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Backward terahertz radiation from the two-color femtosecond laser filament

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One of key research directions for laser−plasma source of terahertz (THz) radiation is study of output THz-radiation spatial distribution from such sources [1–8]. The special interest is focused at the THz radiation propagating at angles close to 90° or larger to the optical axis [9, 10]. In this paper, we report on the first experimental evidence of the backward THz-emission from the two-color laser induced femtosecond plasma. Our findings are supported by the interferometric model [11].

For the optical radiation generation the Astrella 1 kHz laser system (Coherent Inc., USA) was used with central wavelength 800 nm, pulse energy 2.7 mJ, pulse duration 35 fs, beam diameter of 10 mm at e^{-2} level. Laser radiation was partially converted into second harmonic in the BBO crystal ($7\times5\times0.4$ mm, I type, $\sim10\,\%$ conversion efficiency) to form the two-color laser pulse. Output laser radiation passed through a delay compensator plate to compensate the delay between fundamental and second harmonic due to propagation through optical elements (this was done by tilting plate and varying optical path in this plate). This enhances THz-radiation generation efficiency. Further the beam passed through the dual-frequency phase plate (half-wave plate for the fundamental harmonic and wave plate for second harmonic; to get collinearly polarized two-color radiation) and focused by a 2 inch diameter parabolic mirror with 2 inch focal length. Thus, fundamental and second harmonic pulses appeared in the focal area of the parabolic mirror simultaneously and being linearly polarized along the same direction.

Output forward THz-radiation was collimated and focused by two Tsurupica lenses with 10 cm focal length and 5 cm diameter on the Golay cell (Tydex GC-1P). The mechanical chopper (15 Hz modulation frequency) with Lock-in-Amplifier (Stanford Research Systems SR 830 DSP) were used to detect THz-radiation using synchronous detection technique (averaging time 300 ms). The ITO (Indium Tin Oxide) plate was introduced in the optical path between the phase plate and the parabolic mirror at a 45° angle to the incident beam to detect the backward THz-emission. This plate reflects THz-radiation and transmits optical one. The backward THz-emission was collimated by the same parabolic mirror, that was used for focusing of optical pump beams, reflected by the ITO plate and focused by 5 cm focal length Tsurupica lens on the second Golay cell. The PTFE plates (1 mm thick) were introduced between the two Tsurupica lenses used for the forward THz-radiation measurements and in front of the Tsurupica lens for the backward THz-emission to eliminate optical radiation incident at Golay cells. Forward and backward THz-radiation measurements were made separately to eliminate any THz-reflections impact on measurements.

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During the measurements, we observed signal from Lock-in-Amplifier $150 \pm 5\,\mu$V for the forward THz-radiation and $5 \pm 3\,\mu$V for the backward one. These signals correspond to average powers of ~ 1.2 and ~ 0.04 nW accordingly. Note that solid angles of Golay cells were almost the same for the forward and backward THz measurements. Hence, we can estimate backward-to-forward THz emission efficiency taking into account THz pulses attenuation along their optical paths. The ratio of measured forward-to-backward THz-radiation was ~ 25.

A simple interferometric model [7, 11] can be applied to study the angular spectrum of THz-emission from laser plasmas. The two-color laser plasma is considered as a linear set of dipole monochromatic sources. The interference of the field emitted from different points of a channel provides an angular diagram of THz-emission at given frequency. The ratio of the THz-energies emitted in backward and forward directions is represented in Fig. 1 as a function of the plasma channel length for the

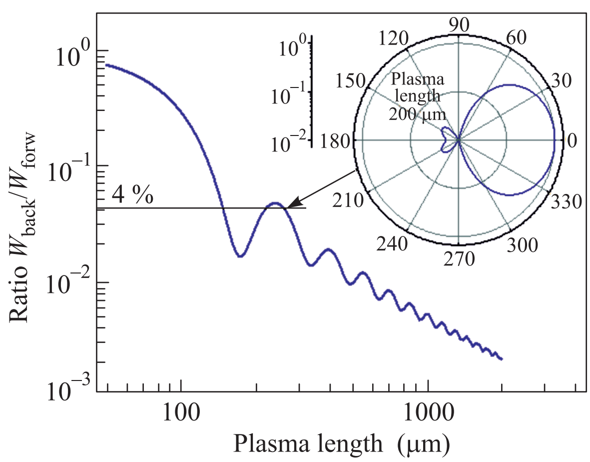

Fig. 1. (Color online) The ratio in logarithmic scales of THz-energies emitted in backward and forward directions on the plasma channel length, obtained from interferometric model for the frequency of 1 THz. Inset represents the angular diagram of THz-emission in the case corresponding to the experimental results

central frequency of 1 THz (wavelength of $300\,\mu$m). Despite it is an oscillating function, it quickly decreases in general with the filament length growth. The experimentally obtained ratio of 0.04 corresponds to the plasma channel length of ~ 200–$260\,\mu$m. This value agrees with visible plasma spark in our experiment. The THz angular diagram for this case is represented in the inset.

Hence, we report the first observation of the backward THz-emission from the two-color laser induced plasma. Its power was two orders less than the forward THz-emission energy. This finding fitted into the interferometric model of THz-emission assuming effective plasma channel length of $\sim 300\,\mu$m and output radiation with 1 THz frequency. Further experimental study is needed to assess full angular spectrum of the THz-emission, that can be quantitatively compared with numerical simulations in the frame of FDTD model [12].

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1. C. D. Amico, A. Houard, M. Franco, B. Prade, A. Mysyrowicz, A. Couairon, and V. Tikhonchuk, Phys. Rev. Lett. **98**, 235002 (2007).
2. A. P. Shkurinov, A. S. Sinko, P. M. Solyankin, A. V. Borodin, M. N. Esaulkov, V. V. Annenkov, I. A. Kotelnikov, I. V. Timofeev, and X.-C. Zhang, Phys. Rev. E **95**, 43209 (2017).
3. F. Jahangiri, M. Hashida, T. Nagashima, S. Tokita, M. Hangyo, and S. Sakabe, Appl. Phys. Lett. **99**, 261503 (2011).
4. H. Zhong, N. Karpowicz, and X.-C. Zhang, Appl. Phys. Lett. **88**, 261103 (2006).
5. Z. Zhang, Y. Chen, M. Chen, Z. Zhang, J. Yu, Z. Sheng, and J. Zhang, Phys. Rev. Lett. **117**, 243901 (2016).
6. T. I. Oh, Y. S. You, N. Jhajj, E. W. Rosenthal, H. M. Milchberg, and K. Y. Kim, New J. Phys. **15**, 75002 (2013).
7. Y. S. You, T. I. Oh, and K. Y. Kim, Phys. Rev. Lett. **109**, 3902 (2012).
8. V. A. Andreeva, O. G. Kosareva, N. A. Panov, D. E. Shipilo, P. M. Solyankin, M. N. Esaulkov, P. González De Alaiza Martínez, A. P. Shkurinov, V. A. Makarov, L. Bergé, and S. L. Chin, Phys. Rev. Lett. **116**, 63902 (2016).
9. F. Buccheri and X.-C. Zhang, Optica **2**, 366 (2015).
10. N. Panov, V. Andreeva, O. Kosareva, A. Shkurinov, V. A. Makarov, L. Bergé, and S. L. Chin, Laser. Phys. Lett. **11**, 125401 (2014).
11. N. A. Panov, O. G. Kosareva, V. A. Andreeva, A. B. Savelév, D. S. Uryupina, R. V. Volkov, V. A. Makarov, and A. P. Shkurinov, JETP Lett. **93**, 715 (2011).
12. J. C. Nedelec, Numer. Math. **35**, 315 (1980).