

# Backward terahertz emission from two-color laser induced plasma spark

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## Introduction

Femtosecond gas plasma created by focusing of two-color laser pulses is one of the promising laser-driven THz sources [1]. Investigation of spatial distribution of THz radiation from plasma is of great interest [2-4]. Several theoretical works have predicted an essential backward emission of terahertz radiation from two-color femtosecond plasma under tight focusing conditions [5]. We proved experimentally the presence of such radiation previously in [6]. However, to get a clear insight into mechanisms leading to backward emission one has to investigate characteristic features of this radiation. Here we perform its spectral and energetic investigation.

## Experimental setup

A Ti:Sa femtosecond laser (800 nm, 40 fs, 2.8 mJ, 1 kHz rep. rate, 12 mm dia.) is used. Laser radiation is partially converted into second harmonic in BBO crystal (10x10x0.2 mm<sup>3</sup>, I-type). To provide efficient THz generation polarizations of fundamental and second harmonic pulses are made collinear by a dual-wavelength phase plate and adjusted for optimal temporal shift by a delay compensator plate. Two-color femtosecond laser pulse is focused in ambient air by a parabolic mirror with 0.8 inch focal length to create plasma.

To perform forward THz radiation measurements we use two PTFE-lenses (5 cm diameter, 6 and 10 cm focal lengths). The first lens collimates radiation and the second focuses it on a THz detector. We use Golyay cell for power measurements and electro-optical sampling in ZnTe crystal (10x10x0.5 mm<sup>3</sup>, <110> cut) for spectral analysis.

The parabolic mirror that is used for laser beam focusing collimates backward THz radiation. Thereafter it is partially reflected on 90° by a metal plate with an aperture cut for passing of the laser beam. Then THz radiation is focused by a PTFE-lens on the THz detector. For power measurements it is 5 cm diameter 6 cm focal length lens. For electro-optical sampling it is 5 cm diameter 4 cm focal length lens with a 1 mm aperture for passing of a probe laser pulse.

## Results

We have obtained waveforms (see Fig.1(a)) and corresponding spectra of THz radiation spreading from two-color femtosecond laser plasma both in forward and backward directions. The backward pulse spectrum is somewhat narrower than the forward one.

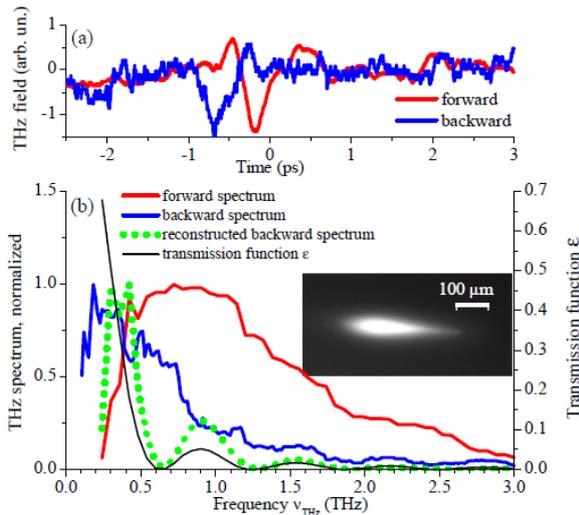
A numerical simulation based on a simple interferometric model is performed to support experi-

mental data [6, 7]. During the calculations we assume the length of plasma channel to be 250 μm; the length of plasma channel recorded in our experiment is (256 ± 6) μm (see inset in Fig. 1b). The backward  $P_{\text{bwd}}$  and forward  $P_{\text{fwd}}$  spectral powers of THz radiation are calculated with taking into account the collecting angles of the parabolic mirror and PTFE lenses; the transmission of the metal plate with Ø15-mm hole is accounted. The spectral powers  $P_{\text{bwd}}$  and  $P_{\text{fwd}}$  are found for the THz frequencies  $\nu_{\text{THz}}$  from 0.05 to 3 THz with the step 0.05 THz. The ratio  $E(\nu_{\text{THz}}) = P_{\text{bwd}}(\nu_{\text{THz}})/P_{\text{fwd}}(\nu_{\text{THz}})$  is the estimation the transmission function from the forward THz spectrum  $S_{\text{fwd}}(\nu_{\text{THz}})$  to the backward one  $S_{\text{bwd}}(\nu_{\text{THz}})$ :

$$E(\nu_{\text{THz}}) = P_{\text{bwd}}(\nu_{\text{THz}})/P_{\text{fwd}}(\nu_{\text{THz}}) \quad (1)$$

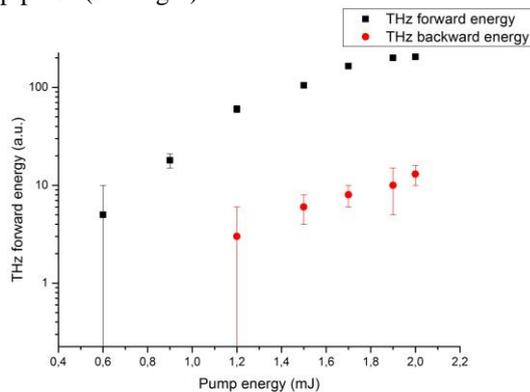
The ratio  $E(\nu_{\text{THz}})$  has the order of unity only for  $\nu_{\text{THz}} \leq 0.5$  THz (see Fig. 1b), so one can expect the shift of backward THz spectrum to the lower frequencies within the agreement with the experiment. We reconstruct the backward THz spectrum from the experimentally measured forward one for calculated function  $E(\nu_{\text{THz}})$ . The adequate semi-quantitative agreement between measured and reconstructed spectra supports the conclusion about the low-frequency bias in the backward THz spectrum. The qualitative explanation of this effect is the following: for the spectral THz components with the wavelength much longer than the plasma channel length of about 250 μm (i.e.  $\nu_{\text{THz}} \ll 1.2$  THz in good agreement with the previous estimation  $\nu_{\text{THz}} \leq 0.5$  THz) the plasma spark is closer to point-source as compared with shorter THz wavelength components. This point-source emits the low-frequency THz radiation both in forward and backward directions. We note, that the THz spectrum of two-color optical breakdown spreads up to ~50 THz, and the EO system can measure its only small part up to 3 THz. However, the transmission function, which determines the backward THz spectrum mostly, has the width of ~0.5 THz (see Fig. 1(b)) within the EO system detection range. Therefore, we measure the whole spectrum of the backward THz emission from two-color microplasma.

They also demonstrate narrowing of the spectrum of radiation emitted in backward direction. This feature arises from destructive interference from local emitters along plasma spark. The less the wavelength is, the more periods of radiation correspond to the plasma length. Thus, overall interference is more destructive. However, the experimentally observed narrowing is less dramatic as compared to the simulations.



**Fig. 1.** (a) Waveforms of THz field measured in backward and forward directions. (b) Spectra of experimentally measured forward (red line) and backward (blue line) THz emission with plasma channel, transmission function received from formula 1 (black line), numerically calculated backward THz emission (green dotted line).

We also get backward/forward emission energy dependencies on the energy of the two-color laser pump pulse (see Fig.2).



**Fig. 2.** Energy of forward and backward THz radiation dependence on laser pump pulse energy.

### Conclusions

We have performed investigation of spectral parameters of forward and backward terahertz radiation

from optical breakdown plasma created by tightly focused two-color femtosecond laser pulses. It appears that backward THz emission spectrum is narrower as compared to that of THz radiation co-directed with the optical pump. This result is supported by numerical simulation with simple interferometric model.

Dependencies of forward/backward THz energy on laser pump energy are measured. This can be useful for indirect control of forward spreading radiation by monitoring of backward one.

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