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# Controlling polarization of terahertz radiation emitted by single-color filament with amlitude modulation of laser beam

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The characteristics of terahertz radiation generated during single-color filamentation of laser pulses with 470 nm wavelength are experimentally studied. It is shown that at high frequencies, terahertz radiation propagates in the form of two local maxima, in contrast to low frequencies, where a unimodal structure with a maximum on the axis is observed. We demonstrate that by amplitude modulation of the laser beam it is possible to change the polarization of terahertz radiation without significantly distorting its direction.

**Keywords:** filamentation, plasma, terahertz emission, terahertz polarization.

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## Introduction

Plasma generated during filamentation of ultrashort laser pulses is a source of wideband terahertz radiation [1], which is suitable for multiple applications [2,3]. In many problems, such as optical excitation [4] and spectroscopy [5,6], polarization of terahertz radiation plays a crucial role. Besides, in some areas the elliptically polarized terahertz radiation is necessary, for example, to visualize the birefringent materials [7] or to study the chirality of organic molecules [8,9]. The question of polarization control for the radiation from such wideband source as laser filament plasma is of wide interest. One of the methods to set the direction of terahertz radiation polarization from the filament plasma is the application of external electric field. In this case polarization will be linear and directed along the field [10,11]. Besides, it was shown numerically that if a more complex configuration of the field is used, it is also possible to produce the elliptical polarization [12]. In case of two-color filamentation it is possible to control polarization of terahertz radiation by changing the phase difference and length of interaction of the first and second harmonic pulses [13,14]. Besides, the simplest scheme to generate terahertz radiation from laser plasma being single-color filamentation in the air is currently much less studied.

The recently published paper [15] demonstrated that during filamentation of laser pulses with wavelength 740 nm the angular structure of terahertz radiation at different frequencies may substantially vary, changing from an axisymmetric hollow cone at low frequencies to two pronounced maxima at high ones. Polarization of the terahertz beam may at the same time vary correspondingly from radial to linear one, perpendicular to the polarization of the laser pulse. At the same time the paper [16] demonstrated the ability to produce unimodal distribution of terahertz radiation at frequencies $0.3 - 1$ THz with filamentation of laser pulses with wavelength 930 nm. In this case the observed polarization in the center of distribution was linear and codirectional with the laser pulse field. Therefore, the initial parameters of the laser pulse may provide significant impact at the characteristics of the terahertz radiation generated under filamentation.

During filamentation of the laser pulses usually two processes are considered — Kerr self-focusing and defocusing of laser radiation on the generated plasma. However, in the papers [17,18] it was shown that in case of using the additional geometric focusing with relatively high numerical apertures it is possible to produce an extended plasma channel in absence of non-linear focus. In this case, in contrast to the non-linear focusing, the self-cleaning of the beam accompanied with appearance of a symmetric mode, will not occur [19]. The resulting asymmety of the plasma channel may provide impact on the terahertz radiation generation. Nevertheless, in the paper [16] with asymmetric distribution of energy density of the laser field in the area of the plasma channel, the symmetric unimodal distributions of terahertz radiation were produced. Therefore, currently there is no unambiguous correlation of plasma distribution, which in case of tight focusing is defined by the profile of the initial laser beam, and directionality of terahertz radiation. Therefore, the objective of our paper was to study the impact of laser beam distortion at amplitude and polarization of terahertz radiation generated under filamentation with prevalence of geometric focusing.

## Experiment and results

The experiment was carried out with radiation of the second harmonic of a titanium-sapphire laser system (Avesta). The central wavelength was 470 nm, the pulse duration was 100 fs, the energy was 3.5 mJ. The laser beam with diameter 1 cm by level $1/e$ was focused by a spherical mirror with focal distance of 40 cm. That is, the numerical aperture determined as the ratio of the beam radius to the focal distance of the mirror was more than 0.01, which corresponds to the propagation in the mode of geometric focusing prevalence [17,20]. Terahertz radiation generated in the filament plasma was registered using a hot-electron bolometer (Scontel). The inlet window of the bolometer was located on the optical axis at the distance of 40 cm from the geometric focus. A terahertz polarizer (Tydex), the zero on the scale of which corresponded to the laser pulse polarization, was located in front of the bolometer inlet window.

Before the focusing mirror, various amplitude masks were added to the beam. To control the effect of the amplitude mask on the beam shape, the distributions of laser beam energy density were produced on the CCD matrix in the near field after passage through the amplitude mask (Fig. 1, *a*). For all four cases the polarization of terahertz radiation was measured, the results are given in Fig. 1, *b*. For the Gaussian beam the registered polarization of terahertz radiation is elliptical to the ratio of axes 1 : 7 (distribution 1 in Fig. 1). The major semi-axis of ellipse is vertical at the same time, i.e. perpendicular to the polarization of laser radiation. Under various amplitude modulations of the laser beam the polarization of terahertz radiation has different degree of ellipticity and different deviation of the major semi-axis angle from the vertical line to almost 60° (distribution 2 – 4 in Fig. 1). From here it may be concluded that using the amplitude modulation of the beam it is possible to vary the polarization of terahertz radiation on the axis of the beam within the wide limits.

It is evident that introduction of the amplitude mask to the beam affected the total energy of the laser pulse, which, in its turn, may affect the energy and angular directionality of the generated terahertz radiation. Therefore, for the corresponding modulations of the laser beam, the two-dimensional patterns of angular distribution of terahertz radiation were obtained. For this purpose, the bolometer was placed on a mobile table rotating in the plane of the table around the point of the focus of the spherical mirror. Observation of the terahertz radiation at various vertical angles was carried out by variation of the beam axis inclination so that the position of the focus remained in the same point of space. In more detail this method of production of the two-dimensional distributions of terahertz radiation is described in [15,16,21].

Fig. 2 provides the measured two-dimensional directional patterns of terahertz radiation at various amplitude modulations of the laser beam. Items (*a–d*) in Fig. 2 comply with the cases 1 – 4 in Fig. 1. Angular distribution of terahertz radiation produced under filamentation of the initial Gaussian beam, is inhomogeneous and is similar to an incomplete ring (Fig. 2, *a*). Additional modulations result in conversion of angular directivity. Besides, despite the substantial distortion of the initial shape of the laser beam (see Fig. 1, *a*), the terahertz radiation pattern shows no pronounced maxima or substantial variation of the propagation angles.

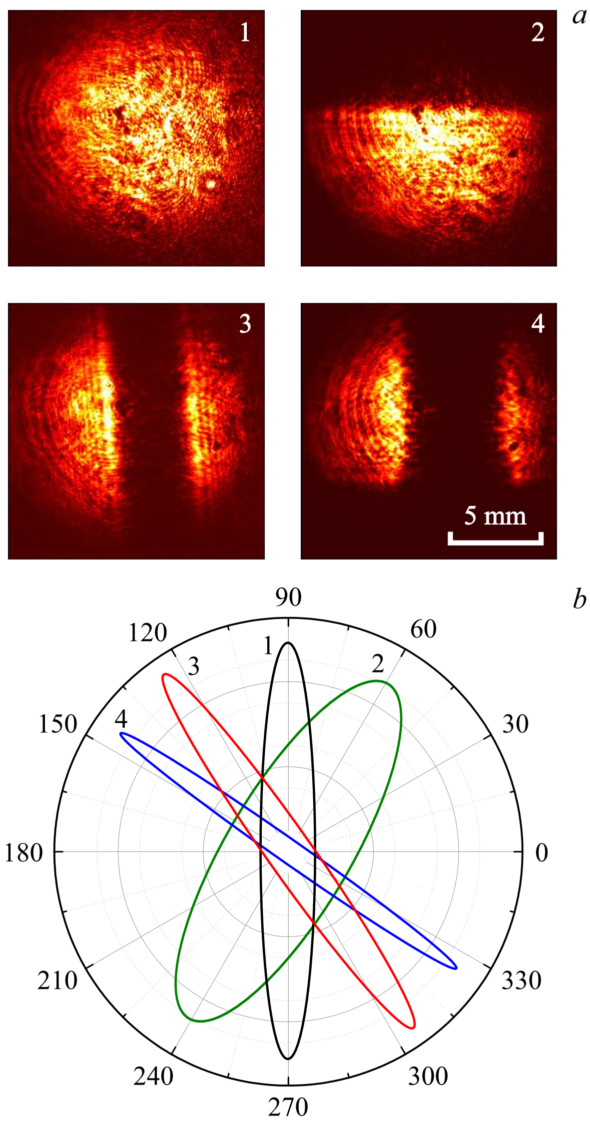


**Figure 1.** Distributions of laser beam energy density in the near field after passage of various amplitude masks (*a*). Polarization of terahertz radiation under various amplitude modulations of laser beam (*b*).

To determine the impact of the amplitude modulation of laser beam on the energy characteristics of terahertz radiation, we integrated the signals from the two-dimensional distributions shown in Fig. 2. In Fig. 3 the dependence is shown between the integral energy of terahertz radiation and energy of laser pulse, which varied as a result of amplitude modulation of the laser beam. In these experi-

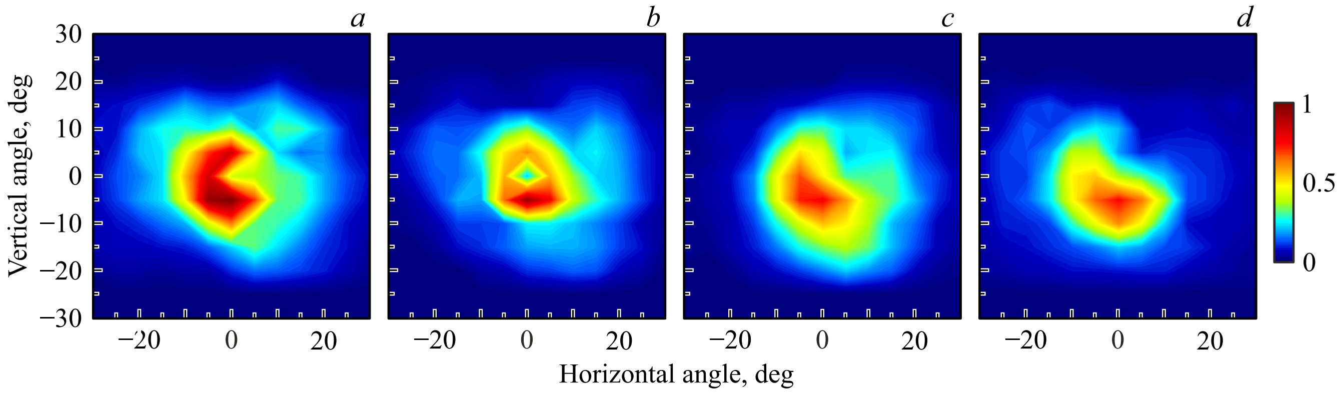


**Figure 2.** Two-dimensional angular distributions of terahertz radiation generated in process of filamentation, at various amplitude modulation of the laser beam. Normalization was performed for the maximum value observed in all these experiments. Items (*a–d*) comply with the cases 1 – 4 in Fig. 1.

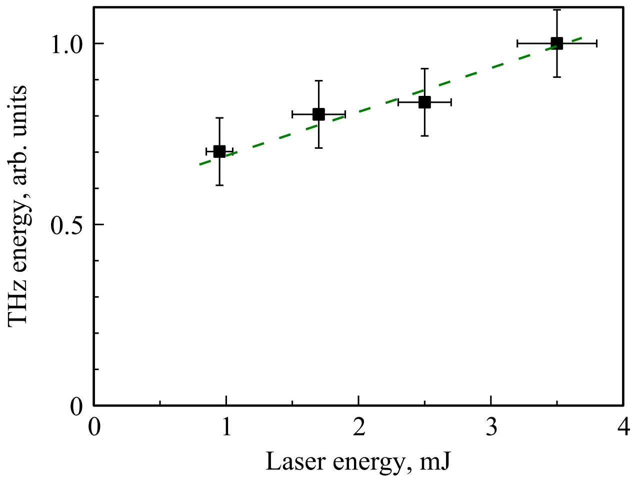


**Figure 3.** Dependence of energy of terahertz radiation generated under filamentation on the laser pulse energy. The dashed line corresponds to linear approximation of experimental points.

ments the strong distortion of the initial beam caused energy reduction from 3.5 to 0.9 mJ. At the same time the energy of terahertz radiation generated in the filament plasma dropped only by 30%. Therefore, in case of filamentation under the conditions of prevalent geometric focusing, introduction of amplitude distortions to the laser beam may rotate the polarization of terahertz radiation, but provides poor effect on its energy characteristics and total directionality.

Spectral-angular characteristics of terahertz radiation are as important from the application point of view. Therefore, in the experiment the two-dimensional angular directionalities of various spectral components of terahertz radiation were also recorded for the non-modulated beam. To separate the individual terahertz frequencies, narrowband filters (Tydex) were used with transmission frequencies 0.3, 0.5, 1 and 3 THz [21]. The measured distributions were shown in Fig. 4. At frequencies 0.3 and 0.5 THz (Fig. 4, *a, b*) the directionality of terahertz radiation is close to unimodal with the maximum on the optical axis. At higher frequencies (1 and 3 THz, Fig. 4, *c, d*) the pattern is slightly different — two pronounced maxima are observed, lying in the axis perpendicular to polarization of the laser pulse. The similar structure of terahertz radiation directionality and discussion of its nature are contained in the article [15]. Polarization measured by us in the maxima of terahertz distributions is vertical at all frequencies.

## Conclusion

Therefore, the characteristics of terahertz radiation generated by single-color filamentation of titanium-sapphire laser second harmonic pulses at wavelength of 470 nm were studied. It was demonstrated that in case of a non-modulated laser beam the angular directionality of low frequencies of terahertz radiation is close to the unimodal one with the maximum in the optical axis, at higher frequencies there are two pronounced maxima. Polarization of terahertz radiation in the maxima at considered frequencies is perpendicular to polarization of the initial laser radiation. It was shown that the amplitude modulation of the laser beam may rotate the polarization of terahertz radiation within wide limits, not impacting substantially its directionality. Reduction of the laser pulse energy 4 times as a result of amplitude modulation of the beam caused reduction of the terahertz radiation energy only by 30%. The obtained results are not described within the existing models, however, may stimulate further studies of the physics of processes providing for the generation of terahertz radiation in the single-color filament plasma.

### Conflict of interest

The authors declare that they have no conflict of interest.

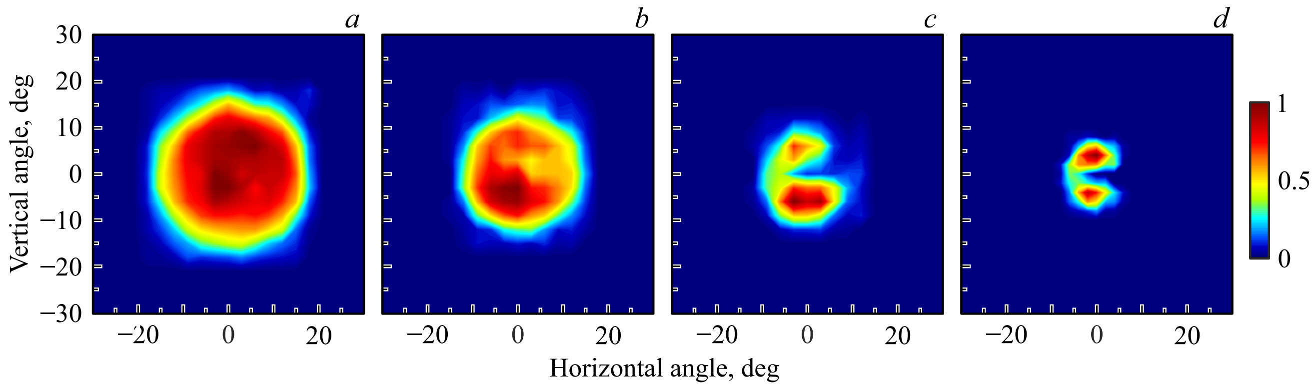


**Figure 4.** Two-dimensional angular distribution of terahertz radiation recorded with a narrowband filter: 0.3 (*a*), 0.5 (*b*), 1 (*c*), 3 THz (*d*).

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