is tailored to a uniform density profile. This advancement is of fundamental importance for numerous applications where pulse control is needed, as well as for adjusting the spectral extent of the terahertz radiation.

Ultrashort laser pulse filamentation is a well-known phenomenon of laser beam self-organization in a narrow intense filamentary structure extending over very long distances, significantly longer than the characteristic Rayleigh length [7]. In the filaments' core, high intensities are achieved and a plasma string is generated along their paths. Owing to the high intensities and the long paths highly, efficient nonlinear wave mixing and plasma processes have been demonstrated and reported in the literature (see, for instance, [8,9]). The plasma wake behind light filaments in air was also shown as a potential source for terahertz radiation [10]. While it is well known that terahertz emission from plasma depends on the plasma density [11], and although in most experimental situations the highly dynamical nature of the filamentation process leads to a nonuniform plasma distribution with strong gradients along the propagation path [7], until today there are no reports on the effect that the plasma density distribution has on the emitted terahertz radiation.

Here, we report measurements of the dependence of the terahertz radiation emitted from a filament upon the on-axis distribution of the plasma string. To tailor the plasma string and control its uniformity and length, we appropriately adjust the input laser beam wavefront. Astigmatism and other wavefront distortions have been proven an efficient tool for gaining partial control of the filamentation process. For instance, it has been used for the suppression of multifilamentation and filamentation stabilizations [12].

For the experiments reported here an amplified kilohertz Ti:sapphire laser system delivering 35 fs pulses at 800 nm central wavelength and a maximum energy of 2 mJ per pulse was used. The laser beam profile was Gaussian with a diameter (FWHM) of 6.6 mm. Part of the initial laser beam with energy equal to 1.3 mJ was focused, as will be described below, in ambient air after partial frequency doubling in a β-BBO crystal (50 μm thick) to produce a two-color filament and subsequently terahertz radiation [1].

For the specific needs of the present study, we create filaments in air using a converging lens (f =200 mm) coupled, in most cases, with an axicon (apex angle of 178°) placed 130 mm after the first lens, while the BBO crystal is placed ~3.5 cm from the focus. The wavefront control is then achieved by tilting one or both optical elements in a combined way. A plethora of combinations is possible, and practically the obtained plasma string profiles can be tuned across a wide range. Typical experimental results are shown in Fig. 1, which presents images of the plasma string fluorescence, obtained with a conventional photographic camera.

To obtain quantitative information about these plasma strings, we employ a simple electric conductivity technique [13] calibrated using a precise, but more complex, holographic method [14]. The electron plasma density distributions for the cases of strong gradient and uniform plasmas are shown in Fig. 2. In our experiments, the strong gradient plasma string is obtained with the plano–convex lens, without the axicon, oriented perpendicular to the input laser beam, while for the uniform plasma string both lenses (plano–convex and axicon) were used and tilted at about 10° each from their initial positions in the same direction.

The emitted terahertz radiation was measured for a wide range of plasma string profiles, like the ones shown in Fig. 1. For this purpose a standard electro-optic detection scheme was employed [15] using a GaP electro-optic crystal (100 μm thick). The emitted terahertz pulses from the filament plasma strings are propagated inside a purge gas chamber, to avoid water vapor absorption of the radiation, until they reached the detection crystal. At the same time a small fraction of the initial laser pulse probed the terahertz-induced birefringence of the electro-optic crystal and monitored the time profile of the terahertz electric field. The GaP crystal offers a useful bandwidth of up to ~7.5 THz, owing to nonlinearity elimination around 7.5 THz [16] and the presence of its first transverse optical (TO) phonon resonance near 11 THz [17].

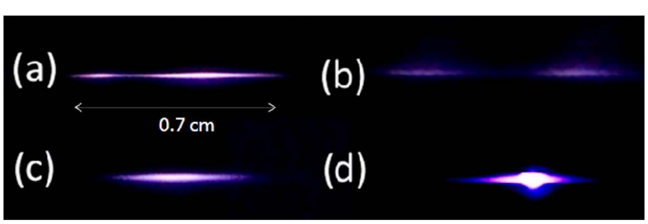

Fig. 1. (Color online) Images of filament plasma string distributions under various experimental conditions (see text for details). (a) Asymmetric and (b) symmetric double peaks; (c) uniform and (d) gradient distributions.

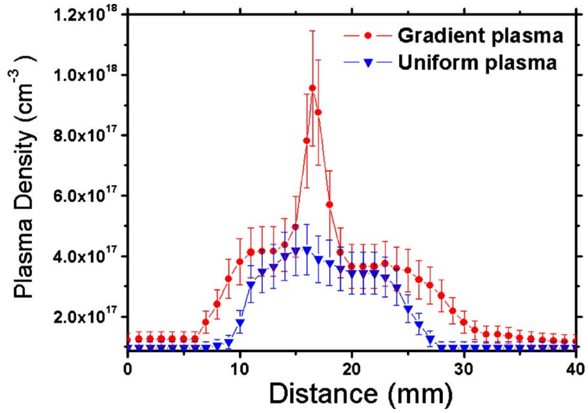

Fig. 2. (Color online) Measured electron density distribution along the laser propagation axis for the case of the uniform density plasma string [Fig. 1(c)] and the one presenting a strong density gradient [Fig. 1(d)].

As we expected the obtained terahertz emission strongly depends on the plasma density distribution. The obtained terahertz fields for the case of the gradient and the uniform strings of Fig. 2 are shown in Fig. 3(a). The terahertz pulse emitted from the uniform plasma string is significantly shorter than the one with the strong gradient plasma string. For the uniform plasma string the emitted terahertz pulse duration was ~250 fs (FWHM), while in the case of the gradient plasma string the corresponding terahertz pulse duration was ~400 fs. Intermediate results were obtained for other plasma string profiles (not shown here). It is worth noting that in all cases the obtained terahertz electric fields were very high, estimated using the electro-optic model described in [18], in the range between 10 and 50 kV/cm.

By Fourier transforming the measured terahertz fields of Fig. 3(a), the corresponding power spectra are obtained as shown in Fig. 3(b). The spectral bandwidth obtained for the uniform plasma string is significantly larger, while the phase (not shown) in both cases was similar.

Finally, we have also measured the terahertz emission pattern, in a comparable way as the one described in [10]. Our findings show that the terahertz emission is on axis with the laser beam and not on a cone as proposed by the transition–Cherenkov model [10]. Several other models were proposed to interpret terahertz generation from two-color laser pulse induced plasmas. The photocurrent point source model attributes terahertz generation to a net ionization current resulting from the asymmetry in the ionizing pulse [1], in good agreement with recent results from

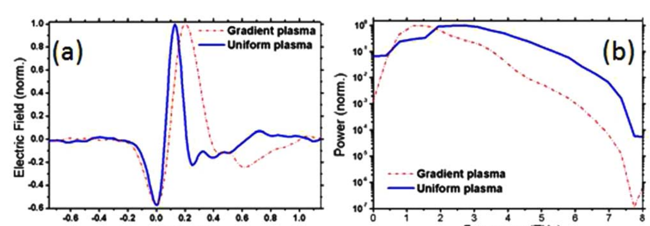

Fig. 3. (Color online) (a) Measured terahertz electric fields and (b) corresponding spectra for the cases of the uniform and the gradient plasma strings of Fig. 2.

particle in cell simulation, which models terahertz emission from an extended longitudinal plasma [19], although it is not so long as a filament.

All the above-mentioned models [1,10,11,19] predict that the squared central frequency of the terahertz emission is directly proportional to the plasma electron density. This seems incompatible with our observations showing that the uniform plasma with the lower density generates higher frequencies than the gradient plasma. However, none of these models considers a strong gradient in the local electron density and a coherent emission from the different parts of a nonuniform plasma string. By focusing a few cycle pulse with an axicon, it was shown [20] that ionization-induced plasma oscillations lead to an optical to a terahertz conversion, which is by far more efficient than that induced by the ponderomotive force [10,21]. The proposed mechanism in [20] is similar to the photocurrent model except that it also accounts for the nonuniformity of the plasma string distribution and shows that a larger spectrum, thus resulting in a shorter pulse, should be emitted from a uniform plasma string compared with the case of a plasma gradient, which explains rather well the results presented in this study.

In conclusion, we provided, to our knowledge, the first demonstration of terahertz pulse optimization using appropriately tailored two-color ultrashort laser filaments in air. Significant terahertz pulse shortening is achieved for uniform plasma strings. These results will prove valuable in applications where tailored terahertz pulses are needed, such as experiments of coherent control or control over motions of molecules and ions, including the control over collective structure and dynamics, as well as electronic responses. The obtained results also bring valuable information for a deeper understanding of the physical processes involved in this coherent emission.

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