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OPTICS AND LASER PHYSICS

Experimental Determination of the Unipolarity of Pulsed Terahertz Radiation

M. V. Arkhipov[a, *], A. N. Tsypkin[b, **], M. O. Zhukova[b, *], A. O. Ismagilov[b, ****], A. V. Pakhomov[a, *****], N. N. Rosanov[a, c, ******], and R. M. Arkhipov[a, c, *******]**

[a] *St. Petersburg State University, St. Petersburg, 199034 Russia*
[b] *ITMO University, St. Petersburg, 197101 Russia*
[c] *Ioffe Institute, St. Petersburg, 194021 Russia*
**e-mail: m.arkhipov@spbu.ru*
***e-mail: tsypkinan@mail.ru*
****e-mail: mozhukova@itmo.ru*
*****e-mail: ismagilov.azat@itmo.ru*
******e-mail: antpakhom@gmail.com*
*******e-mail: nnrosanov@mail.ru*
********e-mail: arkhipovrostislav@gmail.com*

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Energy, pulse duration, and frequency of the spectral maximum are important characteristics of pulsed terahertz radiation. The unipolarity of radiation is another characteristic that is paid less attention to. This paper demonstrates possible ways how to determine the presence of unipolarity in the radiation of pulsed terahertz sources. The first approach is based on integrating the time dependence of the field strength in the far zone obtained experimentally. The second approach uses radio-technical equipment by means of recording low-frequency components of pulses, which exist in the unipolar terahertz radiation. The results of experiments are presented with recording the unipolar component of THz pulses by both methods. The existence of unipolarity is shown for pulses from some types of terahertz radiation sources. Estimations are made for the electric area and the degree of unipolarity of the pulsed radiation for the first time.

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INTRODUCTION

The electric area of the electromagnetic pulse is defined as [1–6]

$$S_E = \int_{-\infty}^{+\infty} E(t)dt, \tag{1}$$

where $E(t)$ is the strength of the electric field at a given point in space and t is the time.

The vector of the electric field strength changes repeatedly its direction many times during the pulse duration in ordinary multicycle electromagnetic pulses. The electric area of such pulses is almost always equal to 0. When the pulse duration is reduced to one cycle of oscillations, it becomes possible to obtain the so-called unipolar half-cycle pulses, where the electric area is not equal to zero. They usually contain a powerful burst (half-wave) of a field of the same polarity and have nonzero electric area. The ways of obtaining such radiation have been actively discussed in the literature recently. We can see, for example, reviews [2–5, 7] and research papers [8–17].

The half-wave of a field with the equal polarity makes it possible to transfer quickly a directed momentum to a quantum system. If the duration of a unipolar pulse is much less than the characteristic period of oscillations of the wave packet in a quantum system, the effect of such pulses is determined by the electric area of the pulse [18–24]. Therefore, they can be used for the efficient and ultrafast control of wave packets in matter in comparison with multicycle bipolar pulses, for acceleration of charges [25], holographic recording with ultrahigh time resolution [26] and other applications [4].

The electric pulse area (1) has the important role in issues of the nonlinear interaction of extremely short unipolar pulses with matter. It is a vector and has a dimension. For quantum systems, an "atomic scale of an electric area" has been introduced, which determines the degree of their impact on micro-objects [23]. In addition to the electric area, there is another characteristic of unipolar pulses. It is the degree of unipolarity, determined by the expression [2–4]

$$\xi = \frac{\left|\int E(t)dt\right|}{\int |E(t)|dt}. \qquad (2)$$

In pulses with a nonzero electric area, the direction of the field strength can change a sign; therefore, this value characterizes the quality of the field "unipolarity."

When unipolar pulses propagate in space and in case of using optical systems, a loss of unipolarity occurs due to diffraction and radiation focusing [27]. Therefore, in the far field of the source, the unipolarity will be lost. The degree of unipolarity (2) can be used to quantify these losses of unipolarity in linear diffraction tasks.

The theory of waveguides indicates the possibility of solving this problem by using coaxial waveguides [28]. They have a lack of mode dispersion and cutoff frequency, which make it possible to transport unipolar pulses without losing unipolarity in general.

It is necessary to obtain unipolar pulses with a large electric area (high degree of unipolarity) for practical applications [4, 21–25]. Therefore, the task of measuring electric area and the degree of unipolarity is relevant. However, such issues have not yet been posed or solved as noted in [4].

In this work, we experimentally demonstrate two approaches to determine the unipolarity of radiation from THz sources. In the first case, the degree of unipolarity can be determined by integrating the time dependence of the field strength in the far zone. This allows to estimate the field in the near field from the source. The electric area is calculated by integrating the near field. In the second case, the registration of unipolarity in the near zone is carried out by radio frequency methods.

METHODS FOR DETERMINING THE FIELD STRENGTH IN THE NEAR-FIELD ZONE OF THE SOURCE

The experimental technique in the optical, infrared and THz ranges does not allow direct recording of the electric field strength. The detectors record signals proportional to the energy or the power of radiation. In this case, the information about the sign of the field is lost, which does not allow to draw conclusions about the existence of radiation pulses unipolarity.

It is possible to register indirectly the electric field strength using electro-optical systems (EOS) in the THz range [29]. The field strength in a THz pulse is determined by the change in the polarization of the probe field in a nonlinear crystal under the action of the THz radiation field strength. The polarization plane rotation of the probe radiation is used to fix the magnitude and the sign of the field strength in the THz pulse.

However, this is a multi-step procedure. It includes focusing of pulsed radiation into a crystal, which is a transition to the far zone. In this zone, the radiation loses its unipolarity. The field strength in the far zone $E_f(t)$ becomes proportional to the time derivative of the field strength created by the source in the near zone $E_n(t)$ [4]. In this case, one can use the integration procedure to restore the field in the near-field zone, which will allow to calculate the degree of unipolarity by formula (2). At the next stage, to find the electric area S_E, it is needed to integrate the field in the near field.

The second approach can be conditionally called radio engineering. It uses radio frequency techniques for registration, since the spectrum of unipolar radiation must contain components in the radio range and at zero frequency. At first glance, the idea of refusing to register high-frequency THz components and looking for a radio-frequency component in pulsed THz radiation looks very strange. However, such a possibility exists and it will be demonstrated below.

EXPERIMENTAL SETUP AND RESULTS

Terahertz pulses can be unipolar upon optical rectification of femtosecond pulses in lithium niobate crystals [30]. The experimental setup is shown in Fig. 1.

The laser system is used as the crystal pumping radiation. It has the pulse duration of 30 fs, energy of 2.2 mJ, rate of 1 kHz, and the pulse central wavelength of 800 nm.

The standard EOS scheme is used to register the field strength of THz radiation [29]. The pump laser radiation is split into two beams with ratio 49 : 1. The first pulse is used to pump a $MgO:LiNbO_3$ crystal. The THz pulse energy is 300 nJ at the crystal output, the pulse duration is 1.5 ps. The second beam passes the delay line DL and it is used in the EOS scheme for recording the field strength of a THz radiation pulse using a 1 mm thick ZnTe crystal.

The parabolic PM1 mirror has the focal length of 12.5 mm. It collimates pulses of THz radiation. The pump radiation is absorbed by filter F. Then, THz radiation is focused onto a ZnTe crystal using a PM2 parabolic mirror 5 cm in diameter with a focal length of 100 mm. A quarter-wave plate, a Wollaston polarizing prism WP, and a balance scheme BD are placed behind the crystal.

As noted above, the pulse field strength is recorded by the EOS and it is proportional to the time derivative of the field in the near field. The operation of integration $E_f(t)$ with a variable upper limit will give us the dependence of the field strength in the near field $E_n(t)$. Then, using formulas (1) and (2), one can find the

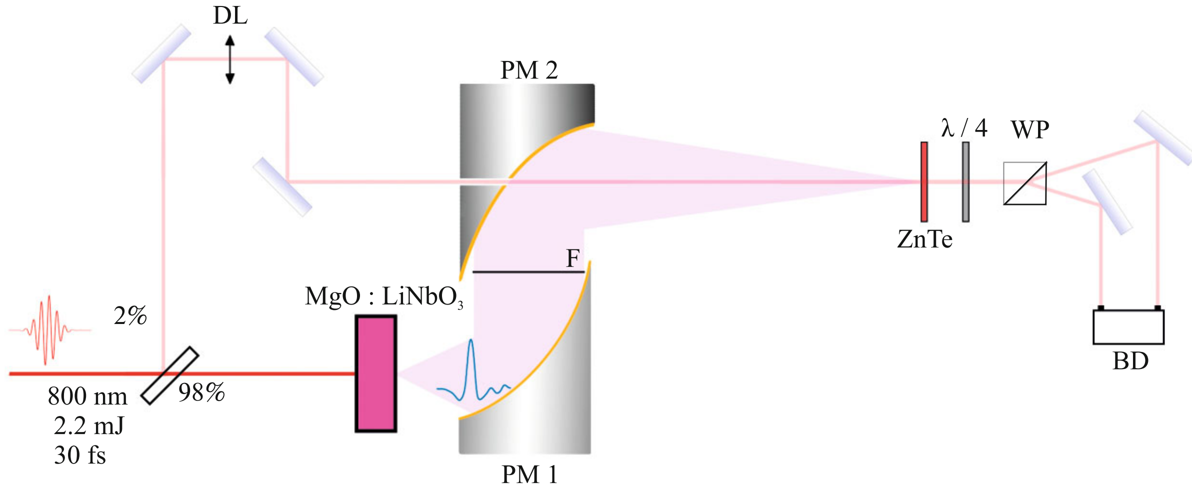

Fig. 1. (Color online) Experimental setup. The source of THz radiation is a lithium niobate crystal pumped by a pulsed laser radiation and a standard EOS for detecting the field strength of pulsed THz radiation using the 1-mm-thick ZnTe crystal.

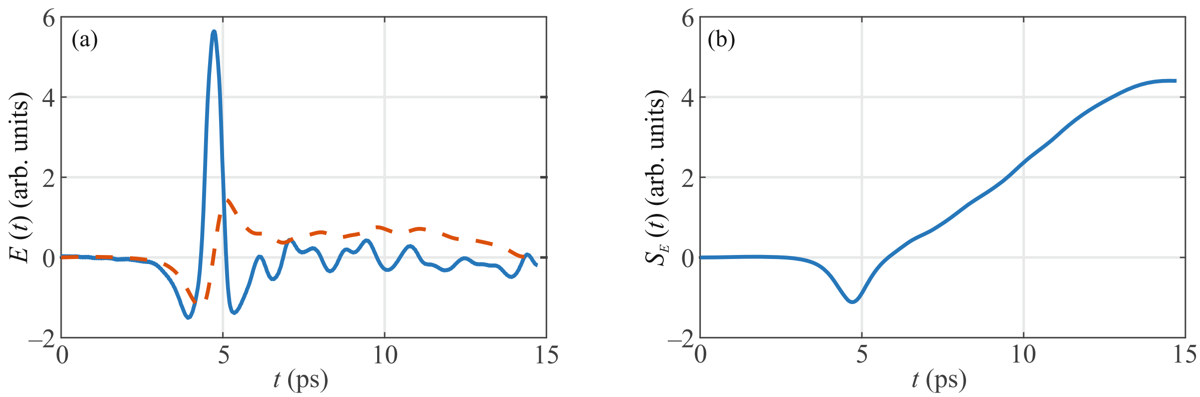

Fig. 2. (Color online) Case of THz radiation generation in the lithium niobate crystal. (a) Solid and dashed lines show the corrected $E_f(t)$ and $E_n(t)$ dependences, respectively. (b) Dependence of the electric area $S_E(t)$ calculated from the corrected value of $E_f(t)$.

electric area and the degree of unipolarity. Let's see how this approach works in practice in case of this typical scheme.

The dependence of the field $E_n(t)$ and the dependence of the electric area $S_E(t)$ are shown in Fig. 2. They have been obtained from the field strength $E_f(t)$ under the elimination of the "zero" drift of the registration circuit as a result of integration on time during the pulse corrected $E_f(t)$. Electrical area constant value has been obtained for the pulse from the Fig. 2b. The estimation of pulse electric area in the near-field zone gives the value $S_E = 10^{-5}$ V/(m s) and the degree of unipolarity $\xi = 0.66$.

It is noted that the lack of systematic error corrections when using EOS lead to an incorrect determination of the field in the near zone and the degree of unipolarity.

The precise measurements of $E_n(t)$ are not such an easy task. Any insignificant zero drift of zero in the balance scheme does not affect the position of the spectrum maximum and its width, but it can significantly change the value of the electric area of the pulse. In the given example, the pulse tail has made the significant contribution to the area.

This technique for determining the presence of unipolarity in the near zone has been used to identify the unipolarity of the pulsed radiation of filaments generated in jets of liquids. The phenomenon of filamentation is the propagation of light in a filamentous luminous channel. They arise during the propagation of powerful-pulsed radiation in a medium [31, 32]. The analysis of generation mechanisms during fila-

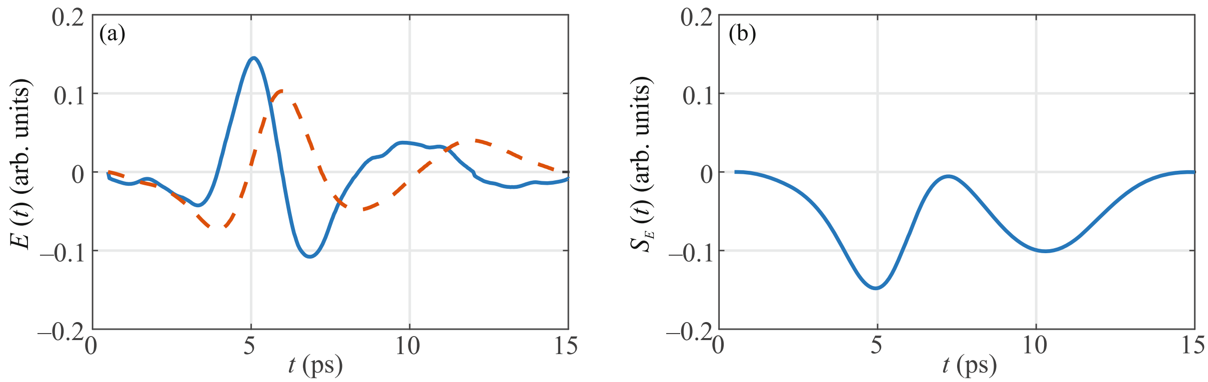

Fig. 3. (Color online) Generation of THz radiation in the water jet in the direction of pump radiation propagation. (a) Solid and dashed lines show the corrected $E_f(t)$ and $E_n(t)$ dependences, respectively. (b) Dependence of the electric area $S_E(t)$ calculated from the corrected value of $E_f(t)$.

mentation in liquids and the experimental setup are given in [33, 34]. According to the results of previously mentioned papers, the THz pulsed field recorded in our experiments is generated after the ionization of the liquid substance due to the appearance of a photocurrent under the action of fifth-order nonlinearity.

In the direction of the pump radiation propagation, the unipolarity of the filament radiation in the water jet has not been detected. The results are shown in Fig. 3. In this example, the near-field pulse $E_n(t)$ (dash-dotted line in Fig. 3a) contains two oscillation cycles. In each cycle, the electric area is zero. This situation is typical for multicycle pulses.

Unipolarity registration in the near field has also been carried out using radiotechnical means for experiments on THz radiation generation in a stream of water. If a pulse of radiation is unipolar, its spectrum contains components in the radio range, including the zero frequency. They can be detected directly with radio electronic means. For an oscilloscope input operating in the mode of measuring dc voltage, it is necessary to apply a signal from the output of the antenna, which should be placed as close to the source as possible.

High-frequency coaxial cables with an open end have been taken as the simplest antennas in our experiments. The open end of the cable acts as an antenna. It should be placed as close as possible to the source of THz radiation. An equivalent circuit of such registration and the example of the oscillogram are shown in Fig. 4.

The results of the experiments have shown that in this way it is possible to register the low-frequency components in the radiation coming from the filamention in the liquid jet in the opposite direction to the pump radiation propagation direction (see Fig. 4b). Low-frequency components have not been detected in the transmitted radiation, which is consistent to the result obtained using the EOS.

Such a simple system allows, first of all, to qualitatively assess the presence of a unipolar component. Quantification requires to calculate the effect of a unipolar pulse on an antenna, which is not such an easy task. To estimate the field strength of a unipolar pulse, the following reasons can be carried out. A pulse in the simplest antenna induces an EMF $\varepsilon = E_0 h$, where E_0

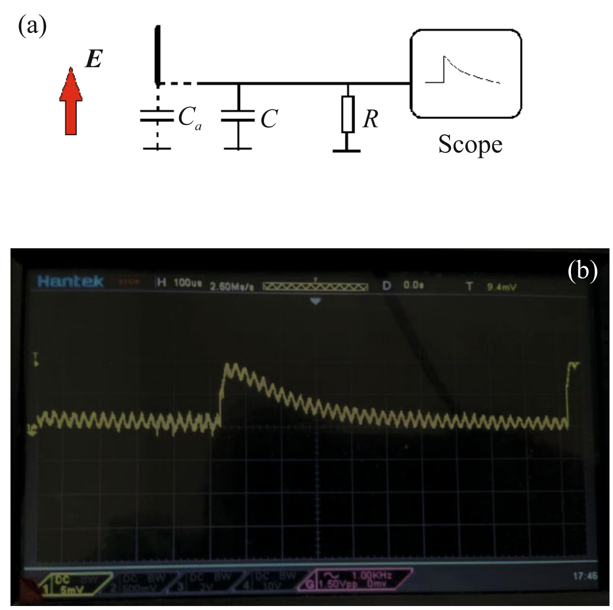

Fig. 4. (Color online) (a) Circuit for recording low-frequency components in a THz radiation pulse. C_a and C are capacitances of the antenna and the cable, R is the input impedance of the oscilloscope. (b) Example of pulses on the screen of the Hantek DSO 4254C oscilloscope from the open end of the cable located at a distance of 1 mm near the water jet. It is illuminated by laser pulses that excite pulsed THz radiation. The sinusoidal noise with the small amplitude is a consequence of the interference from electronic control circuits of the pump laser.

is the field strength and h is the effective antenna height. We will assume that the EMF exists during the pulse duration Δt. An extremely short pulse charges the antenna capacitance C_a. The charge $Q_a = \varepsilon C_a$ charges the capacitance of the cable C. Two capacitors are connected in parallel and therefore the voltage U on both capacitors becomes equal, then the value $\varepsilon = U(C_a + C)/C_a$. The voltage value U is displayed on the oscilloscope screen.

Assuming $C = 10^{-11}$ F, $C_a = 10^{-14}$ F, $h = 0.001$ m and considering $U = 0.02$ V, we obtain an estimation for the field strength $E_0 = 20\,000$ V/m and the value of the electric area $S_E = 2 \times 10^{-8}$ V/(m s). This estimation is made using an extremely rude measurement model. The accurate antenna design is required to obtain correct values, which is a challenging task.

Let's compare the values of the electric areas determined experimentally with the value of the "atomic scale of electric area" for a quantum oscillator in the THz range $S_{0,HO}$, introduced in [23]. It is a measure of the effectiveness of unipolar pulses action onto quantum objects. For a quantum oscillator, we get $S_{0,HO} = \frac{\sqrt{2\hbar\omega_0 m}}{q} \cong 10^{-5}$ V/(m s). The following parameter values are used in the estimation: the natural frequency of the oscillator $\frac{\omega_0}{2\pi} = 1$ THz, the mass of the oscillator $m = 1.67 \times 10^{-27}$ kg (proton mass), the oscillator charge q been equal to the electron charge.

The parameters S_E and $S_{0,HO}$ are of the same order of magnitude for the near-field zone of the crystal. $S_E/S_{0,HO} = 0.002$ is in the case of the emission in the water filament, moving towards the pump pulse. It is in contrast to the situation with rectification in a crystal. Such electric area is clearly insufficient for the efficient excitation of molecular systems.

Additionally, we have carried out in this way experiments to observe a constant component in the emission of a spark in the air and sparks on the surfaces of various metals in the near zone. In these cases, the presence of a constant component is also observed, which allows us to conclude that the radiation is unipolar.

In these situations, the appearance of unipolarity should be associated with the formation of the nonstationary plasma, where a powerful current pulse arises due to a short-term directed motion of electrons. The possibility of a photoelectric effect from the antenna surface should be also take into account under the action of UV radiation accompanying laser filaments and sparks. It will lead to the appearance of a current pulse that is not associated with unipolar components. Filters must be installed to eliminate the contribution from the photoelectric effect. Filters, due to their finite size, move away the antenna from the source and the signal decreases.

CONCLUSIONS

The paper proposes approaches to recording the unipolarity of pulsed THz radiation.

The first approach is based on the double integration of the time dependence of the electric field strength. It is obtained by recording the time dependence of the electric field strength of THz pulses in EOS systems. It is shown that the method requires careful consideration of the systematic errors inherent for such systems. Using it, the presence of unipolarity in the near zone of a THz radiation source based on optical rectification in a lithium niobate crystal has been shown. The electric area and the degree of unipolarity of radiation in the near zone of the crystal has been determined. The absence of unipolarity for pulsed radiation arises during filamentation in the liquid jet (distilled water). It happens under the action of pulsed laser radiation in the femtosecond range of duration and goes in the direction of pumping.

The second approach is based on the registration of the THz pulse unipolar signal of low frequency by radio technical means. In our study, we use the open end of a coaxial cable as an antenna, which is located as close as possible to the source. The measurements show the absence of a constant field component in the filament radiation in the direction of the propagation of the laser pumping radiation. It agrees with the results of measurements by integration methods. The unipolar component has been found in the radiation of the filament in the opposite direction to the propagation of the laser pump pulse. Unipolar components have also been recorded when laser sparks are created in the air and on the surface of metals.

These studies are the first experimental demonstration of the presence of unipolarity in the radiation of pulsed sources of the THz range, the estimation of the electric area and the degree of unipolarity of pulses. In addition, for the first time, comparisons have been made of the electric area of generated pulses with the "measure of electric area" for quantum systems introduced in [23].

It is noted that these approaches have disadvantages. In the first case, a very accurate registration of the time dependence of the field strength by the EOS system is required. This is not an easy task. The approach is sensitive to systematic, hard-to-control errors. The radio engineering method requires the use of small broadband antennas and their placement near the sources. Nevertheless, in our opinion, these are the only valid and practically applicable approaches to detecting the unipolarity of radiation. They can be used to solve the problems of detecting the unipolarity of radiation.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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