

Application of a Balanced Electro-Optical Detector in a Terahertz Pulse Spectrometer

G. I. Kropotov^{a,*}, D. I. Tsyphka^{a,**}, and V. E. Avitsyuk^a

^aOOO TIDEKS, St. Petersburg, 194292 Russia

*e-mail: grigorykropotov@tydex.ru

**e-mail: dmitrytsyphka@tydex.ru

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Abstract—An electro-optical detector (EOD) of terahertz (THz) radiation has been developed. The basic operating principles of the device and the advantages of its application in THz spectroscopic systems are discussed.

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1. INTRODUCTION

The development of time-domain spectroscopy (TDS) and related THz technologies has led to the emergence of another way to study the world around us. Its progress is due the emergence of pico- and femtosecond lasers, which made it possible to implement an optical method for generating THz radiation based on the fact that the interaction of short laser pulses with matter leads to the emergence of polarization pulses in nonlinear optical media, the relaxation of which creates waves of electromagnetic THz radiation. Femtosecond laser radiation can also be used to detect pulsed THz radiation.

Several methods can be used to detect THz radiation. The first receiver of THz radiation was a photoconductive antenna. Electro-optical detection has also gained widespread acceptance due to its wide bandwidth and parallel imaging capabilities. The broadband pulse spectrometer developed by TIDEX uses the method of optical rectification of femtosecond pulses to generate THz radiation [1]. To register pulses, the electro-optical detection method [2] is used, using an electro-optical detector of pulsed THz radiation.

The TIDEX pulsed THz spectrometer is a comprehensive device for broadband THz spectroscopy in the time domain. It consists of the following components (Fig. 1):

1. Solid-state femtosecond laser;
2. Electro-optical detector (EOD) of pulsed THz radiation;
3. Optomechanical components for optical and THz paths;
4. Delay line;

5. Control electronic units of the optical delay line, optical-mechanical modulator, and laser;

6. PC with installed software.

The basic optical diagram of the pulsed THz spectrometer is shown in Fig. 2.

The radiation of the ytterbium TeMa-1050/100 solid-state femtosecond laser (OOO Avesta) is divided into two beams: a pump beam and a probe beam. A more powerful pump beam is used to generate a THz pulse. Generation occurs due to the effect of optical rectification of femtosecond laser pump pulses in a 1% MgO:LiNbO₃ crystal. The effect of optical rectification is that when an intense optical pulse passes through a nonlinear optical crystal, nonlinear polarization occurs in the latter, repeating the shape of the optical pulse envelope (Fig. 3) [3]. The probe beam is used to detect the THz pulse. An electro-optical detector is used to detect THz pulses. Detection occurs due to a change in the polarization of the probing pulse in the presence of a THz pulse.

The mechanisms of generation of THz pulses in a broadband pulse spectrometer are described in [4]. This paper provides a detailed discussion of the operating principles of EOD and the benefits of its use in such systems.

2. ELECTRO-OPTICAL DETECTION OF THz RADIATION USING AN ELECTRO-OPTICAL DETECTOR

A classical balanced photodetector is a device that measures the difference between photocurrents and generated light falling on two photodiodes. This difference then intensifies with the help of a built-in amplifier, is supplied to the external blocking ampli-

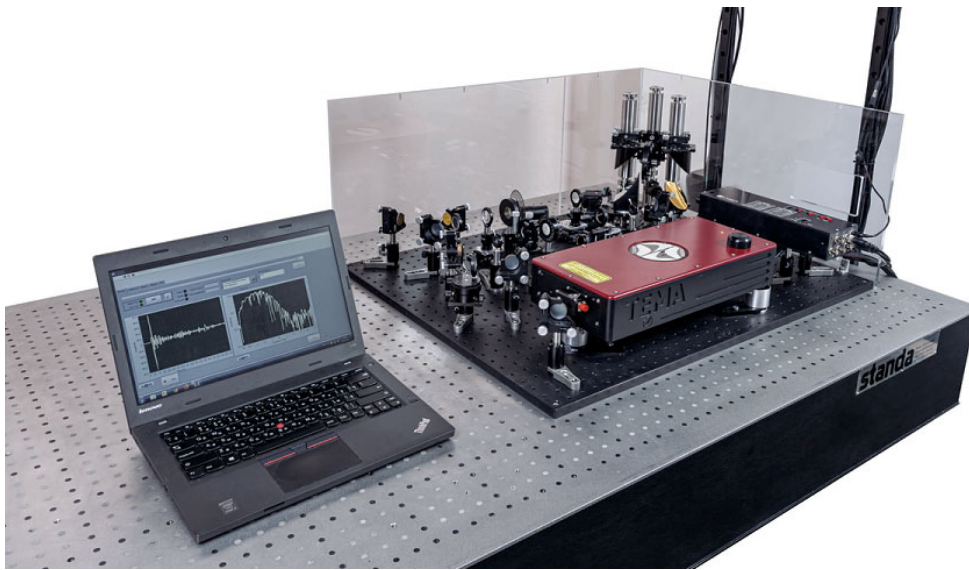


Fig. 1. Pulsed THz spectrometer from TIDEX.

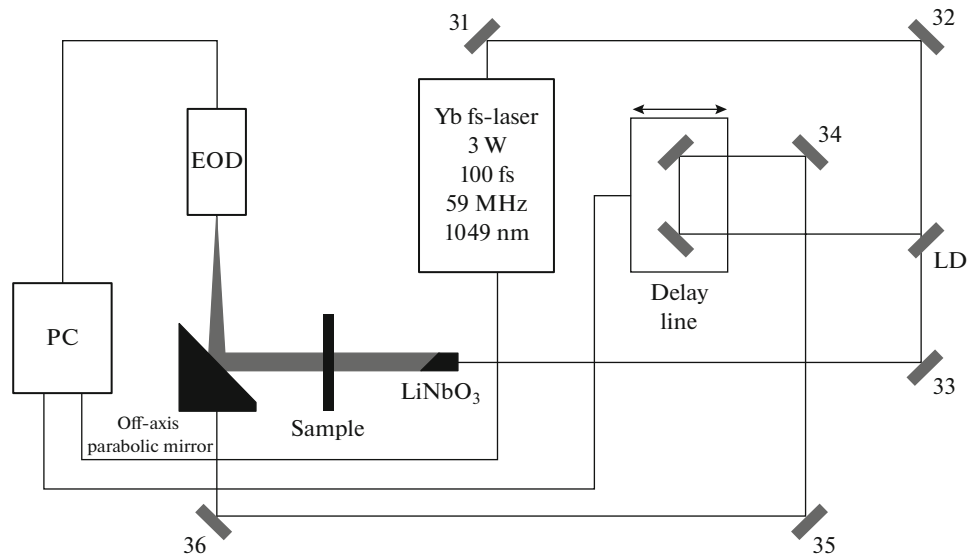


Fig. 2. Schematic diagram of a broadband pulsed spectrometer.

fier, and is displayed on a visualizer (oscilloscope or computer).

An electro-optical detector based on a balanced detector is used to detect coherent THz radiation in a broadband pulsed THz spectrometer operating in the time domain since it allows the magnitude of the THz radiation field to be directly determined. In a broader sense, EOD can be used as a THz field detector in all cases where optical mixing of the THz laser and reference beams can be performed on a nonlinear crystal.

Progress in the development of EOD is associated with the integration of electronics and optics into a single system, which allows for the production of an

analyzed signal at the output, suitable for output to a personal computer. On the other hand, calculating in electronics not the difference between photodiode signals but their ratio allows for greater stability of the device with respect to fluctuations in the reference laser beam.

The operation of EOD is based on the use of the electro-optic effect caused by the action of low-frequency THz radiation in a nonlinear optical crystal when probing radiation passes through it. A THz-range beam is focused onto an electro-optic crystal, and a beam of probing radiation is directed coaxially into the crystal.

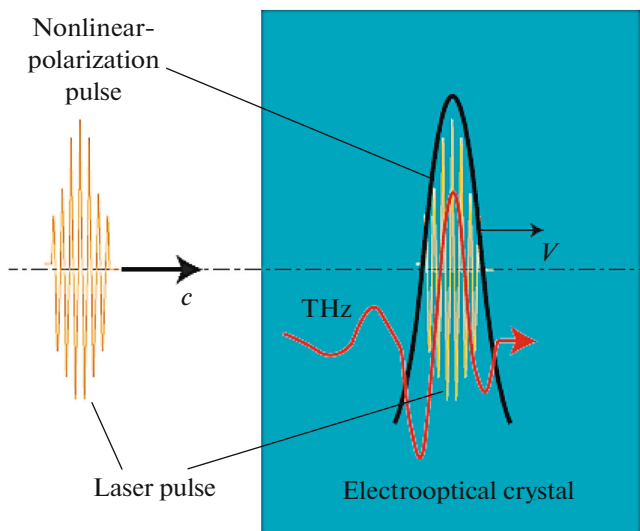


Fig. 3. Optical straightening.

To efficiently record weak THz signals, a synchronous detection method is used in which the THz beam is premodulated and the EOD signal is sent to a synchronous amplifier. By changing the delay of the test pulse step by step, we write the time profile of the THz pulse field.

The electro-optical detector records the electric field of THz pulses in time representation, determining not only the amplitude of the field but also its phase [5]. The basis of electro-optical detection is the Pockels effect for electro-optical crystals, which consists of a change in the refractive index of a medium in the optical range in the presence of an external electric field, which is a THz pulse field in this case. The difference in refractive indices is proportional here to its

amplitude ($\Delta n \propto E_{\text{THz}}$). The converse is also true: the amplitude of the applied field can be determined by measuring the birefringence it induced.

Figure 4 shows a typical scheme for electro-optical detection of a THz signal by measuring the THz-field-induced birefringence. If the group velocity of an optical pulse is well matched to the phase velocity of a THz pulse in an electro-optic crystal, the optical pulse will change its polarization during its propagation through the crystal under the influence of birefringence caused by the constant THz field. The same figure shows the change in polarization of the test pulse as it passes through the setup in the presence and absence of a THz signal.

During the passage of a linearly polarized optical pulse and a THz pulse through an electro-optic crystal, under the influence of the THz field-induced birefringence, the polarization becomes elliptical as a result of the different phase shifts for the ordinary and extraordinary waves. The magnitude of ellipticity, proportional to the magnitude of the THz field, can be recorded using a polarization analyzer. In EOD, a quarter-wave plate and a Wollaston prism are used as the polarization analyzer. The Wollaston prism splits the probe beam into two orthogonal polarized beams obtained using a polarization analyzer. Each of the beams is detected by its own photodiode. An electro-optical detector measures the difference in intensity between two orthogonal components $I_s = I_y - I_x$. This difference is proportional to the amplitude of the applied THz field.

To increase the sensitivity of the circuit, the pump beam is modulated using a mechanical chopper, and the modulation of the probe beam polarization caused by the THz pulse is detected using a lock-in amplifier built into the EOD.

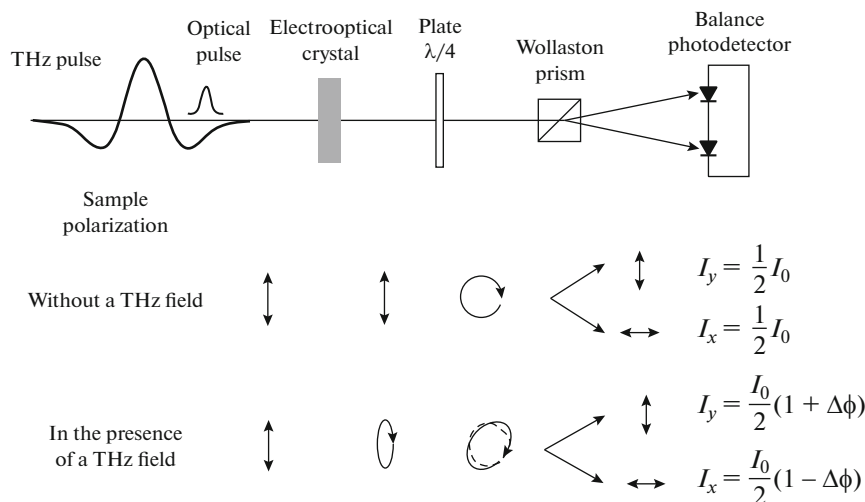


Fig. 4. Schematic diagram of an experiment to study the electro-optic effect. The polarization of an electro-optic crystal is shown before and after the beam passes through polarizing optics.

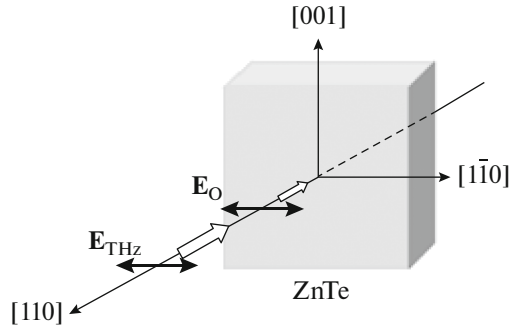


Fig. 5. Directions of polarization of the THz field and the probe laser beam in a ZnTe crystal.

For electro-optical detection purposes, an electro-optical crystal, such as zinc telluride (ZnTe), is used. Good matching of the phase velocity of the THz pulse with the group velocity of the optical pulse with a wavelength of approximately 800 nm, high transparency at both optical and THz frequencies, and a large electro-optical coefficient $r_1 = 4$ pm/V make this crystal suitable for electro-optical detection. The choice of crystal type is made taking into account the requirements for the signal-to-noise ratio of the device as well as the spectrum width of the detected signal. A set of crystals of different thicknesses can cover a significant part of the THz spectrum with a given signal-to-noise ratio.

A typical direction of polarization of optical and THz beams with respect to the crystallographic axes of the crystal is shown in Fig. 5. The THz field-induced birefringence will be maximum when both the optical and THz pulses are linearly polarized parallel to the axis $[1\bar{1}0]$ of the ZnTe crystal.

The nonlinear polarization of an optical pulse is orthogonal to the electric field of the pulse. Therefore, when an optical pulse passes through a ZnTe crystal, its polarization, under the influence of the THz field, changes from linear to elliptical.

Phase shift of the polarization of the probe beam due to the Pockels effect when an optical pulse passes through a crystal of thickness L is determined by the formula

$$\Delta\varphi = (n_y - n_x) \frac{\omega L}{c} = \frac{\omega L}{c} n_0^3 r_1 E_{\text{THz}}, \quad (1)$$

where n_0 is optic refractive index at the frequency of the probe beam and r_1 is electro-optic coefficient. The intensities of orthogonally polarized beams incident on a balanced photodetector are determined as follows:

$$I_x = \frac{I_0}{2} (1 - \sin\Delta\varphi) \approx \frac{I_0}{2} (1 - \Delta\varphi), \quad (2)$$

$$I_y = \frac{I_0}{2} (1 + \sin\Delta\varphi) \approx \frac{I_0}{2} (1 + \Delta\varphi), \quad (3)$$

where I_0 is intensity of the test beam. The $\Delta\varphi \ll 1$ approximation is used here, performed with electro-optical detection. Accordingly, the signal at the output of the balanced photodetector is determined by the amplitude of the THz field:

$$I_S = I_y - I_x = I_0 \Delta\varphi = \frac{I_0 \omega L}{c} n_0^3 r_1 E_{\text{THz}} \propto E_{\text{THz}}. \quad (4)$$

In a real situation, the time or frequency resolution of the electro-optical detection method is limited by three factors: the finite duration of the probe pulse, the dispersion of the nonlinear susceptibility, and the velocity mismatch of the optical and THz signals in the nonlinear crystal. Accordingly, the signal at the output of the electro-optical detector is a convolution of the THz pulse field and the detector response function $F(\omega, \omega_{\text{THz}})$, determined by all three factors [2]:

$$E_S(t) = \int_{-\infty}^{\infty} E_{\text{THz}}(\omega_{\text{THz}}) F(\omega, \omega_{\text{THz}}) e^{-i\omega_{\text{THz}} t} d\omega_{\text{THz}}, \quad (5)$$

where $E_S(t)$ is time representation of the signal at the detector output and $E_{\text{THz}}(\omega_{\text{THz}})$ is complex amplitude of the THz pulse. The Fourier transform of both sides of the equation yields a simple relationship between the THz pulse and the output signal in frequency representation:

$$E_S(\omega_{\text{THz}}) = F(\omega, \omega_{\text{THz}}) E_{\text{THz}}(\omega_{\text{THz}}). \quad (6)$$

Here, $F(\omega, \omega_{\text{THz}})$ is the detector response, which is the product of three frequency-dependent components:

$$F(\omega, \omega_{\text{THz}}) = A_{\text{Opt}}(\omega_{\text{THz}}) \chi^{(2)}(\omega, \omega_{\text{THz}}, \omega - \omega_{\text{THz}}) \Delta\Phi(\omega, \omega_{\text{THz}}), \quad (7)$$

where $A_{\text{Opt}}(\omega_{\text{THz}})$ is the autocorrelation function of the electric field of the probe optical pulse, defined as follows:

$$A_{\text{Opt}}(\omega_{\text{THz}}) = \int_{-\infty}^{\infty} E_{\text{Opt}}^*(\omega' - \omega) E_{\text{Opt}}(\omega' - \omega - \omega_{\text{THz}}) d\omega', \quad (8)$$

$\chi^{(2)}(\omega; \omega_{\text{THz}}, \omega - \omega_{\text{THz}})$ is second-order nonlinear susceptibility. Function $\Delta\Phi(\omega, \omega_{\text{THz}})$ takes into account the mismatch between the group velocity of the optical pulse and the phase velocity of the THz radiation.

Figure 6 shows the frequency dependence of the second-order nonlinear susceptibility in ZnTe. The burst of the function in the region of 5 THz shows that the main physical factor influencing this value is the transverse phonon mode with a frequency of 5.3 THz. The magnitude of $\Delta\Phi(\omega, \omega_{\text{THz}})$ determines the frequency filtering caused by the speed mismatch; it is given by the formula

$$\Delta\Phi(\omega, \omega_{\text{THz}}) = \frac{e^{i\Delta k(\omega, \omega_{\text{THz}})L} - 1}{i\Delta k(\omega, \omega_{\text{THz}})}. \quad (9)$$

Wave vector mismatch Δk is defined as follows:

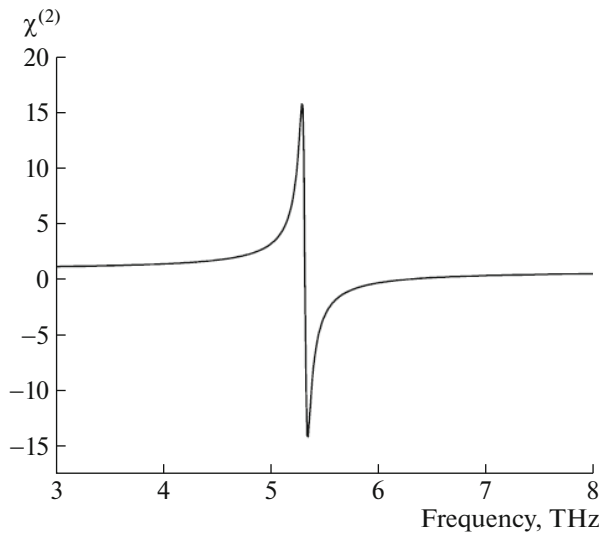


Fig. 6. Second order nonlinear susceptibility in ZnTe.

$$\Delta k = k(\omega) + k(\omega_{\text{THz}}) - k(\omega + \omega_{\text{THz}}) \\ = \frac{\omega}{c} n_o(\omega) + \frac{\omega_{\text{THz}}}{c} \{n_T(\omega_{\text{THz}}) + ik_T(\omega_{\text{THz}})\} \\ - \frac{\omega + \omega_{\text{THz}}}{c} n_o(\omega + \omega_{\text{THz}}), \quad (10)$$

where n_o and $n_T + ik_T$ are optical and THz refractive indices in ZnTe. Due to nonlinear absorption involving two-phonon processes, the imaginary part of the THz refractive index k_T must be corrected for the measured absorption coefficient.

Figure 7 shows the normalized amplitude of the detector response function in the range of 0–5 THz for ZnTe crystals of different thicknesses with a probe pulse duration of 100 fs. Due to the transverse phonon resonance at 5.3 THz, the detector response at frequencies above 4 THz is negligible. As the crystal thickness increases, the sensitivity increases linearly, but the bandwidth decreases due to the speed mismatch.

Thus, the magnitude of the electro-optic effect depends on the thickness of the crystal and on the magnitude of the spectral response of the crystal. The thinner the crystal, the higher the spectral response in the range of 0.2–2 THz and in the range above 3 THz. As the crystal thickness increases, the magnitude of the spectral response in the range of 0.2–2 THz decreases and the signal in the range of values above 3 THz begins to be distorted. In the frequency region of 2.5 THz, the magnitude of the spectral response remains constant. Due to the transverse phonon resonance at a frequency of 5.3 THz, the spectrum of the measured THz radiation is limited to 5.3 THz. The highest signal amplitude and the most informative curve are obtained when using a 1-mm thick ZnTe crystal.

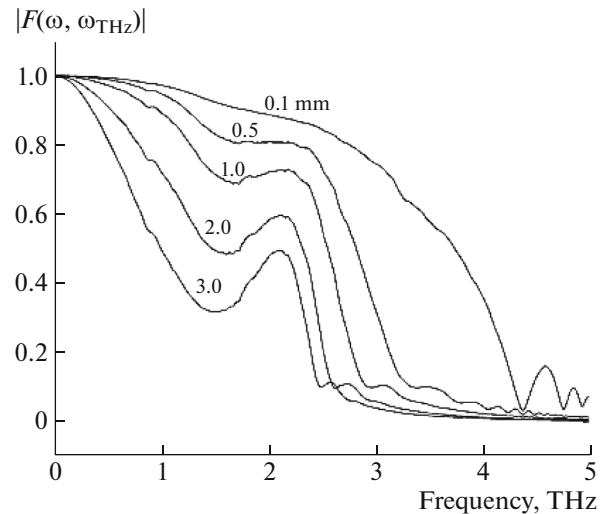


Fig. 7. Normalized amplitude of the detected response function $F(\omega, \omega_{\text{THz}})$ for ZnTe with an optical pulse duration of 100 fs and different crystal thicknesses.

It follows from formula (4) that it is necessary to know the ratio $(I_y - I_x)/I_0$ to calculate the THz field using EOD. In addition, with fluctuations I_0 , there will be fluctuations in the values in the numerator. This allows us to conclude that it is advisable to implement hardware for calculating the specified ratio rather than the difference in values in the numerator.

3. ELECTRO-OPTICAL DETECTOR FROM THE COMPANY TYDEX

The model of a THz pulse detector developed at TIDEX [6] is based on dividing the difference in photocurrent signals by their sum. This allows for a more stable result to be obtained with temporary fluctuations of the reference laser beam than in common models where the difference in signals is divided by the reference signal [7, 8]. By using this model, it became possible to directly measure the field strengths of THz radiation pulses without additional calculations.

Due to the complexity of isolating the sum of signals optically, the addition of signals is performed after digitization on programmable logic. For this purpose, individual amplification of signals from each photodiode is carried out.

A special feature of the detectors produced by TIDEX is the presence of built-in optics as well as a built-in synchronous amplifier (lock-in amplifier). The detector implements signal normalization functions, automatic signal balance adjustment on photodetectors, and also provides the ability to control the mechanical delay line from the original software supplied with the EOD. The scope of application of this device is time domain spectroscopy systems. Built-in optics make it possible to quickly and easily integrate



Fig. 8. Appearance of electro-optical pulse detector THz-radiation from TIDEX.

the detector into a ready-made measuring (experimental, etc.) circuit. The synchronous amplifier provides a high signal-to-noise ratio and makes the detector itself more compact and convenient to install and use. The signal normalization function ensures that a high signal-to-noise ratio and accurate measurement of the THz pulse time shape are maintained during fluctuations in the input signal and pump laser power levels. Modern software developed for Windows (XP, Vista, 10) allows one to easily manage EOD parameters, display measurement results, and control the device both independently and as part of a TDS system, including control of a typical delay line.

In the EOD models produced by TIDEX, depending on the range of signal radiation wavelengths, electro-optical crystals ZnTe (60–1100 nm) and CdTe (1100–1700 nm) are used. The main technical characteristics of EOD are given in Table 1.

A USB 2.0 port is used to connect the detector to the PC, and an RF connector is used to output the signal to the oscilloscope.

4. CONCLUSIONS

The EODs produced by TIDEX implement hardware division of the difference in photocurrents by their sum, which allows for a result that is more stable with respect to temporary fluctuations in the reference laser beam.

The synchronous amplifier integrated into the device's common board increases the device's signal-to-noise ratio. All passive optical elements (electro-optic crystal, quarter-wave plate, Wollaston prism) are integrated into a single device. This allows for reducing the dimensions of TDS systems and simplify the procedure for aligning circuit elements.

Table 1. Main technical characteristics of EOD

Name of characteristic, unit of measurement	Meaning
Spectral width of signal radiation, nm	11–20
Spectral sensitivity, THz	0.1–4
Duration of signal radiation pulse, fs	<120
Signal beam power, mW	1–20
Minimum required power of THz radiation in the frequency range of 0.1–4 THz, nW	1
Modulation frequency of the synchronous amplifier, Hz	15–250000
Gain of a synchronous amplifier	100–30000
Time constant of a synchronous amplifier, s	0.003–10

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CONFLICT OF INTEREST

The author of this work declares that he has no conflicts of interest.

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