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Characterization of a Large-Area Pyroelectric Detector from 300 GHz to 30 THz

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Abstract The national metrology institute of Germany, the Physikalisch-Technische Bundesanstalt (PTB), together with the company Sensor and Lasertechnik (SLT), develops pyroelectric detectors for radiation in the terahertz (THz) spectral range. The intention of this development is to deliver a highly sensitive, accurately calibrated detector for power measurement in the power range of time-domain spectroscopy (TDS) systems. This work reports about a large-area thin-film pyroelectric (TFP) detector applicable within a wide spectral range from 300 GHz to 30 THz and its radiometric characterization by PTB's THz radiation sources. Applying coherent synchrotron radiation from the Metrology Light Source (MLS), laser radiation from a molecular gas laser and blackbody radiation from a water-heated blackbody to this detector reveal its potential to be capable of spanning an even wider THz frequency range than covered by TDS systems. To demonstrate this, its spectral responsivity was measured at different frequencies between 300 GHz and 30 THz by means of those three THz radiation sources.

Keywords Far infrared detectors · Terahertz detectors · Radiometry · Metrological instrumentation · Infrared and far infrared lasers · Optics

1 Introduction

The terahertz and sub-terahertz frequency ranges down to approximately 100 GHz are the longest wavelength ranges where optical methods can still be used to measure the power of electromagnetic radiation. The adjacent lower frequency spectrum is attributed to the radio frequency range where the local electrical field strength is the more suitable measurand

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because it is rather the electrical field than its absolute square which describes the action of an electromagnetic wave at radio frequencies.

The power measurement in the extended THz range from 300 GHz up to 30 THz by optical methods needs a suitable detector with a well-known absorptance in this range. If this measurement shall be accurate, reliable, and reproducible, the spectral responsivity of this detector has to be traceably calibrated to an accepted standard. If the power of a radiation source with a broad spectrum within the THz frequency range shall be measured with this detector, the spectral responsivity of the detector has to be known for the complete frequency range of interest. Additionally, if the spectrum of the THz radiation source is more or less unknown, the spectral responsivity of the detector has to be flat within the frequency range of the source.

A time domain spectroscopy (TDS) system typically has a broad spectral range from approximately 100 GHz to a few THz which is emitted simultaneously due to the nature of the generation process in the photoconductive antenna [1]. The spectral distribution is also hardly known because of many possible nonlinear effects during the detection process. To make it even worse, the up-to-know existing coarse measurements show that the overall generated power is in the nano- or lower microwatt range [2]. Therefore, TDS systems lack any reliable power measurement even so TDS is widely used in THz spectroscopy throughout the world.

This work represents a first step towards reliable and calibrated power measurement of TDS systems by introducing a recently developed new detector technology and showing its metrological potential by applying three different THz radiation sources available at PTB. One of these sources is the Metrology Light Source (MLS) [3], an advanced electron storage ring especially equipped to generate coherent synchrotron radiation in the sub-terahertz range around 300 GHz [4]. Secondly, the molecular gas laser of the THz detector calibration facility of PTB is used. The laser generates THz radiation at different frequencies within the range from 1 to 5 THz. Finally, an experimental setup of a water-heated blackbody radiator in combination with a set of spectral filters was used for the frequency range up to 30 THz [5]. The detector was characterized for its spectral responsivity in the whole frequency range provided by the three sources from 300 GHz to 30 THz with the ultimate goal to demonstrate its flatness.

2 Thin-Film Pyroelectric Detector

The detector and its underpinning technology are described in detail in [6]. It consists of a pyroelectric polyvinylidene fluoride (PVDF) foil coated on both sides with a thin layer of a metal oxide. These layers are conductive and serve two objectives: Each layer is one electrode to catch the charge generated by the pyroelectric effect of the foil when the temperature changes; both layers, together, compose the absorber for the THz radiation. The physical principle of the absorption process can be derived from Maxwell's equations and was first described in the 1930s [7]. The sheet resistance of both layers can be carefully adjusted via their combined thicknesses to match half the vacuum impedance. In this case, 50 % of the power is absorbed in the metal oxide layers whereas 25 % of the power is reflected and 25 % transmitted. Following Maxwell's theory, this absorbance is frequency independent in a wide spectral range at least from the low GHz range to several THz depending on the resistance of the metal oxide used for the coating. This is why these TFP detectors are assumed to be suitable for TDS power measurements. The detector is shown in Fig. 1.

Bonding wires on each layer give access to amplify and measure the current generated by the pyroelectric effect when the foil is heated by absorbed radiation in the coating layers. This

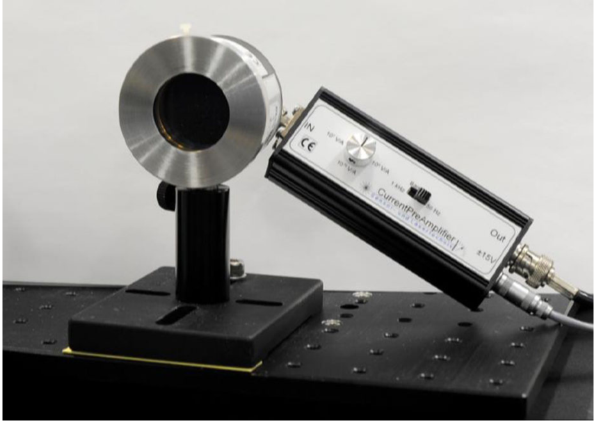

Fig. 1 Photograph of the thin-film pyroelectric (TFP) detector with the aperture mounted in front of it. The current amplifier is seen to the *right*

current is converted into a voltage output by a specifically designed amplifier with adjustable amplifications of 10^7 V/A, 10^8 V/A, 10^9 V/A, or 10^{10} V/A. The amplifier has a cutoff frequency of 50 Hz limiting the chopper frequency to approximately 20 Hz.

The pyroelectric effect is known to be linear to the temperature change over many orders of magnitude [8]. In order to be able to generate a continuously refreshed signal, periodic temperature changes have to be applied to the detector, i.e., chopped radiation is necessary. Therefore, an initial study on the time performance of the detector was conducted, see Fig. 2.

It is also of great interest up to which size the detector can be fabricated. The sensitive area of the detector was defined by a high precision circular aperture with 31 mm in diameter just in front of the detector foil; the diameter of the foil itself was 36 mm. It is therefore a large-area detector. The spatial uniformity of its spectral responsivity is depicted in Fig. 3. The maximum responsivity deviation between different positions on the sensitive area is 8 %. Good

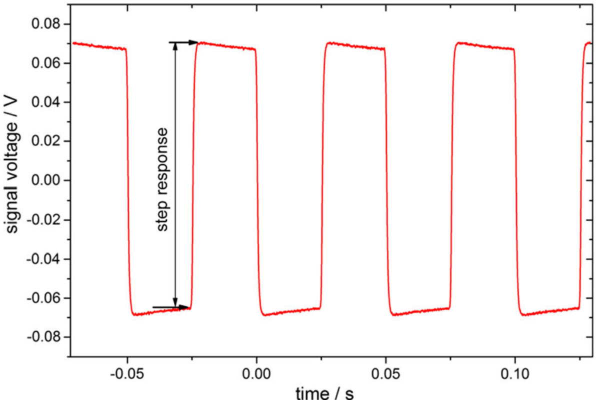

Fig. 2 Amplified output signal of the TFP detector irradiated with chopped THz radiation. The THz radiation frequency was 1.4 THz, the chop frequency was 20 Hz. The step response signal is proportional to the absorbed power and is the basis to calculate the spectral responsivity. The beginning decay of the signal during the irradiated and dark sections of the chopper wheel is due to the temperature relaxation of the absorber foil

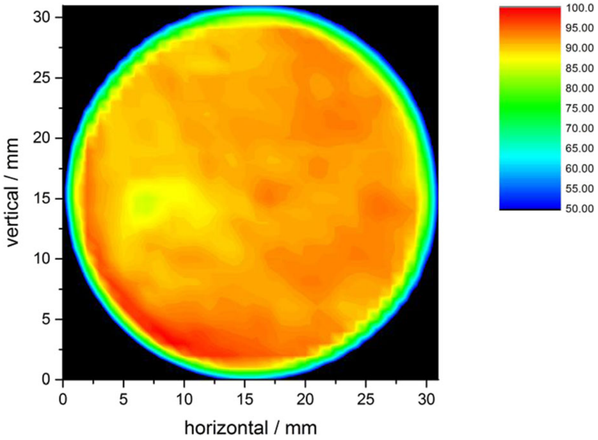

Fig. 3 Two-dimensional diagram of the normalized spatial uniformity of the spectral responsivity of the TFP detector including the front aperture, given in %. The measurement was performed using a focused THz beam at 2.52 THz with a focus diameter of approximately 2 mm and scanning this focus across the sensitive area of the detector. The smooth edge reproduces the beam size

uniformity in combination with good linearity indicates that the detector signal is independent of the spot size of the radiation and only depending on the power.

It is important to determine the noise equivalent power (NEP) of the detector because this limits the minimum detectable power, a crucial point as TDS systems only have a total power of some microwatts at best. The detector noise is strongly depending on the environmental conditions as it is sensitive to vibration and acoustic disturbance. This is obviously evident because it is a widely spanned thin foil acting just as a microphone. The NEP was therefore measured in an almost perfectly silent and vibration-free environment. Using the responsivity determined below, it is 200 nW/√Hz.

This concludes the general information about the TFP detector. The following sections deal with the measurement of its spectral responsivity in different parts of the THz and sub-THz frequency range using different radiation sources.

3 Measurement of the Spectral Responsivity with Synchrotron Radiation

The measurement of the spectral responsivity of the detector was performed with radiation generated by the MLS and delivered to the setup by the terahertz beamline [9]. The MLS was operated in a low-alpha mode to provide coherent synchrotron radiation (CSR). CSR is radiation in the THz frequency range enhanced by at least three orders of magnitude compared to the standard incoherent operation mode of the MLS. The maximum of the spectral distribution of CSR is at 300 GHz.

A similar setup as described in [10] was used to attenuate when necessary, chop, and focus the radiation on the TFP detector or the photoacoustic detector of Thomas Keating Ltd used as a reference detector (Fig. 4). The chop frequency was 17 Hz. The photoacoustic detector was operated with its support unit and according to the manual under Brewster's angle. It is important to properly absorb all radiation transmitted through the detector as back reflections of this radiation may disturb the measurement. The photoacoustic detector was used to get an absolute measurement of the power. Assuming a stable power of the CSR, the setup was

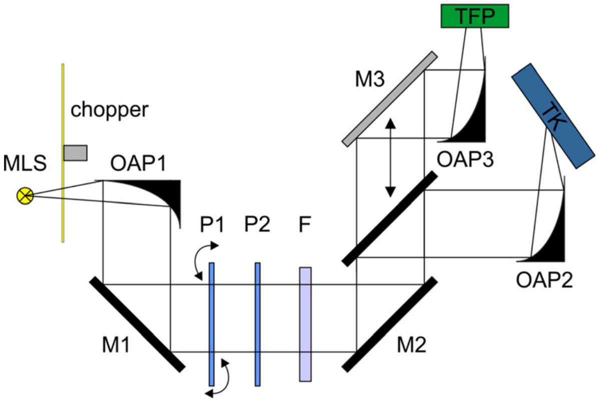

Fig. 4 Experimental setup of the measurement of the spectral responsivity at 300 GHz with coherent synchrotron radiation from the MLS. The beamline setup is omitted. The synchrotron radiation of the beamline is chopped, reflected by several mirrors, parallelized or focused by off-axis parabolic mirrors (OAP), and eventually directed (depending on the position of mirror M3) to one of the detectors: TFP is the thin-film pyroelectric detector, TK the photoacoustic detector from Thomas Keating Ltd, UK, at Brewster's angle. A longpass filter F is used to cut off mid infrared and visible light, two polarizers (one rotatable) P1 and P2 performed smooth attenuation

modified by moving M3 (see Fig. *4*) to direct the radiation onto the pyroelectric detector. The amplified signal (amplification 10^9 V/A) has similar timing characteristics as shown in Fig. 2. Therefore, the step response of this signal divided by the power measured by the photoacoustic detector is the spectral responsivity of the detector, in this case at 300 GHz.

The uncertainty of the power measurement of the reference detector is 10 % as stated in the manufacturer's manual. The result and its uncertainty are marked in Fig. 6.

4 Measurement of the Spectral Responsivity with Laser Radiation

The measurement of the spectral responsivity of the TFP detector with laser radiation was done at the THz detector calibration facility of PTB which is described in [11]. The applied laser system is providing radiation at several fixed frequencies in the range from 1 to 5 THz; eight of them were used in this case, see Fig. 6. The amplifier of the detector was set to the amplification of 10^8 V/A or 10^9 V/A depending on the output power of the laser for the different frequencies. The chop frequency was 20 Hz. The calibration for each frequency was performed according to the quality management approved rules and regulations (according to ISO17025) that are offered to external customers as well. The relative standard uncertainty of the calibration at these frequencies is 6 % (expansion factor $k=1$) and takes the spatial uniformity of the detector into account. The results and uncertainties are marked in Fig. 6.

5 Measurement of the Spectral Responsivity with Blackbody Radiation

The measurement with blackbody radiation is based on the experimental setup and procedure described in [5] and [12]. In this work, the TFP detector was used to measure the radiation difference between a water-heated THz blackbody and a liquid nitrogen-cooled reference blackbody, see

Fig. 5. The temperature of the heated blackbody was 80 ° C. The filters are a combination of longpass and bandpass filters to suppress the mid infrared radiation and transmit the THz radiation only. According to Planck's law and due to the low temperature of the blackbody, the radiation intensity in the THz range is low. In order to get maximum signal, a large-area detector like the TFP detector is advantageous. It was homogeneously irradiated by the radiation of the blackbodies.

The filter combinations and the resulting center wavelengths are listed in Table 1. The center wavelengths were determined from the condition that the integrated radiation powers to the lower and higher wavelength sides of the center wavelength have to be equal. The signal with reference to the cold blackbody was measured for each filter combination with a lock-in amplifier. The chop frequency was 20 Hz. In contrast to the measurement method described in the previous sections, the modulation of the radiation by the chopper is not rectangular in the time domain but in good approximation sinusoidal since the beam size at the position of the chopper is almost as large as the free segment of the chopper wheel. A correction factor was determined from a Fourier analysis of both modulations. This factor was applied to the signal measurement to enable comparability to the values measured with the other THz radiation sources.

The spectral responsivity can then be calculated as the ratio of the corrected signal and the incoming power. The incoming power is the product of the aperture area (circular with 31-mm diameter) and the irradiance. The irradiance can be calculated according to Planck's law taken into account the geometric dimensions of the distances and the blackbody output aperture, the combined filter transmission and the air absorption due to humidity. It is obvious that the relative uncertainty of the overall measurement might be large due to the considerably high number of possibly imperfect corrections.

The spectral responsivity measurements for each center wavelength were repeated several times to get the type A uncertainties [13] which are given in Table 1 and marked in Fig. 6 as red error bars.

6 Conclusion

A large-area thin-film pyroelectric (TFP) detector with a diameter of 31 mm was characterized for its spectral responsivity over a spectral range from 300 GHz to 30 THz by applying three different THz radiation sources. This investigation revealed that

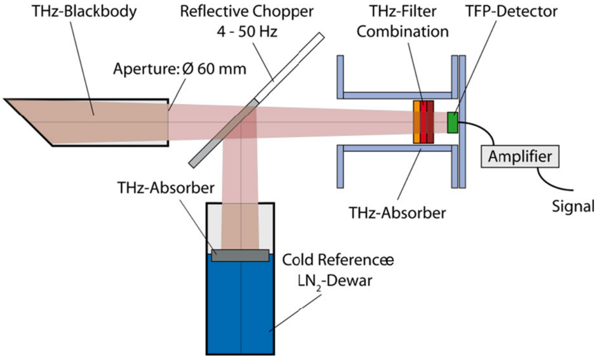

Fig. 5 Experimental setup for the measurement of the spectral responsivity by blackbody radiation. The liquid nitrogen cooled blackbody is used to increase the temperature difference seen by the detector. The optical beam path is defined by the exit aperture of the blackbody and the entrance aperture of the thin-film pyroelectric (TFP) detector

Table 1 Data of the blackbody measurements of the spectral responsivity of the TFP detector using different filters or set of filters

Filter(s)	Center wavelength in μm	Amplification in V/A	Spectral responsivity in nA/W	Standard deviation in nA/W
No filter	11.5	10^7	367	0.3
LP33	41.6	10^8	434	0.3
LP33+LP100+BP125	119	10^8	346	50
LP33+LP100	131	10^8	362	5
LP33+LP100+BP187	193	10^9	407	60

The "filter(s)" column specifies the filter or filter combination, LP denotes longpass, BP bandpass filters. The center wavelength is calculated using Planck's law and the measured transmission curves of the filters; in case several filters were used, the transmission values of the filters are multiplied. The "amplification" column specifies the setting of the current amplifier. The standard deviation is calculated from several repeated measurements and gives an indication of the statistical uncertainty

- the spectral responsivity measured with different radiation sources in the frequency range from 300 GHz to 30 THz is flat within the respective uncertainty interval
- the spectral responsivity is (351±14)nA/W calculated as the mean value of the measurements, see Fig. 6
- the spatial uniformity within the sensitive area is better than 8 % and the time response is faster than 4 ms.

In this work, main emphasis was on the flatness of the spectral responsivity that was measured using all three THz radiation sources available at PTB. The flatness was theoretically predicted and experimentally confirmed for a wide spectral range from 300 GHz to 30 THz. Spatial uniformity and time response meet the requirements for power measurement of time

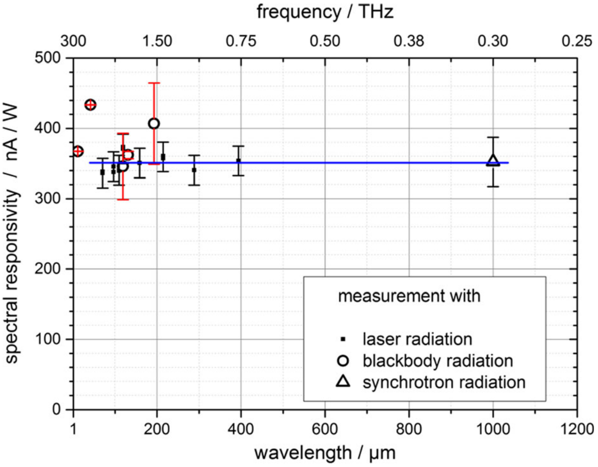

Fig. 6 The spectral responsivity of the large-area TFP detector measured with three different radiation sources: coherent synchrotron radiation (*triangle* at 1000 μm), laser radiation (*squares*), and blackbody radiation (*circles*). *Red error bars* indicate that the corresponding uncertainty is assessed by statistical methods only (according to type A evaluation described in [13]), uncertainties indicated by *black error bars* are estimated by a scientific judgment of the variability of all input parameters (according to type B evaluation described in [13]). The *blue line* indicates the mean value (351 nA/W) calculated from measurements with *black error bars* only

domain spectroscopy (TDS) systems. However, the spectral responsivity of the detector limits its application for power measurement of TDS systems to specialized high-power devices.

Further work has to be done to increase the detectivity of the detector, i.e., decreasing the NEP below 200 nW/√Hz currently achieved for this detector. The pyroelectric foil might be fabricated even thinner to decrease the NEP. This will finally pave the way to a thin-film pyroelectric detector capable of measuring the power of standard TDS systems strongly needed for further development of this widely used spectroscopy technique in the THz frequency range.

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