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Comparison of an electro-optical system and photo-conducting antenna employed as detectors of pulsed terahertz radiation by means of a new method for measuring spectral width*

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Abstract. **Two detection systems, electro-optical system and photo-conducting system, are tested by the method suggested previously for determining the boundaries of broadband terahertz radiation in time-domain spectroscopy. From a series of measurements the error in determining the operation ranges is calculated. The terahertz spectrometer with an electro-optical detector based on a ZnTe (110) crystal of thickness 2 mm has the operation spectral range of 0.059–1.092 THz. The detector utilizing an iPCA-21-05-1000-800-h photo-conducting antenna with the same source of signal demonstrates a wider operation band ranging from 0.017 to 1.6 THz. The method developed makes it possible to experimentally compare the parameters of the considered terahertz spectrometers obtained under the same quality of adjustment.**

Keywords: *pulsed terahertz radiation, time-resolved terahertz spectroscopy, spectral width.*

1. Introduction

The term ‘terahertz radiation’ denotes radiation in the spectral range 300 GHz–10 THz. Residing in the frequency scale between IR and millimetre spectral ranges, THz radiation provides wide possibilities for studying molecular structures of materials because most vibration and rotation spectra of molecules fit this range [1–4].

In systems of pulsed terahertz spectroscopy the actual problem is to determine the frequency range in which the device provides authentic data [5–8]. Presently, the operation range in such systems is found by determining the range of crossing the spectrum of power distribution of a terahertz pulse with the noise spectrum of the detection system, obtained in the absence of a terahertz signal. However, if the detection system has a very low noise, the latter may become lower than the noise of the terahertz pulse which makes it impossible to reliably determine the operation spectral range [3]. We have elaborated the method capable of determining the width of frequency ranges of operation in the systems of pulsed terahertz spectroscopy in which the signal amplitude definitely prevails over that of noise [9]. The present work is aimed at testing the method developed previously for finding the boundaries of the spectrum of wide-band terahertz radiation in time-domain spectroscopy systems and at comparing the spectral width of the terahertz pulse detected from the same source by two detection systems based on the linear electro-optical effect and on the photo-conducting antenna.

2. Experimental setup

The scheme of the time-domain terahertz spectrometer [3] used in our experiments has two detection systems with the possibility of switching between them (Fig. 1).

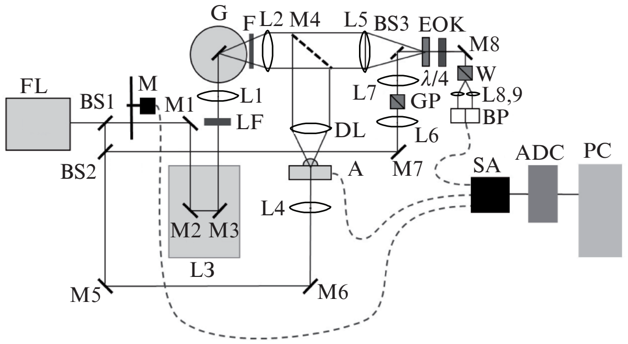

Figure 1. Experimental setup of a pulsed THz spectrometer: (FL) femtosecond laser; (BS1–BS3) beam splitters; (M1–M8) mirrors; (M) modulator; (DL) delay line; (LF) neutral light filters; (L1–L9) lenses; (G) generator of THz radiation; (F) filter of THz radiation; (A) photoconducting antenna; (GP) Glan prism; (EOC) electro-optical crystal; ($\lambda/4$) quarter-wave plate; (W) Wollaston prism; (BP) balance photodetector; (SA) synchronous amplifier; (ADC) analogue-to-digital converter; (PC) personal computer.

The spectrometer employed a TiF-15 femtosecond laser (Avesta-Project, Russia) with the radiation pulses of duration 35 fs at a centre wavelength of 800 nm. The average output power of the laser was 350 mW and the pulse repetition rate was 70 MHz. The source of terahertz radiation was an undoped InAs crystal placed into a field of the permanent magnet with the induction of 2.4 T. Then, radiation was collimated by a polymethylpentene lens (Tideks, Russia) with a focal length of 50 mm and reflected by mirror M4 to the system with an iPCA-21-05-1000-800-h photo-conductive antenna–detector (BATOP, Germany) or to an electro-optical detection system with a ZnTe crystal (110) of thickness 2 mm. The power of pump radiation can be varied by a set of neutral light filters. The intensity of the probe beam in the

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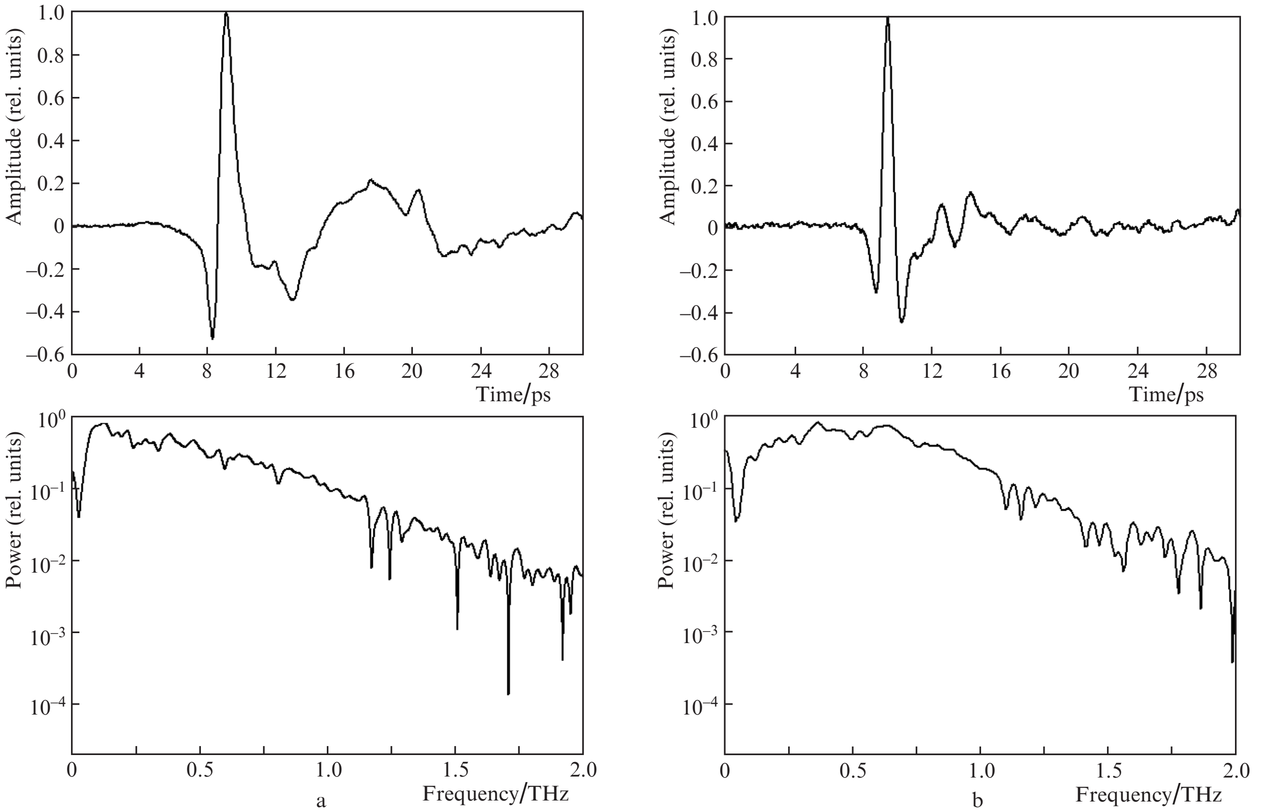

Figure 2. Time-domain and frequency-domain presentation of a terahertz pulse detected by (a) a photo-conducting antenna and (b) an electro-optical detection system.

electro-optical system was made lower to provide a linear operation regime for diodes of the balance detector. In single measurements the signal/noise ratio was 200 for the photo-conducting antenna and 80 for the electro-optical detection scheme (Fig. 2).

3. Method for determining the spectral width

The method for determining the spectral width of pulsed terahertz spectrometers developed previously was described in [9]. In this method it is necessary to detect terahertz pulses of various amplitudes by varying the power of pump radiation, for example, using light filters (Fig. 3a). Then, the spectra are analysed in the terahertz range, and the dependence of the power spectral distribution of terahertz radiation on the pump radiation power is determined for each frequency. The power of pump radiation is chosen to provide a linear dependence of the power of terahertz radiation without saturation. In this case, the derivative of the power spectral distribution with respect to the pump power ($\mathrm{d}P_{\mathrm{THz}}/\mathrm{d}P_{\mathrm{pump}}$) corresponds

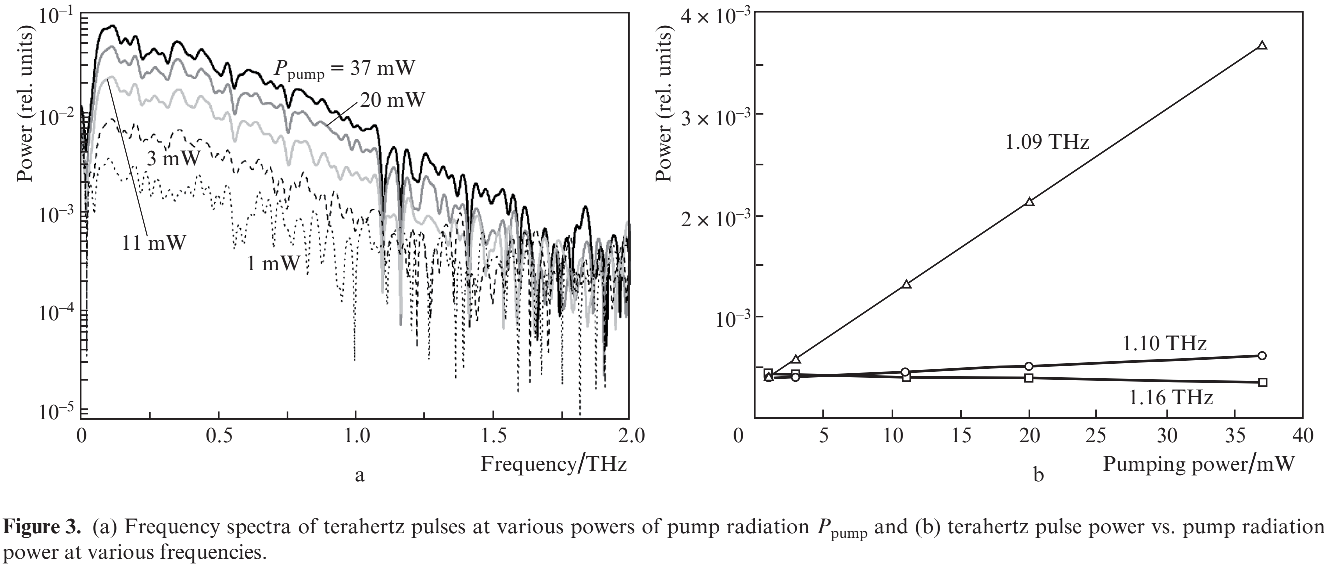

Figure 3. (a) Frequency spectra of terahertz pulses at various powers of pump radiation P_{pump} and (b) terahertz pulse power vs. pump radiation power at various frequencies.

to the angle of slope of an approximating curve. If the angle is positive, then radiation is generated at this particular frequency and detected in the spectrometer. If the angle is negative or zero at some frequency, then either radiation is absent or its power is not sufficient to be detected by the spectrometer (Fig. 3b).

4. Comparison of the electro-optical system and photo-conductive antenna used for detecting terahertz radiation

For each of the detection systems, a series of field measurements of terahertz pulses have been performed at the average pump radiation power of 37, 20, 11, 3 and 1 mW. For each value of the pump power, eight measurements of the THz pulse field were taken which provided a single series. In each measurement series, the spectral distribution of the derivative of the terahertz radiation power with respect to pump power was calculated by the method described above and the average spectrum $\langle dP_{\mathrm{THz}}/dP_{\mathrm{pump}}\rangle$ was found (Fig. 4).

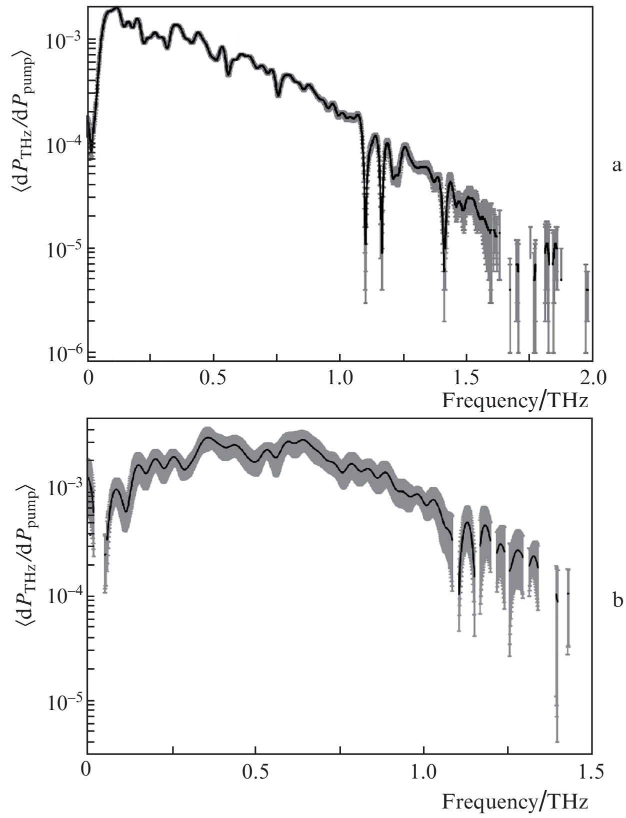

Figure 4. Spectra of the average derivative terahertz radiation power with respect to the pump radiation power in the case of (a) a photo-conducting antenna and (b) an electro-optical detection system.

Results of detecting the signal from the same source by the two detection systems noticeably differ. The system based on the photo-conductive antenna which in the present experiment has a higher signal/noise ratio exhibits a wider frequency band ranging from 0.017 to 1.6 THz, whereas the band of the electro-optical system varies from 0.059 to 1.092 THz (Fig. 4). Usually, the spectral band of a system with electro-optical detection is wider than that with an antenna–detector [10]. However, in the present work the installation with the antenna–detector was more exactly adjusted than that with the electro-optical detection system.

In the low-frequency range both spectra demonstrate bursts of the power distribution near the zero frequency which is explained by a nonzero level of the measured signal prior to the terahertz pulse in the time-domain presentation. For the start of the operation range we choose the point corresponding to the positive growth of the power spectral distribution while increasing the frequency. In the high-frequency spectral range one can see water absorption lines at the frequencies of 1.1 and 1.2 THz (Fig. 4). The dynamic range of our electro-optical system is not sufficient for measuring the shapes and intensities of these lines in the range 1.1–1.5 THz as well, despite the presence of ranges with positive derivatives $dP_{\mathrm{THz}}/dP_{\mathrm{pump}}$ (Fig. 4). Hence, reliable measurements are difficult in this case. Thus, for the end of the range of reliable measurements of the installation one should take the frequency of 1.1 THz. At higher frequencies there are water vapour transparency windows which can be used in investigations, but under the condition of additional statistical verification of adequacy of measurements.

The experiments performed show that this method makes it possible to determine the operation frequency range for time-domain terahertz spectrometers with the aim of their correct employment in investigations.

5. Conclusions

By using the method developed previously for determining the spectral width of the terahertz pulse in time-domain spectroscopy systems, the frequency ranges of operation have been experimentally determined for two detection systems and the error in finding the operation ranges has been calculated from a series of measurements. The terahertz spectrometer with the electro-optical detection based on the ZnTe crystal has the spectral operation range of 0.059–1.092 THz. The iPCA-21-05-1000-800-h photo-conductive antenna used for detecting the signal from the same source demonstrated the wider operation band ranging from 0.017 to 1.6 THz. The method developed was used for the experimental comparison of widths of operation bands, performed at high, however, not perfect adjustment of terahertz spectrometers with two different detection systems.

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