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Generation of terahertz radiation by focusing femtosecond bichromatic laser pulses in a gas or plasma

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Abstract. **The generation of terahertz radiation by focusing two-frequency femtosecond laser pulses is studied. Focusing is carried out both in an undisturbed gas and in a pre-formed plasma. The energy of the terahertz radiation pulses is shown to reduce significantly in the case of focusing in a plasma.**

Keywords: *laser plasma, terahertz radiation.*

1. Introduction

One of the promising areas of radiation – matter interaction physics is the study of laser-plasma sources of terahertz radiation [1, 2]. These sources have a number of advantages in comparison with sources using optical rectification in nonlinear crystals, namely, generation of ultrabroadband THz radiation (up to several tens of THz [3]) and the ability to scale under a significant change in the intensity of the exciting laser light. However, the energy conversion efficiency of optical radiation into the terahertz range is small in comparison with other nonlinear-optical methods of generation (see, for example, [4]). In this regard, the current challenge is to find the methods to increase the conversion efficiency. This requires a detailed study of the terahertz radiation generation mechanisms in a plasma. In addition to the method of optical breakdown by two-frequency pulses [2, 3, 5 – 12], different schemes of breakdown upon axicon focusing of single-frequency radiation are considered in the literature [13 – 15]. The problem of generating terahertz pulses by passing a single-frequency laser beam through a low-density plasma is also addressed [16].

It is known that at the same femtosecond laser pulse energy the presence of radiation at the fundamental frequency and at the second harmonic frequency (bichromatic pulse) allows the generation of radiation in the terahertz range, which is hundreds of times more efficient [2, 3, 5 – 12]. Despite the large number of works on this generation technique, the mechanisms that lead to significant differences in the efficiency of conversion of laser radiation into the terahertz radiation are still discussed in both theoretical and experimental papers [2, 3, 5 – 12]. To this end, two basic mechanisms are considered that can lead to the efficient generation of terahertz radiation in a plasma in the case of a two-frequency breakdown: four-wave mixing and excitation of macroscopic photocurrents.

When the medium has the cubic nonlinearity, four-wave mixing of fundamental and second harmonic radiation can cause constant (low-frequency) polarisation of the medium (the original gas and plasma), which results in the generation of a terahertz radiation pulse [2, 3, 5, 6, 11]. However, the energy of generated terahertz pulses, measured in numerous papers, corresponds to the abnormally high cubic nonlinearity of plasma [5].

Another mechanism is the generation of current due to the tunnelling ionisation of air by a bichromatic pulse [8, 9, 11, 12]. The field ionisation probability in this case is highly dependent on the intensity of the total electric field, the photoelectrons being produced predominantly in the vicinity of the maximum of the field intensity oscillations. As a result, after the action of laser radiation, electrons have a finite speed. In case of breakdown by single-frequency laser radiation, the photoelectron speed is directed in the direction of polarisation of the laser pulse, and the average current is zero, since approximately the same number of electrons is ionised on half-cycles with opposite directions of the electric field in the pulse. The symmetry of the field in the pulse is violated, for example, in case of breakdown by a femtosecond pulse consisting of several cycles of the radiation. The presence of the second harmonic in the laser pulse also allows one to remove the symmetry and, therefore, to generate a current pulse.

The aim of our research is to find the influence of processes related to the ionisation of the medium on the generation of radiation in the terahertz range under focusing of two-frequency laser radiation.

2. Experiment

The scheme of the experimental setup is shown in Fig. 1. As a source of femtosecond pulses, use was made of a Spitfire Pro XP Ti : sapphire laser (Spectra-Physics) with the following parameters: pulse duration, τ = 50 fs; laser wavelength, λ = 800 nm; laser pulse energy, up to 3 mJ; Gaussian beam diameter (at a 1/e^2 level), 12 mm; and pulse repetition rate, 1 kHz.

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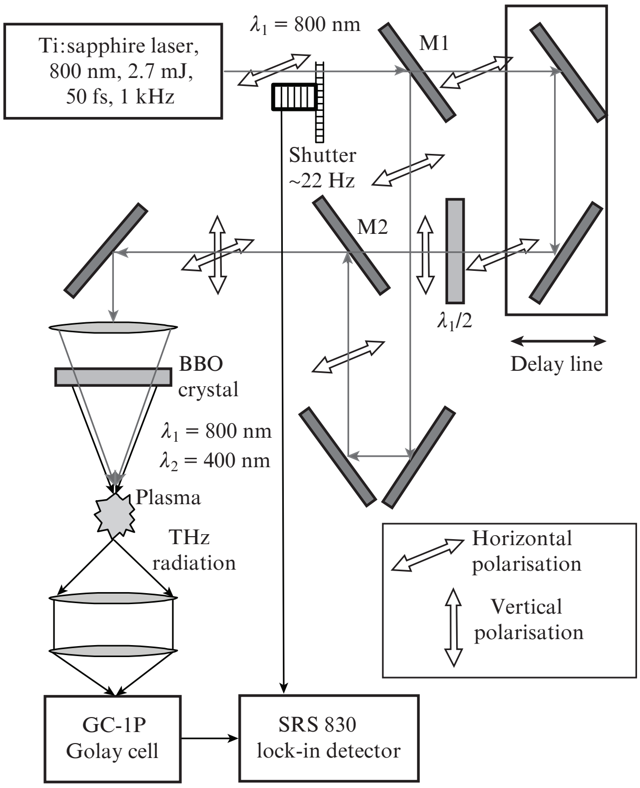

Figure 1. Experimental setup.

Horizontally polarised radiation of the Ti:sapphire laser was split by a semitransparent mirror M1 into two roughly equal parts, forming two optical pulses at the fundamental frequency. On the way of one of the pulses was placed a $\lambda/2$ plate, which changed the polarisation to vertical. Then, the pulses were superimposed by a semitransparent mirror M2. The time delay between the pulses was varied by the delay line. The laser beam was focused by a lens ($f = 15$ cm), with a spark in the focus. The plasma density assessed by the interferometric method was $\sim 10^{18}$ cm^{-3} [17]. Behind the lens was mounted a type-I phase-matching BBO crystal configured to convert horizontally polarised radiation to the second harmonic. The distance from the lens to the crystal was chosen to maximise the terahertz signal [9].

Thus, the optical breakdown of the gas (air at atmospheric pressure) was caused by the pulsed bichromatic laser field (simultaneously by the horizontally polarised fundamental and vertically polarised second harmonic of the Ti:sapphire laser with the total pulse energy of 400 μJ) and by the fundamental harmonic pulse (vertically polarised with the energy of 450 μJ). By varying the mutual time delay, the bichromatic radiation was focused either into an undisturbed gas or plasma, previously formed in the gas in the focus. A system of two Teflon lenses (each 5 cm in diameter with a focal length of 6 cm) focused the terahertz radiation to the input GC-1P Golay cell (Tydex), closed with black paper, which prevented it from incident optical radiation. A decrease in the power of the detected signal due to the addition of an additional sheet of black paper was about 10%. We also introduced into the scheme a shutter to modulate laser (and terahertz) radiation, which allowed us to measure the average power of the terahertz radiation via synchronous detection.

In the case of a delay of the bichromatic pulse with respect to the single-frequency pulse, i.e., upon focusing it into the plasma, the measured energy of terahertz pulses, E, was $\sim$0.1 pJ. If the bichromatic pulse arrived before the single-frequency pulse, the energy of the detected terahertz pulses was $E = 0.9$ pJ. In the case of the air breakdown by single-frequency pulses only, the technique used did not allow us to measure the signal because of its smallness. Thus, in our scheme we measured only a terahertz signal from the bichromatic optical pulse. The spectrum of the detected pulses was not measured.

Similar measurements of the signal at the third harmonic frequency in the scheme described (which is generated due to the nonlinearity of the same order) showed that the presence of a pre-formed plasma reduces the signal level by only 15%.

3. Conclusions

A significant drop in the power of the measured terahertz signal suggests that photoionisation processes of an undisturbed gas play a fundamental role in the mechanisms of generation of terahertz radiation.

At the same time, the presence of a dense plasma in the focusing region of the bichromatic pulse can lead to the screening of terahertz radiation (without screening at the same time the signal at the third harmonic frequency).

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