Terahertz Wave Emission from Dual Color Laser-Induced Microplasma

F. Buccheri[1], and X.-C. Zhang[1,2]
[1]The Institute of Optics, University of Rochester, 275 Hutchison Road, Rochester, NY, 14627 USA
[2]Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan 430074, China

***Abstract*—We investigated the THz emission from a microplasma induced by a dual color laser field. The addition of the second color significantly enhances the generated terahertz (THz) radiation up to directions perpendicular to the laser propagation axis. Unlike with elongated plasmas, we were able to observe the interplay between two THz generation driving mechanisms: ponderomotive force and AC biasing of the plasma.**

I. INTRODUCTION

We recently demonstrated that broadband THz generation from laser-induced plasmas can be achieved with sub-μJ pulse energies by replacing elongated plasmas with microplasmas [1]. This constitutes an improvement of two orders of magnitude of the previous state of art.

A Terahertz plasma source offer some advantages compared to the most widely utilized solid-state emitters. The most significant one is an extended spectral coverage limited by the laser excitation pulse duration. Spectral contents reaching up to 200 THz have been demonstrated with a 10 fs laser source [2]. The interested reader is referred to [3] for a more detailed discussion.

We believe that the use of laser induced microplasmas will lead to a new generation of plasma-based terahertz techniques that will be more accessible to the scientific community.

Microplasmas are created by focusing ultrafast laser pulses with high-NA microscope objectives. The study in ref. [1] was limited to the so-called "one-color" case, in which the laser excitation consists in the output of the ultrafast laser without any spectral manipulation. In that condition, the generation mechanism is attributed to longitudinal electron currents driven by the laser ponderomotive force [4], which result in an emission pattern whose peak is almost perpendicular to the laser propagation axis [1].

In this proceeding, we expand our study to the "two-color" case, in which the output of the laser is combined with its second harmonic (SH) creating a dual color laser excitation. The presence of the second harmonic acts as an ultrafast AC bias creating transverse electric currents whose radiation is phase-matched in the forward direction [5]. For an elongated plasma, the addition of the second color results in more than three order of magnitude increase of optical-to-THz power conversion efficiency.

The experimental setup employed is similar to the one described in ref. [1], which allows to characterize the angle-dependent emission of the coherent THz radiation from the laser-induced microplasmas.

We used a commercial amplified laser producing 100 fs pulses with central wavelength at 800 nm, energy of 750 μJ, and repetition rate of 1 kHz. The linearly polarized pump beam was focused through a 0.40 NA reflective objective, obtaining plasmas with longitudinal and transverse sizes less than 50 μm. The pump beam passed through a Type I 1 mm-thick β-BBO. By rotating the azimuthal angle of the nonlinear crystal, the SH harmonic of the pump beam can be added to the laser field. The relative phase between the fundamental beam and its SH can be controlled by changing the position of the crystal respect to the microplasma along the laser propagation axis.

II. RESULTS

We measured THz waveforms for ten different detection angles ranging from 0 to 90 degrees. The detection angle is defined as the angle between the optical axis of the THz collecting mirror and the propagation axis of the laser excitation beam. A detection angle of zero degree corresponds to a direction parallel the laser beam propagation axis.

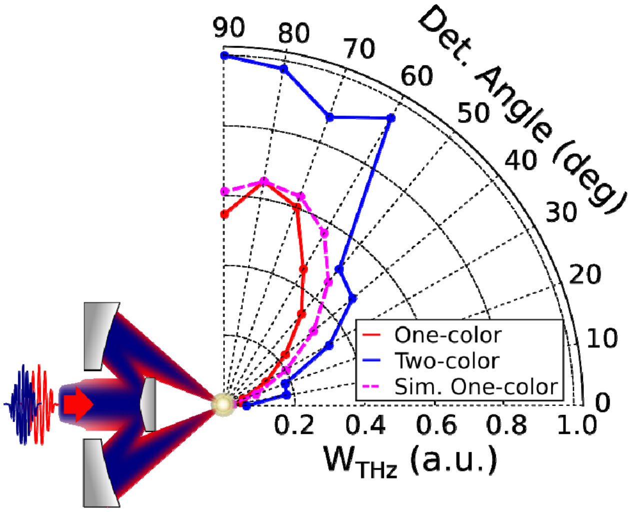

Fig. 1. THz pulse energy as a function of the detection angle. The solid blue line depicts the case of the two-color microplasma, while the solid red plot the one-color microplasma. The dashed magenta line is the numerically simulated emission for the one-color case. The energy is calculated as the time integral of the absolute square of the measured THz waveform. The microplasma was generated in ambient air with 95μJ pump pulse energy focused with a 0.40 NA reflective objective.

For each detection angle we acquired a THz waveform for two different values of β-BBO azimuthal angle, ϕ. For ϕ equals to zero, crystal's ordinary axis parallel to the excitation laser polarization, the efficiency of the SH generation process is negligible, therefore this corresponds to the "one-color" case. For the "two-color" case we employed ϕ equals to 48 degrees, being the value at which the THz peak electric field is the highest, despite the SH generation efficiency is maximum for a value of ϕ equals to 90 degrees. This occurrence is well understood and reported in the literature [6, 7]. The distance of the β-BBO crystal from the microplasma, i.e., the relative phase between the fundamental beam and its SH, is chosen such that the THz peak electric field is maximum.

Fig. 1 shows the comparison between the angle-dependent emission from microplasmas induced by a "one-color" laser field (solid red plot) and a "two-color" laser field (solid blue plot) with same laser energy. Each point represents the THz pulse energy, computed as the time integral of the absolute square of the measured THz waveforms. The dashed line is the numerical simulation for the "one-color", whose procedure is described in [1].

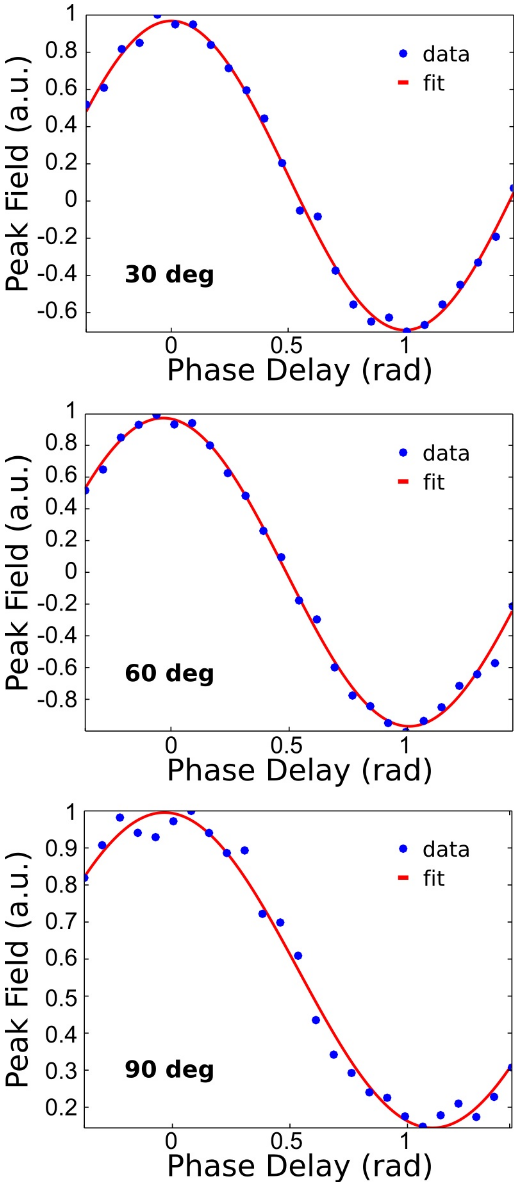

Fig. 2. THz pulse peak field as a function of the phase delay between the fundamental beam and its second harmonic. The curves are shown for three different values of detection angle. Those values are 30 degrees (top), 60 degrees (middle), and 90 degrees (bottom). The dots represent the experimental value, while the solid line is the best fit with a sinusoidal function.

The presence of the SH increases the THz emission for all the considered detection angles. The highest energy enhancement is obtained in the forward direction and it is close to 300%, due to the almost negligible THz emission from the one-color microplasma in that direction. Remarkably, an unexpected significant enhancement of 47% is present for a detection angle of 90 degrees.

We confirmed that the signal increase is due by the presence of the SH by observing the occurrence of the signature sinusoidal modulation of the THz peak electric field as a function of the relative phase delay between the fundamental beam and the SH [6, 7], as shown in Fig. 2. We observed the modulation of the THz peak electric field for all the values of detection angle. However, the measured modulation depth, defined as the difference between maximum and minimum value of the normalized THz peak electric field changes as a function of the detection angle. This is due to the interplay between the two different physical mechanisms responsible for terahertz generation. In fact, in the laser-induced microplasma the efficiency of the ponderomotive force driven emission and of the AC bias generation process have the same order of magnitude. Changes in the phase delay between the fundamental beam and its SH do not affect the first generation mechanism, but only the second one. As a result, the THz emission due to the ponderomotive force, which changes as a function of the observation direction, offsets differently the modulation curves depending on the detection angle.

III. SUMMARY

We compared the angle-dependent THz emission from microplasmas in both "one-color" and "two-color" regimes. We observed enhancement of the emitted THz radiation for all the measured angles. Due the small size of the plasma and the high electron density we were able to observe the interplay between the two different THz generation mechanisms, namely ponderomotive force and AC bias. Furthermore, the experimental results provide significant insights on electron dynamics in dense plasmas.

This work was supported by NSF and ARO. F.B. acknowledges a Fulbright scholarship. We wish to thank B. Bousquet, P. Mounaix, S. Skupin, and J. Dai for useful discussions.

REFERENCES

[1] F. Buccheri and X.-C. Zhang, Terahertz emission from laser-induced microplasma in ambient air. *Optica* 2, 366 (2015).

[2] E. Matsubara, M. Nagai, and M. Ashida, Ultrabroadband coherent electric field from far infrared to 200 THz using air plasma induced by 10 fs pulses. *Appl. Phys. Lett.* 101, 011105 (2012).

[3] B. Clough, J. Dai and X.-C. Zhang, “Laser air photonics: beyond the terahertz gap”, *Mat. Today,* vol. 15, pp. 50-58, 2012.

[4] H. Hamster, A. Sullivan, S. Gordon, W. White, and R. Falcone, Subpicosecond, electromagnetic pulses from intense laser-plasma interaction. *Phys. Rev. Lett.* 71, 2725–2728 (1993).

[5] D. J. Cook, and R. M. Hochstrasser, Intense terahertz pulses by four-wave rectification in air. *Opt. Lett.* 25, 1210 (2000).

[6] K. Y. Kim, J. H. Glownia, A. J. Taylor and G. Rodriguez, Terahertz emission from ultrafast ionizing air in symmetry-broken laser fields. *Opt. Express*, 15, 4577 (2007).

[7] H. Wen and M. Lindenberg, Coherent terahertz polarization control through manipulation of electron trajectories. *Phys. Rev. Lett.*, 103, 023902 (2009).