First absolute power measurement of a terahertz time domain spectroscopy system based on InGaAs/InAlAs photoconductors

B. Globisch[1], R. J. B. Dietz[1], A. Steiger[2], W. Bohmeyer[3], T. Göbel[1], M. Schell[1]
[1]Fraunhofer Institute for Telecommunication, Heinrich Hertz Institute, Einsteinufer 37, 10587 Berlin, Germany
[2]Physikalisch-Technische Bundesanstalt (PTB), Abbestr. 2-12. 10587 Berlin, Germany
[3]Sensor und Lasertechnik, Schulstr. 15, 15366 Neuenhagen bei Berlin, Germany

***Abstract*—We present the first absolute power measurement of a photoconductive terahertz (THz) emitter developed for time domain spectroscopy. The broadband THz radiation is generated by a high mobility InGaAs/InAlAs multilayer heterostructure photoconductive emitter packaged into a fiber-coupled housing. For detection a recently developed ultrathin pyroelectric thin-film detector with special conductive electrodes is employed. The detector signal is traceable to the International System of Units since the power responsivity of the detector was calibrated with a standard detector at the German national metrology Institute (PTB). Absolute THz power exceeding 0.1 mW was detected.**

I. INTRODUCTION

THz time domain spectroscopy (THz-TDS) with photoconductive emitters and receivers evolved from an expensive and bulky scientific setup employed in laboratory environments to an easy-to-use and cost-effective tool for industrial applications within the last decades [1]. This development was accelerated by the use of 1.5 µm fiber lasers and InGaAs/InAlAs-based photoconductive emitters and detectors leading to spectrometers that cover a spectral range from 0.1 - 6 THz with a peak signal to noise ratio (SNR) of 90 dB [2,3].

Even today, THz-TDS systems have to be characterized by quantities like detected pulse amplitude, SNR and maximum detectable bandwidth due to the lack of reliable THz power measurements. This is due to the broad spectrum of the emitted THz radiation and the relatively low THz power which amounts to several tens of µW [4]. Thus, a direct comparison of THz-TDS emitters from different manufacturers is not possible without a reliable absolute power detector.

In the last few years, the *Physikalisch-Technische Bundesanstalt* (PTB), which is the German national metrology institute, and *Sensor und Lasertechnik* developed a pyroelectric thin-film (PTF) detector designed for absolute power measurements in the frequency range from 100 GHz to 5 THz. These detectors consist of a pyroelectric thin-film coated with conductive layers as readout electrodes on both sides. The sheet resistance of the coating is designed to match half of the value of the vacuum impedance such that the transmission of the entire structure is 25 % within the desired frequency range [5]. The underlying principle of these transmission properties of metallic thin-films has been investigated already by W. Woltersdorff in 1934 [6]. The PTF detectors studied by the authors of Ref. [5] showed a spectrally flat transmission from 100 GHz to 5 THz and could be calibrated with a standard detector of the PTB [7]. Hence, these detectors enabled broadband absolute THz-power measurements traceable to the International System of Units (SI). However, the sensitivity of those PTF detectors was not sufficient to detect THz power below 10 µW, which is one of the principal demands on power detectors suitable for the characterization of THz-TDS emitters. Recently, a new ultrathin pyroelectric film with 4 µm thickness could be employed as a new generation of absolute THz power detectors. The reduction of the thickness led to an increased detector sensitivity such that these ultrathin PTF (UPTF) detectors for the first time offer the opportunity of absolute power measurements of THz-TDS emitters traceable to SI units.

In this paper we employ the UPTF detector for absolute power measurements of photoconductive THz emitters designed for the illumination with 1.55 µm femtosecond fiber lasers. These emitters consist of an InGaAs/InAlAs multilayer heterostructure which combines high resistivity (>1000 Ω cm) and high electron mobility (>1000 $cm^2V^{-1}s^{-1}$) for efficient THz generation [4]. The detected average THz power exceeded 0.1 mW.

II. RESULTS

The fiber coupled photoconductive emitter modules were excited by an erbium doped fiber laser with 100 MHz repetition rate, 90 fs optical pulse width and 1550 nm central wavelength. The emitted radiation was focused by two 90 ° off-axis parabolic mirrors onto the active area of the UPTF detector, which measured 20 mm in diameter. Due to the principle of detection of pyroelectric detectors the THz radiation was modulated with 16 Hz and the resulting time trace was read out by an oscilloscope. In order to ensure that the detected signal originated from THz emission other sources were systematically ruled out. Residual light of the exciting laser was blocked by coating the hyperhemispherical silicon lens of the THz-module with a layer opaque for 1550 nm radiation. In order to ensure that the detector signal was independent of the THz modulation technique two different methods were used. First, the THz signal was modulated by chopping the exciting 1550 nm femtosecond laser. With this technique the small amount of infrared radiation that is neither absorbed by the photoconductor nor by the coating of the Silicon lens may contribute to the detector signal. Second, we used bias voltage modulation of the THz emitter. Here, the modulated current within the photoconductor may act as a source of thermal radiation that can contribute to the detector signal whereas the residual infrared light is not modulated and therefore not measured by the detector. For both modulation techniques, the detected THz power was comparable within the uncertainty obtained from the calibration at PTB.

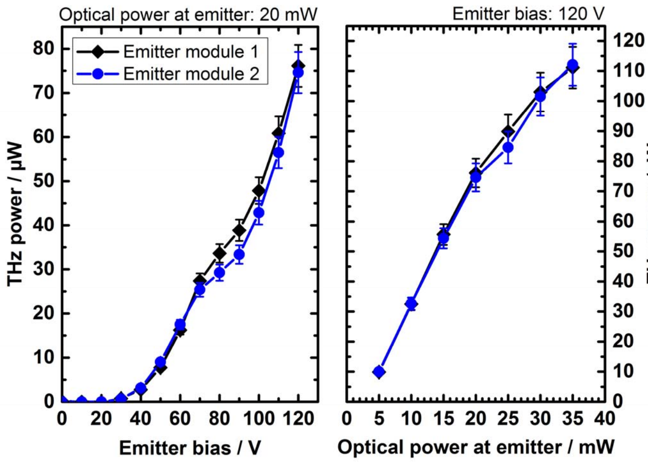

Fig.1. THz power versus emitter bias (a) and optical power (b) for two emitter modules. Error bars were calculated from the calibrated sensitivity of the UPFT detector (160 ± 10 V/W) and the resolution of the oscilloscope. Each data point is an average of 128 signal traces from the oscilloscope.

Fig. 1 shows the results of the absolute power measurements for two fiber-coupled THz emitters, which are equal in construction. Each data point is an average of 128 traces detected by the oscilloscope. Error bars were calculated from the resolution of the oscilloscope and the uncertainty of the detector calibration at PTB. The calibrated sensitivity of the detector was 160 ± 10 V/W. In Fig. 1(a) the detected THz power is plotted against the bias voltage of the emitter for a constant average optical illumination power of 20 mW. The THz power increases from below 1 µW for 30 V bias to above 70 µW at 120 V. Fig. 1(b) shows the detected THz power in dependence of the average optical power at the emitter for a constant emitter bias of 120 V. Note, that the THz power exceeds 0.1 mW for an optical power higher than 30 mW. This corresponds to an optical-to-THz power conversion efficiency higher than 0.3 %.

III. Summary

We presented the first absolute power measurement of photoconductive emitters designed for THz-TDS. The recently developed UPTF detector employed for these measurements features a spectrally flat transmission from 100 GHz to 5 THz and enables the detection of THz power down to 1 µW. The power responsivity of the detector was calibrated with a standard detector at PTB traceable to SI units. This new generation of pyroelectric detectors allows the direct comparison of TDS emitters from different manufacturers. Since the UPTF detector is not only sensitive to THz radiation, particular care has to be taken to ensure that neither modulated infrared light nor radiation from other thermal sources enters the active area of the detector. For the latest generation of fiber-coupled photoconductive emitters from Fraunhofer Heinrich Hertz Institute the detected absolute THz power exceeded 0.1 mW.

References

[1] T. Hochrein, "Markets, Availability, Notice, and Technical Performance of Terahertz Systems: Historic Development, Present, and Trends", J Infrared Milli Terahz Waves 36, 235 (2015).

[2] R. J. B. Dietz, B. Globisch, H. Roehle, et. al. "Influence and adjustment of carrier lifetimes in InGaAs/InAlAs photoconductive pulsed terahertz detectors: 6 THz bandwidth and 90 dB dynamic range", Optics Exp., vol. 22, No. 16, Aug. 2014.

[3] N. Vieweg, F. Rettich, A. Deninger, H. Roehle, R. J. B. Dietz, T. Göbel, "Terahertz-time domain spectrometer with 80 dB peak dynamic range", J Infrared Milli Terahz Waves 35, 823 (2014).

[4] R. J. B. Dietz, B. Globisch, M. Gerhard, et. al. "64 µW pulsed terahertz emission from growth optimized InGaAs/InAlAs heterostructures with separated photoconductive and trapping regions", *Appl. Phys. Lett.,* vol. 103, 061103, Aug. 2013.

[5] R. Müller, W. Bohmeyer, M. Kehrt, et. al. "Novel detectors for traceable THz power measurements", J Infrared Milli Terahz Waves, vol. 35, pp. 659-670, Apr. 2014.

[6] W. Woltersdorff, "Über die optischen Konstanten dünner Metallschichten im langwelligen Ultrarot", Z. Physik 54, 230 (1934).

[7] A. Steiger, M. Kehrt, C. Monte, R. Müller, "Traceable terahertz power measurement from 1 THz to 5 THz", Opt. Express 21, 14466 (2013).