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► **To cite this version:**

Alexandre Stathopoulos, Stefan Skupin, Luc Bergé. Effect Of A Deformable Mirror On THz Wave Production By Laser-Created Air Plasmas. International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Aug 2022, Delft, Netherlands. 10.1109/IRMMW-THz50927.2022.9896003 . hal-03771686

HAL Id: hal-03771686

<https://hal.science/hal-03771686v1>

Submitted on 1 Mar 2024

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Effect of a deformable mirror on THz wave production by laser-created air plasmas

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Abstract — We numerically simulate THz pulse generation by air photoionization using 2-color laser pulses whose phase fronts are modified by a deformable mirror (DM). By introducing controlled aberrations at the medium entrance, we investigate manipulations of the spatial structure of the filaments generated in gas cell setups. We find that non-axisymmetric aberrations (astigmatism, coma) tend to decrease the generated THz energy. By contrast, spherical aberrations can significantly increase the THz yield. DM effects on THz conical emission and in long-range filamentation are addressed as well.

I. INTRODUCTION

Optical methods offer promising ways to produce intense THz radiation usable for spectroscopy [1]. THz pulses generated by photoionization of air are usually not limited by laser-solid damage thresholds. Operated with femtosecond laser systems, they provide broadband and intense spectra that can be used over long propagation ranges to perform coherent spectroscopy of various materials.

Efficient THz emitters can be obtained by focusing into air a two-color femtosecond light pulse, composed of fundamental (FH) and second (SH) harmonics, in order to create a plasma spot that acts as a frequency converter [2]. Recent studies [3,4] showed that increasing the number of laser harmonics (or colors) leads to noticeable enhancement in the laser-to-THz conversion efficiency driven by photocurrents. Also, changing the polarization state of the two colors can improve the THz performances of laser-plasma emitters [5]. So far much less studies have been devoted to the modifications of the laser phase fronts and their impact on the plasma structure and related emission of low-frequencies. Applying phase control by using a deformable mirror allows to exploit variable wave front distortions that modify the structure of the laser-plasma interaction zone and thus the performance of the THz source. In the present study, coupled FH and SH fields with 200 TW/cm² laser intensity create an air plasma by tunnel ionization. The laser field induces photocurrents that radiate THz waves depending on the SH/FH energy ratios and their phase offset. Emphasis is put on the THz energy gains reported from comprehensive 3D numerical simulations based on a unidirectional solver that accounts for input phase distortions. These are modelled by Zernike polynomials inducing various smooth surfaces that lead either to spherical focusing of the laser pulse or to different asymmetric aberrational (de)focusing such as coma or astigmatism.

Our propagation code integrates the Unidirectional Pulse Propagation Equation (UPPE) [3] accounting for linear dispersion, diffraction and nonlinear effects such as plasma generation, Kerr effect and plasma losses. Below we explore a gas cell configuration along which an intense laser pulse, fully ionizing dioxygen molecules at the medium entrance, relaxes

onto a cm-long filamentary structure generating THz waves. Astigmatism, coma and spherical aberrations are shown to modify the laser propagation dynamics and the characteristics of the emitting plasma (length, electronic density and shape), which deeply impacts the THz performances and radiation emission angles. Astigmatism and coma introduce asymmetric spatial defects that shorten the plasma by defocusing the laser pulse and lead to less THz production over the relaxation of the beam to a long filament. They also break the symmetry of the radiation. By contrast, spherical aberrations may increase the laser clamping intensity in the plasma zone and hence the THz efficiency increases by a factor of ~ 3 . Spherical aberration also keeps a net symmetrical conical emission. Similar properties are discussed for meter-range filaments coupled to extended tenuous plasma channels.

II. RESULTS

Gas cell simulations were performed for a two-color Gaussian beam undergoing DM distortions at the medium entrance. A fundamental pulse at 1 μm and its second harmonic with 60-fs FWHM duration and 60- μm diameter propagate in air (20% of oxygen molecules). The two colors are linearly polarized with a 20% SH energy ratio.

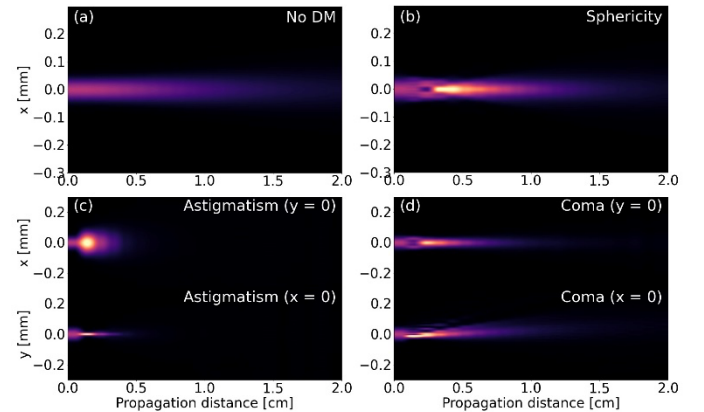


Fig. 1. Simulated laser fluency during linear propagation of 60- μm , 60-fs FWHM, 2-color (FH = 1 μm) laser pulses with (a) no DM effect, (b) spherical aberrations, (c) astigmatism and (d) coma. Sphericity tends to focus the beam symmetrically; astigmatism and coma break the spatial beam symmetry and defocus the pulse after ~ 3 mm. Color maps are identical.

To start with, we first numerically evaluated the beam dynamics under linear propagation affected by the DM, employing a solver integrating the paraxial wave equation in Fourier space. Figure 1 shows the linear propagation of laser fluency in ambient air for a beam intensity less than 1 TW/cm². Here, sphericity symmetrically focuses the beam after ~ 2.5 mm propagation, making it about twice more intense than its counterpart without phase distortions (compare figs. 1a - 1b). Astigmatism and coma also increase the laser fluency between

1.5 to 5 mm, but they defocus the pulse over longer ranges (figs. 1c – 1d). Note how coma aberration deflects part of the beam away from the hot spot, making it less efficient for further photoionization at high intensity.

We now consider plasma generation and subsequent filament formation [3]. With ~ 200 TW/cm² intensity the two-color pulse first fully ionizes air, then relaxes to a characteristic long-range light string clamped with a plasma of 10^{17-18} cm⁻³ electron density. Here, ionization is modelled using the quasi-static tunnel rate.

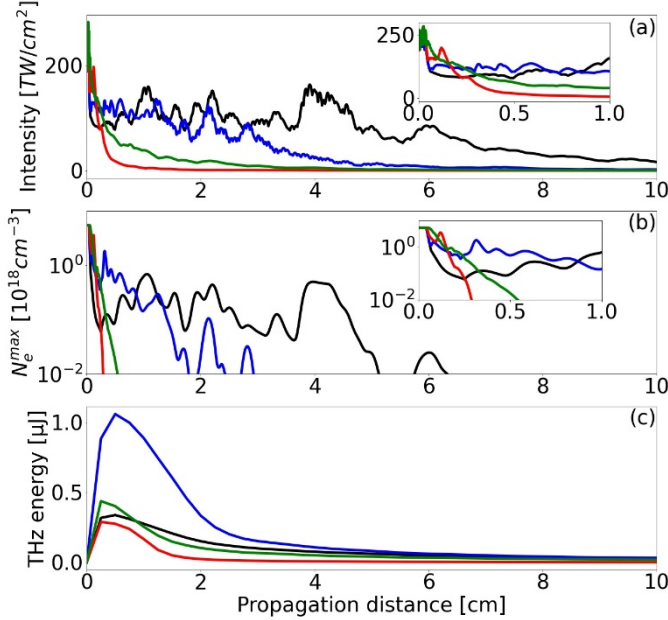


Fig. 2. (a) Maximum laser intensity, (b) maximum electron density and (c) THz energy produced along the propagation axis during the nonlinear propagation of 60- μ m, 60-fs Gaussian pulses using no DM (black), sphericity (blue), astigmatism (red) and coma aberration (green curve). In (a,b) the insets zoom in on the first cm of propagation path. Introducing different phase fronts directly affects O₂ ionization. Sphericity produces ~ 3 times more THz energy than its counterpart without DM. THz energy decreases after a peak due to losses at the boundaries of the spatial window in the simulation.

The presence of both negative (defocusing) and positive (focusing) curvature of different phase-front areas from the beginning of propagation leads to the collision of energy flows emerging from the center and the beam periphery. This causes interference of multidirectional optical waves, which locally enhances the intensity profile. During the first 2 mm of nonlinear propagation all beams affected by a DM phase are more intense and ionize air more than their counterpart without a DM (figs. 2a - 2b). This agrees with the linear patterns of fig. 1 where those three cases present a hot spot around 2 mm, unlike the configuration with no DM. However, following this first focusing stage, the beam intensities and resulting electron densities relax faster with DM-induced asymmetric aberrations. In particular, the electron density drops after ~ 2 mm with astigmatism and coma. This corresponds to the approximate location where the beam center is defocused in figs. 1c – 1d. For comparison, a spherical aberration preserves a higher electron density over ~ 8 mm than with no DM, which justifies the gain by a factor of 3 in THz conversion efficiency observed in fig. 2c.

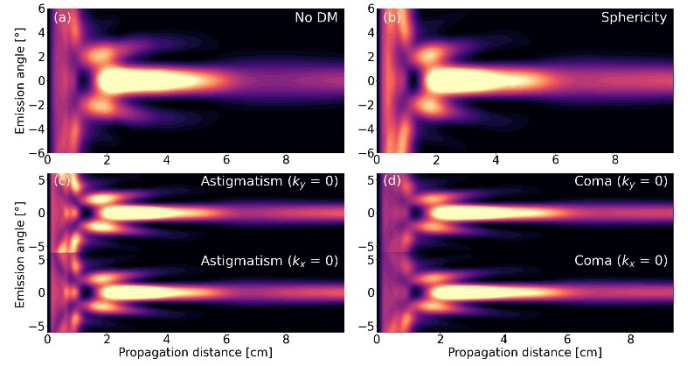


Fig. 3. Far-field THz fluency generated by 60- μ m, 60-fs Gaussian pulses (a) without DM, (b) with sphericity, (c) astigmatism or (d) coma. THz radiation is emitted first along a cone then on-axis in the air.

While the near-field THz fluencies rather follow the main trends of fig. 1 (not shown), an interesting point is to appreciate how different phase fronts may impact the angular far-field emission of THz radiation in air. As can be seen from fig. 3, this radiation is usually a cone. With sphericity, astigmatism and coma, on-axis emission seems more intensively maintained over longer distances (figs. 3b – 3d). However, the DM does not change much the main angular features in THz emission, namely a cone followed by on-axis emission. We shall discuss estimations of those angles using a semi-analytical model inspired from Gorodetsky et al. [6], which can offer new insights about the influence of electron density gradients on THz conical emission.

Another set of simulations was performed with THz wave generation through meter-range filamentation (not shown). Amplitudes of the phase fronts have been chosen to fit the performances of 19-actuators DM in order to reproduce ongoing experiments. We shall report corresponding simulation results for ~ 2 cm broad beams and evidence a more limited impact of the DM on the THz performances.

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