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OPTICS AND SPECTROSCOPY. LASER PHYSICS

The Focal Length Effect on Energy Absorption and Terahertz Generation upon Focusing Two-Color Radiation in Air

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Abstract—Generation of terahertz radiation upon filamentation in air of two-color radiation in loose focusing conditions with focal lengths from 30 to 312 cm and a beam diameter of 0.8 cm was studied. Two-color radiation was generated in a nonlinear BBO crystal irradiated by a converging laser beam. Measurements show that the energy input into the medium increases dramatically with a decrease in the focal length to 50 cm or less; at $F = 30$ cm, the energy of a terahertz pulse linearly depends on the laser pulse energy and increases significantly at $F = 50$ cm. Terahertz radiation is still not observed at longer focal lengths, which is apparently due to a spatio–temporal mismatch of the radiation of the first and second harmonics.

Keywords: femtosecond filamentation, terahertz radiation, energy input, two-color radiation, numerical aperture.

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INTRODUCTION

Femtosecond laser filaments in air [1] are a source of terahertz radiation [2], including upon propagation in the atmosphere, and can provide remote diagnostics of objects. As an example, in [3], the possibility of recording a terahertz signal from a set of filaments formed at a distance of approximately 30 m from the output of the laser system was demonstrated experimentally. However, the conversion efficiency of the optical pulse energy into terahertz energy is small, $\sim 10^{-6}$ and less.

Mixing of the fundamental and second harmonics (two-color filamentation) [4] allows one to increase the conversion efficiency to terahertz radiation by approximately 3 orders of magnitude [5]. In the majority of studies, the two-color radiation is focused rather tightly, NA > 0.05 [6], up to the formation of microplasma terahertz source [7, 8]. The use of this scheme in soft focusing and on extended paths is limited primarily by the loss of temporal and spatial overlap between optical harmonics due to the normal dispersion in air: at a distance of $\sim$1 m, the second harmonic lags behind the first by $\sim$70 fs. Nevertheless, the use of chirped pulses with a duration of $\sim$1 fs or more enabled the effective generation of terahertz radiation by two-color pulses at a distance of 70 cm [9] and 10 m [10] from the laser system output. These studies are in many ways unique.

Terahertz radiation, which arises upon filamentation, propagates in a narrow cone relative to the optical axis of the laser beam [3] with the cone angle being determined by the length of the emitting region of the filament [3, 11]. With an increase in the focal length, i.e., at small NA, a significant part of the terahertz radiation propagates forward, which is essential for most applications of this radiation. In addition, the use of loose focusing allows the use of high laser pulse energies. In this paper we present the results of the first studies of the generation of terahertz radiation at loose focusing (NA $= 0.001$–0.01) of spectrally constrained two-color laser pulses in air.

1. EXPERIMENTAL SETUP AND RESULTS

The experimental setup scheme is shown in Fig. 1. Femtosecond radiation (central wavelength 805 nm,

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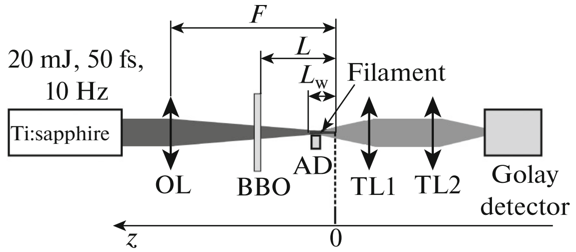

Fig. 1. The experimental setup scheme: OL is an optical lens, TL1, TL2 are Teflon lenses, BBO is a nonlinear optical crystal, and AD is an acoustic detector.

pulse duration 50 fs, pulse energy 1–20 mJ, pulse repetition rate 10 Hz, beam diameter 8 mm at half height) was focused by an optical lens OL in the air. A broadband acoustic detector AD (based on PVDF film) was installed in the area of focal waist at a distance of 3–4 mm from the optical axis. The signal the detector was sent to the input of a high-speed analog-to-digital converter (PLX9054 PCI PC card, 500 MHz, 8 bits). Based on the measurement of the amplitude and duration of the recorded pulse, the diameter of the acoustic source and the volume energy density in it (assuming that the initial acoustic source has the form of a cylinder) was estimated according to the previously developed method [12, 13]. To increase the efficiency of the terahertz radiation generation, a nonlinear optical BBO crystal with a thickness of 200 μm (*ooe* synchronism) was installed in the path of the convergent laser beam. This ensured the generation of a second harmonic radiation with a maximum efficiency of approximately 10%.

Terahertz radiation was collected in a Golay detector (Tydex, GC-1P) using two Teflon lenses TL1 and TL2 with a diameter of 5 cm and focal lengths of 10 and 6 cm. The entrance window of the detector was additionally closed by a Teflon plate to prevent the penetration of electromagnetic radiation of other ranges (primarily optical) into the detector. The pulse from the detector was sent to a Techtronics TDS20204 digital oscilloscope. The position of the lenses corresponded to the maximum amplitude of the recorded terahertz signal. Since the length of the source (laser filament) was approximately several millimeters, the distances between the lenses, the source and the detector were chosen close to those calculated on the basis of the thin lens formula for a point-like source. The position of the nonlinear BBO crystal relative to the focus point was chosen based on two criteria. First, the intensity of laser radiation at the entrance to the crystal should not exceed the thresholds of its surface breakdown and self-focusing in the crystal volume. Second, to compensate for the phase mismatch of the first and second harmonics in the region of the focal waist [14], fine tuning was carried out to find the position corresponding to the maximum of the terahertz radiation energy recorded by the Golay detector. Note that in our experimental scheme, the polarizations of the first and second harmonics are orthogonal, which is not optimal for the generation of terahertz radiation in the two-color scheme [15]. For each focusing lens used in the experiments, the position of the Teflon lens close to the filament was also optimized (so that the maximum output of the terahertz radiation was obtained), while the distances between the lenses and between the second lens and the Golay detector were kept constant.

Since the Golay detector is intended primarily for recording the power of quasi-continuous terahertz radiation, we conducted a test experiment to calibrate the Golay detector in the mode of registration of a single terahertz pulse. For this purpose, we used terahertz radiation obtained by optical rectification of femtosecond pulses with a tilted intensity front in a lithium niobate crystal [16]. A titanium-sapphire laser with a pulse repetition rate of 1 kHz was selected as the pump source. A mechanical chopper with a modulation frequency of 15 Hz was installed in the circuit. To detect signals, a key-type synchronous detector (Stanford Research Systems SR830 DSP) or an oscilloscope (Techtronics TDS 2000) were used at a pulse repetition rate reduced to 10 Hz. The average power of the terahertz source was 2.1 ± 0.1 μW, i.e., the energy of a single terahertz pulse was 2.1 ± 0.1 nJ. At a repetition rate of 10 Hz, the amplitude of a single pulse was 56 ± 0.5 mV, i.e., the calibration coefficient of the detector when registering single terahertz pulses was 36 ± 2 nJ/V.

The diameter of the terahertz beam on the first lens was evaluated using a diaphragm with a diameter of 7 mm, which was installed in front of this lens and could be shifted across the beam. The evaluation showed that this diaphragm slightly reduces the amplitude of the recorded signal, i.e., the diameter of the measured beam is approximately 7 mm. This confirms that our recording system ensures that the entire terahertz beam reaches the detector.

Figure 2 shows the dependences of the maximum volumetric (a) and linear (b) energy densities absorbed in the filament on the focal length of the lens. In each case, the acoustic sensor was placed in a position along the optical axis in which the acoustic signal was maximal. This corresponded to shifting the sensor from the plane of the precise focus by 3–30 mm in the direction of the focusing lens depending on its focal length. The data in Fig. 2 were obtained at laser pulse energies of 3 and 20 mJ. The first energy value corresponds to the formation of a single filament at $F = 312$ cm, and the second corresponds to the formation of a set of filaments,

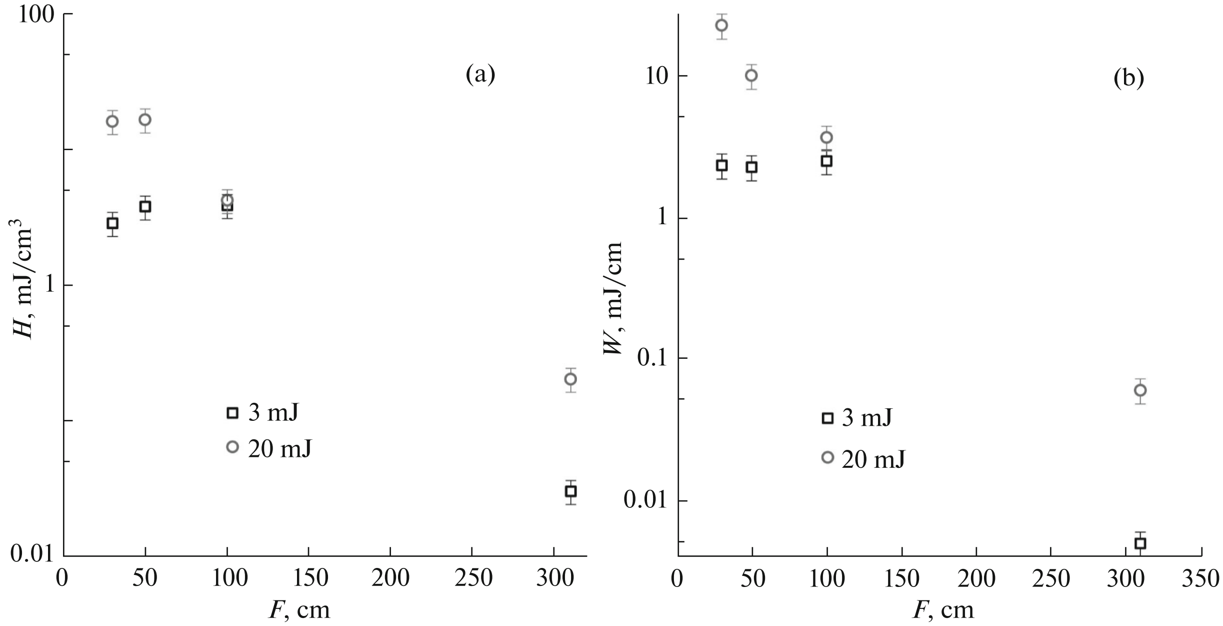

Fig. 2. The dependence of (a) volume and (b) linear energy densities absorbed in the filament on the lens focal length at a laser pulse energy of (squares) 3 and (circles) 20 mJ.

which then merge into a single superfilament with a high energy density [17]. As one can see from Fig. 2, the maximum energy density (both volumetric and linear) is achieved at the shortest focal lengths. Since the energy is absorbed primarily due to the ionization of atoms and molecules, this irradiation regime corresponds to the maximum electron concentration and maximum ionization currents. These currents are the source of terahertz radiation [21, 22]; therefore, we should expect the maximum efficiency of terahertz radiation generation at shorter focal distances. The measurements of terahertz radiation at different focal lengths showed that this dependence is not monotonic. The maximum energy of the terahertz pulse was recorded at $F = 50$ cm, while at $F = 30$ cm the recorded terahertz signal was slightly smaller. However, the terahertz radiation was not detected at large focal lengths of 75, 100, and 312 cm. Figure 3 shows the dependence of the terahertz pulse energy on the energy of the input laser pulse. It can be seen that for focusing with a $F = 30$ cm lens, the dependence is close to linear. In the case of focusing with a $F = 50$ cm lens, the terahertz signal exhibits a significant increase, which is a factor of 3.7 at a laser pulse energy of 10 mJ. Further increase in energy in this focusing mode leads to a decrease in the terahertz signal. This behavior requires further studies.

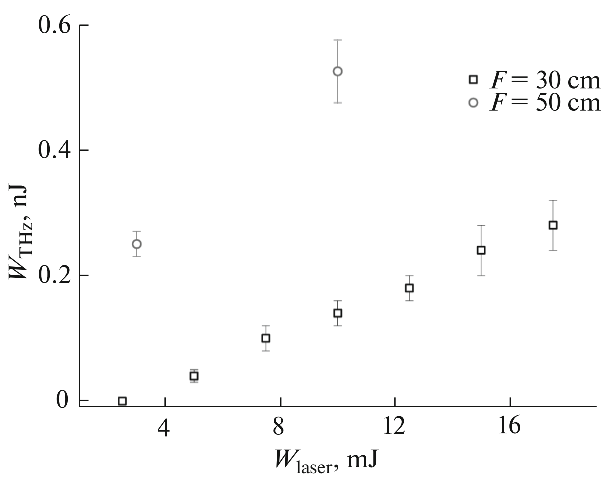

Fig. 3. The dependence of the terahertz pulse energy on the laser pulse energy for two focal lengths: (squares) $F = 30$ and (circles) 50 cm.

2. DISCUSSION

The following simple model can explain the observed linear growth of the terahertz pulse energy with an increase in the laser pulse energy when focusing with a $F = 30$ cm lens as well as the increase in the terahertz pulse energy when a $F = 50$ cm lens is used instead. Suppose that terahertz radiation is generated in the entire region where the filament exists, and the generation efficiency is determined by the intensity of the second harmonic field (since the intensity field of the first harmonic within the filament is limited at 5×10^{13} W/cm^2 [18]). It is known that, as a rule, the filament is formed before the linear focus of the lens, and quickly vanishes behind the focus [19]. Thus, the length of the region, in which terahertz radiation is generated, is approximately equal to the distance l_w from the point of filament formation to the geometric focus of the lens. The filament formation point in the absence of the lens can be calculated by the Marburger relation [20], but for the focusing with a lens, there is no unambiguous relation. Since the radiation self-focusing is determined by the effect of self-action, we assume that the distance to the focus point from the lens is determined by value of the nonlinear phase on the axis, i.e., by the B-integral,

$$B = \frac{2\pi}{\lambda} \int_F^z n_2 I(z) dz,$$

where λ is the radiation wavelength, $n_2 = 10^{-19}\text{cm}^2/\text{W}$ is the Kerr nonlinearity coefficient of air and

$$I(Z) = I_0 \frac{F^2}{(F-z)^2}$$

is the intensity of laser radiation. The latter formula assumes that the waist length $\propto \lambda F^2/D^2$ (D is the initial diameter of the beam) is less than distance to the filament start point l_w and, consequently, the change in intensity with the distance can be described in the approximation of geometric optics. If we assume that the start point of the filament corresponds to the condition $B = 2\pi$, then the start coordinate is given by

$$l_w = \frac{\beta I_0 F^2}{1 + \beta I_0 F} \approx \beta I_0 F^2 = \beta P_0 F^2/D^2,$$

since $\beta I_0 F \ll 1$ (here $\beta = \lambda/(4\pi P_c)$, $P_c = 10$ GW [19] is the critical power of self-focusing). The estimate gives $l_w = 0.5-1.5$ cm at $F = 30-50$ cm, i.e., the starting point of the filament is out of the laser beam waist in fact. Note that the obtained estimate is in good agreement with the experimentally observed filament length in our experiment. The radiation intensity of the second harmonic in the starting point of the filament is

$$I_0^{2\omega} = \eta \left(I_0 \frac{F^2}{l^2} \right)^2 \frac{l^2}{l_w^2} = \eta \frac{D^2}{l^2 \beta^2},$$

where η is the conversion coefficient to the second harmonic, l is the coordinate of the crystal for the second harmonic generation. We suppose that the intensity of the second harmonic along the filament is constant and equal to $I_0^{2\omega}$. Then the energy W_{THz} emitted in the terahertz range will be proportional to $I_0^{2\omega} l_w$, i.e.,

$$W_{\text{THz}} \propto \frac{\eta}{\beta} P_0 \frac{F^2}{l^2}.$$

The obtained dependence corresponds to the experimental data presented in Fig. 3 both in the sense of dependence on the laser pulse energy (or power P_0), and in the sense of dependence on the focal length F. Note that in our experiments the values of distance l at $F = 30$ and 50 cm were almost the same.

CONCLUSIONS

Thus, we presented experimental results on the generation of terahertz radiation at soft focusing of a two-color subterawatt femtosecond laser pulse in air. It was found that at focal length $F = 30$ cm, the energy of the terahertz pulse linearly depends on the energy of the initial laser pulse and increases significantly when the focal length is increased to 50 cm. It was shown that the observed regularities, including the dependences on the energy of the laser pulse and the focal length, can be adequately described by a simple model. At the same time, we did not observe terahertz radiation at large focal lengths (75 cm and more); furthermore, for the $F = 50$ cm lens, the terahertz signal significantly decreased at high energies of the laser pulse. This may be due to the spatial-temporal mismatch of the pulses of the first and second harmonics in the filamentation area and will be the subject of further experimental studies and numerical simulations.

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