Terahertz Laser Power Measurement Comparison

Andreas Steiger, Ralf Müller, Alberto Remesal Oliva, Yuqiang Deng, Qing Sun, Malcolm White, and John Lehman

Abstract—A comparison of terahertz (THz) laser power measurements was undertaken among three national metrology institutes. At two laser frequencies, 2.52 THz (119 μm) and 0.762 THz (394 μm), a power level of approximately 3 mW was compared at one place at one time by means of national standard THz detectors, which had been calibrated by each participant at their own metrology institute beforehand. The measurements took advantage of the power stability and Gaussian beam profile of the THz radiation source, consisting of a molecular gas laser pumped with a line-tunable CO$_2$ laser at the THz detector calibration facility of Physikalisch-Technische Bundesanstalt. A reference value was determined as weighted average of the measurement results with a maximum weight obtained from the arithmetic mean of the uncertainties stated by the participants. All measurement results agreed with the reference value and to each other within the stated expanded uncertainties.

Index Terms—Metrology, radiometry, terahertz (THz) detector, THz laser.

I. INTRODUCTION

Measurements of terahertz (THz) power are important for a variety of technical areas including climate science, security, medicine, communications, and manufacturing. THz instrumentation and sensors have been commercially developed for remote sensing, THz imaging, high-speed telecommunications, and time-domain spectroscopy. All these applications benefit from accurate characterization of THz radiation detectors that are capable of measuring radiation in the frequency range of 0.3–3 THz. In the past, such characterization by detectors with a calibrated responsivity traceable to the International System of Units (SI) has been elusive. Several national laboratories have undertaken independent measurements traceable to their respective national scales [1]–[3], but there has never been a documented attempt to compare such measurements under conditions prescribed by an international authority such as the Consultative Committee for Photometry and Radiometry (CCPR) [4]. In this instance, such a comparison is termed a pilot comparison of the CCPR.

The first international comparison of THz laser power measurements took place at Physikalisch-Technische Bundesanstalt (PTB) in Berlin, Germany, from May 4–8, 2015. Three national metrology institutes (NMIs), National Institute of Standards and Technology (NIST), National Institute of Metrology (NIM), and PTB, attended this comparison. PTB acted as the pilot laboratory. The pilot comparison was organized in a new manner. The participants met in Berlin to compare their standards at one place at one time. Therefore, the first key comparison ever undertaken in the far-infrared spectral region was carried out in a relatively short period. It represents a milestone which will greatly benefit commercial development of instrumentation and sensors for remote sensing, THz imaging, high-speed telecommunications, and time-domain spectroscopy.

II. EXPERIMENTAL SETUP

The basis of the comparison was THz radiation emitted from a molecular gas laser. Two laser lines were chosen: 2.52 THz (119 μm) and 0.762 THz (394 μm) at a power level of approximately 3 mW [5]. Such THz laser radiation was focused to a well-defined focal spot with a nearly Gaussian beam profile small enough to fit through the apertures of the THz detectors under test. A monitor detector, sampling the beam at a frequency of 15 Hz (50% duty cycle) provided information of the relative power during the course of the measurements. The measurement setup is shown in Fig. 1.

As depicted in Fig. 1, the experimental setup consisted of a CW laser source, focusing optics and a spatial filter, a reflective optical chopper, a monitor detector, a THz camera, and the standard detectors (SD) being evaluated [2]. The camera and the detectors were mounted upon a platform, the position of which was controlled remotely by a computer. A photo of the two SDs of PTB with the THz camera on the platform is shown in Fig. 2.
The THz laser is a molecular gas laser which consists of a 2 m long THz resonator with the molecular gas at low pressure (<1 Pa) as active medium inside, and a grating-tuned CO\textsubscript{2} laser for optically exciting the molecules. Two radiation lines were selected from exciting molecules of formic acid (0.762 THz) and methanol (2.52 THz).

The wavelength of the laser radiation was determined by filling the molecular gas to its nominal pressure in the THz resonator and by selecting the appropriate CO\textsubscript{2} laser line according to a look-up table for the setting of its grating. The exact frequency of the THz line emission was checked by comparing its published value with the result of a frequency measurement by means of a calibrated vacuum Fourier-transform spectrometer [6].

The laser beam profile was determined by a pyroelectric THz camera with an active area of 12.4 mm × 12.4 mm and 100 µm pixel spacing. Three-dimensional images of both laser beam profiles are shown in Fig. 3. Circular, nearly Gaussian beam profiles could be achieved by using the diaphragm at the intermediate focus as a spatial filter, which is imaged enlarged by a factor of two at the detector plane (see Fig. 1). Due to the more than three times longer wavelength, the profile at 0.762 THz is twice as wide as the profile at 2.52 THz. Regardless, the full width at the bottom of the beam profile (see Fig. 3) is less than 6 mm at 0.762 THz. In addition, a weak first-order-diffraction ring is barely visible in Fig. 3. The diameter of the ring is less than 12.4 mm even at 0.762 THz. The apertures of the detectors used at a frequency below 1 THz are 20 mm (PTB), 15 mm (NIM), and 25 mm (NIST), respectively. Therefore, the THz beam completely fits through the aperture of all of these detectors without any clipping, which is a prerequisite for a precise power measurement.

The laser beam amplitude stability was recorded by a time series of the monitor detector, which is a thermopile of the same type as one of the SDs of PTB, namely a pyroelectric detector (center) and a thermopile (right) are mounted upon a platform.

The following procedure was performed before the comparison measurements started. First, each detector was aligned to the center of the beam by means of the moveable platform. The platform was used to shift the laser beam to the horizontal and vertical edges of the detector aperture, defined as the position where the signal drops to 50%. The center is calculated as the arithmetic mean of each pair (left/right and up/down) of such positions. All subsequent measurements were performed with the detector aligned in this way. A background measurement with the beam blocked at the output port of the laser was acquired before and after the signal measurement with the beam open. The signal of the monitor was recorded simultaneously because it was aligned to the beam reflected from the surface of the gold plated chopper disc, which symmetrically modulates the output power 50% on and 50% off. The modulation frequency of 15 Hz was fast enough that the three thermopiles saw the temporal average of the laser power, which was half the power recorded without the chopper. In contrast, the pyroelectric detector was fast enough to record the switching on and off of the laser power by the 15 Hz chopper, i.e., it recorded twice the power of a thermopile.
The monitor detector recorded the temporal variation of the laser output power. The value of the monitor detector \( r_{\text{mon}} \) determined the relative THz power value for each measurement. This value was mathematically included to normalize the measured powers \( r_1, r_2, \) and \( r_3 \) for each detector measurement. Thus, the coefficients \( c_i, i = 1, 2, 3, \) represent the THz power result of each participant’s SD

\[
c_i = \frac{r_i}{r_{\text{mon}, i}}, \quad i = 1, 2, 3.
\]

The reference value was calculated from the weighted average of the individual results acquired by each detector. This is given by

\[
c_{\text{ref}} = \frac{\sum_{i=1}^{3} c_i U_i^2}{\sum_{i=1}^{3} U_i^2}.
\]

In the present case, the uncertainty \( U_1, U_2, U_3 \) determination of each participant was not part of the comparison. It was claimed by each participant before the measurements started. Under the guidelines provided by the CCPR, if the uncertainty of any responsivity value is significantly different from the others, it is acceptable and reasonable to define a minimum uncertainty for the weighting procedure. This cutoff value for the uncertainty, as a default, is determined as the average of the uncertainty values of those participants that reported uncertainties smaller than or equal to the median of all the participants [9]. Since there were merely three participants, it was agreed that the minimum uncertainty in (2) was the arithmetic mean of all participants.

The procedure for acquisition and handling of data was straightforward:

1) acquire the “monitor value,” “signal value,” and “background value” for each measurement episode;
2) subtract the background value from the signal value;
3) normalize the power by dividing this difference by its “monitor signal” according to (1);
4) state the values of each measurement (four values in all, two for each wavelength);
5) average the two values at each wavelength;
6) calculate the reference value using the cutoff corrected uncertainty for each wavelength according to (2);
7) present the result for each institute compared to the reference value.

IV. STANDARD DESCRIPTION AND UNCERTAINTY BUDGET

Besides the description of the different SDs, the individual uncertainty budget is reported in this section in order to explain the stated uncertainty value of each participant, which was used in the comparison. The uncertainty components are separated into Type A uncertainties, whose magnitudes are obtained statistically from a series of measurements, and Type B uncertainties, whose magnitudes are determined by subjective judgments or other nonstatistical methods. The second prerequisite was the responsivity value of the standard detector of each participant. These values were determined traceable to the SI at each home institute before the comparison was undertaken at PTB Berlin. The uncertainty results are the expanded measurement uncertainty obtained by multiplying the standard measurement uncertainty by the coverage factor \( k = 2 \). It has been determined in accordance with the “Guide to the Expression of Uncertainty in Measurement (GUM)” [10]. The value of the measurand then normally lies, with a probability of approximately 95%, within the attributed coverage interval.

A. Description of PTB SDs

The THz SD of PTB for the spectral range from 1 to 5 THz is a modified commercial laser power meter. It is a highly sensitive thermopile, model 3A-P from Ophir Optronics Ltd., with a 0.6 mm thick disc of a 12 mm diameter NG1 glass as a volume absorber for optical frequencies. Instead of a matt surface, the NG1 disc is optically polished on both sides and coated with reflecting gold on its back side. The optical loss of this radiation absorber is specular reflection from its plane front surface. This reflection loss is precisely determined at the THz laser lines and at the 632.8 nm wavelength of a He–Ne laser. The latter optical laser is used to calibrate the power responsivity of such a thermopile with this special NG1 absorber traceable to SI with low uncertainty. The known specular reflection losses are used to convert this optical responsivity to the THz responsivity at the THz laser lines. The main uncertainty contribution of 1% originates from the spatially nonuniform absorption of the NG1 absorber. The calibration result for 2.52 THz in Table I is the correction factor of the digital power reading of the connected power meter. A long wavelength limit for this calibration is caused by the increased THz transmission of NG1 below 1 THz, which adds up to 3% at 0.8 THz [2]. That is the reason why a different THz detector, namely a pyroelectric thin film detector with a 20 mm aperture, is used as SD at 0.762 THz [8]. The pyroelectric thin film is made from a 12 \( \mu \)m thick PVDF foil, which is transparent at THz frequencies below 2.5 THz. It is coated on both sides with ultrathin conducting metal-oxide layers. Their conductivity is impedance-matched in order to achieve a spectrally flat absorption of 50% of the THz radiation [11]. Therefore, this pyroelectric detector is calibrated at 1.40 and 1.04 THz by comparing its responsivity with the PTB thermopile SD. The resulting constant value is used as the responsivity value also at 0.762 THz and causes the main uncertainty contribution of 1.5% in Table II. The responsivity in Table I is calculated as the voltage difference of the connected amplifier (\( 10^8 \) V/A, 25 Hz 3 dB bandwidth limit) when the signal is turned ON and OFF with a 15 Hz repetition rate. For this purpose, the chopper symmetrically modulates the laser power.

| Frequency | Detector type | Correction / Expanded
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2.52 THz</td>
<td>Thermopile Ø 12 mm</td>
<td>1.100</td>
</tr>
<tr>
<td>0.762 THz</td>
<td>Pyroelectric Ø 20 mm</td>
<td>52.0 V/W</td>
</tr>
</tbody>
</table>
TABLE II
PTB MEASUREMENT UNCERTAINTIES BUDGET

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>Relative standard uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration at 632.8 nm</td>
<td>B</td>
<td>0.2%</td>
</tr>
<tr>
<td>Absorption at 632.8 nm</td>
<td>B</td>
<td>0.03%</td>
</tr>
<tr>
<td>Absorption at 2.52 THz</td>
<td>B</td>
<td>0.6%</td>
</tr>
<tr>
<td>Equivalence of absorption</td>
<td>B</td>
<td>0.5%</td>
</tr>
<tr>
<td>Repeatability</td>
<td>A</td>
<td>0.3%</td>
</tr>
<tr>
<td>Linearity</td>
<td>B</td>
<td>0.5%</td>
</tr>
<tr>
<td>Stability of the THz laser</td>
<td>A</td>
<td>0.5%</td>
</tr>
<tr>
<td>Spatial uniformity</td>
<td>B</td>
<td>1.0%</td>
</tr>
<tr>
<td>Path length variation</td>
<td>B</td>
<td>0.5%</td>
</tr>
<tr>
<td>Digital reading resolution</td>
<td>B</td>
<td>0.2%</td>
</tr>
<tr>
<td>Uncertainty at 2.52 THz (k = 1)</td>
<td></td>
<td>1.6%</td>
</tr>
<tr>
<td>Spatial uniformity at 0.762 THz</td>
<td>B</td>
<td>1.0%</td>
</tr>
<tr>
<td>Spectral uniformity near 0.762 THz</td>
<td>B</td>
<td>1.5%</td>
</tr>
<tr>
<td>Uncertainty at 0.762 THz (k = 1)</td>
<td></td>
<td>2.4%</td>
</tr>
</tbody>
</table>

The calibration results reported by PTB are given in Table I. The uncertainty contributions are presented in Table II.

B. Description of NIM SD

The THz SD of NIM is a home-made THz radiometer using a self-fabricated 1.2 mm thick black paint coating with embedded 300 μm SiC particles as the radiation absorber [3]. This coating has a broad absorption bandwidth and high absorbance. The radiometer is capable of measuring the THz radiation from 0.1 THz to several THz [12] because a THz time-domain spectrometer (TDS) was used to measure the reflectance of the absorber from 0.1–3 THz [3]. The result is shown in Fig. 4, which depicts a reflectance of less than 0.05% at THz frequencies. At 2.52 THz, the signal reaches the noise floor of the THz TDS. Considering a solid angle of 0.32 sr in this measurement, we estimate total hemispherical reflection losses of 1.6% at 2.52 THz and 2.0% at 0.762 THz. Hence, there is a gold-coated hemispherical reflector in front of the thermopile detector, which sends the radiation back to the detector. A conservative estimate yields half of the original reflection value as the uncertainty of complete THz radiation absorption, namely 0.8% at 2.52 THz and 1.0% at 0.762 THz. This is the main contribution of the uncertainty budget shown in Table IV.

The responsivity of the THz SD is traceable to a cryogenic radiometer standard at a wavelength of 632.8 nm via a transfer standard because the hemispherical reflector ensures nearly complete absorption for visible radiation. An integrating sphere was applied to measure 1.2% as total reflection losses of the coating at the He–Ne laser wavelength. Half of this measurement result is used again as a final uncertainty contribution listed as “absorption at 632.8 nm” in Table IV.

The radiometer has a second compensating cavity to minimize the effect of ambient temperature fluctuations of the radiometer. Both cavities are of the same design, calibrated separately, and used to acquire the signal and the background synchronously via a two-channel voltmeter. The measured power value is displayed by a computer with software consisting of a sampling, averaging, and subtracting procedure.

TABLE III
NIM CALIBRATION RESULTS

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Responsivity</th>
<th>Expanded uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.52 THz</td>
<td>355 mV/W</td>
<td>2.8% (k = 2)</td>
</tr>
<tr>
<td>0.762 THz</td>
<td>355 mV/W</td>
<td>3.2% (k = 2)</td>
</tr>
</tbody>
</table>

The reported calibration results are given in Table III. The uncertainty contributions are presented in Table IV.

C. Description of NIST SD

The thermopile detector responsivity was determined by means of a direct substitution with a transfer standard calibrated by a NIST cryogenic radiometer standard at a wavelength of 632.8 nm and then evaluating optical reflectance losses at the much longer THz wavelengths of 119 and 394 μm. The signal and background values are acquired from an average of multiple measurement episodes, each episode consisting of the average of 99 samples acquired at 1 s intervals.

The reflectance was measured by comparison with a highly reflecting reference sample. The source at 0.762 and 2.52 THz was a molecular gas laser, pumped with a CO₂ waveguide laser. The beam was focused from a diameter of approximately 10 cm at the reference sample, converging to a reference pyroelectric detector. The laser was directed at the reflectance-measurement.
TABLE V
NIST CALIBRATION RESULTS

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Responsivity</th>
<th>Expanded uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.52 THz</td>
<td>87.2 mV/W</td>
<td>6.6% (k = 2)</td>
</tr>
<tr>
<td>0.762 THz</td>
<td>84.8 mV/W</td>
<td>6.6% (k = 2)</td>
</tr>
</tbody>
</table>

TABLE VI
NIST MEASUREMENT UNCERTAINTIES BUDGET

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>Relative standard uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path length factor</td>
<td>B</td>
<td>1.7%</td>
</tr>
<tr>
<td>Laser amplitude stability</td>
<td>B</td>
<td>0.9%</td>
</tr>
<tr>
<td>Thermopile voltmeter</td>
<td>B</td>
<td>0.06%</td>
</tr>
<tr>
<td>SI transfer standard</td>
<td>B</td>
<td>0.2%</td>
</tr>
<tr>
<td>Spatial uniformity</td>
<td>B</td>
<td>2.0%</td>
</tr>
<tr>
<td>Thermopile linearity</td>
<td>B</td>
<td>1.2%</td>
</tr>
<tr>
<td>Carbon nanotube reflectance</td>
<td>A</td>
<td>0.5%</td>
</tr>
<tr>
<td>Copper reference reflectance</td>
<td>A</td>
<td>0.1%</td>
</tr>
<tr>
<td>Thermopile background</td>
<td>A</td>
<td>0.8%</td>
</tr>
<tr>
<td>Thermopile signal</td>
<td>A</td>
<td>0.9%</td>
</tr>
<tr>
<td>Total uncertainty (k = 1)</td>
<td></td>
<td>3.3%</td>
</tr>
</tbody>
</table>

samples such that the radiation was incident at approximately 45°. The reflectance of the copper mirror reference was determined to be 0.972. The uncertainty of the reflectance has not been thoroughly evaluated. The numbers depend substantially on our original assumption with respect to the copper reference. Furthermore, the measurement does not account for diffuse reflectance. The uncertainty of the reflectance of the nanotube witness sample is accounted for with a value described as carbon nanotube reflectance in Table VI. The uncertainty for spatial uniformity was determined by sampling the detector’s responsivity across its 25-mm-diameter surface. The value reported in Table VI represents the maximum variation across the area, which is attributable to the uniformity in height of the nanotubes as well as to their thermal coupling (bonding) to the thermopile.

The reported calibration results are given in Table V. The uncertainty contributions are presented in Table VI.

V. EXPERIMENTAL RESULTS

It was agreed using guidelines of the CCPR that the minimum uncertainty would be defined from the arithmetic mean of the reported uncertainty values as

\[ U_{\text{cutoff}} = \frac{1}{3} \sum_{i=1}^{3} U_i. \]  

(3)

So that if a reported uncertainty \( U_i \) of (3) is less than \( U_{\text{cutoff}} \), then the uncertainty for the weighting procedure of (2) is \( U_i = U_{\text{cutoff}} \). From the report of each laboratory, \( U_{\text{cutoff}} = 0.042 \) at 2.52 THz and \( U_{\text{cutoff}} = 0.049 \) at 0.762 THz. Therefore, to calculate the reference value at 2.52 THz, \( U_{\text{PTB}} = U_{\text{NIM}} = 0.042 \) and \( U_{\text{NIST}} = 0.066 \). The value at 0.762 THz is calculated with \( U_{\text{PTB}} = U_{\text{NIM}} = 0.049 \) and \( U_{\text{NIST}} = 0.066 \).

VI. CONCLUSION

The deviations of the measurements from the calculated reference value of (2) are presented graphically for 2.52 THz (see Fig. 5) and 0.762 THz (see Fig. 6). As a quantitative measure of the deviation, the ratio \( c_i/c_{\text{ref}} - 1 \) is plotted for each participant “i” with stated expanded uncertainty as error bars. The extended uncertainty with coverage factor \( k = 2 \) corresponds to a confidence interval of 95%. It is depicted by both figures that all measurements are consistent with the reference value.

The deviations of the measurements from the calculated reference value of (2) are presented graphically for 2.52 THz (see Fig. 5) and 0.762 THz (see Fig. 6). As a quantitative measure of the deviation, the ratio \( c_i/c_{\text{ref}} - 1 \) is plotted for each participant “i” with stated expanded uncertainty as error bars. The extended uncertainty with coverage factor \( k = 2 \) corresponds to a confidence interval of 95%. It is depicted by both figures that all measurements are consistent with the reference value.

A pilot comparison of the measurement of radiant power in the THz spectral range was performed between the NMLs of China, USA, and Germany. Two laser lines, 2.52 and 0.762 THz of a molecular gas laser with an output power of a few milliwatts, were used to compare the spectral responsivity of the national THz SDs. This first international THz comparison was conducted subject to the regulations of the CCPR at PTB in Berlin.

The measurement results are in agreement within the stated uncertainties of the THz power scales of the three participating countries. This is an excellent step forward in bringing traceable THz measurements from the research laboratory to industrial applications.
ACKNOWLEDGMENT

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REFERENCES


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Malcolm White received the undergraduate degree from the University of Canterbury, Christchurch, New Zealand, and the M.Sc. degree in solid-state physics from Waikato University, Hamilton, New Zealand, in 1984.

Over the past 27 years he has worked as a Research Scientist in various national metrology institutes: 6 years with the Measurement Standards Laboratory, New Zealand, 16 years with the NPL, U.K., 7 months as a Guest Researcher with the INRIM, Italy, and for the last 5 years in NIST, Boulder, USA, in the Laser Radiometry Group. At MSL and NPL he was responsible for maintaining and disseminating the optical primary standard scale of radiant power and spectral responsivity. He was the Technical Work Package Leader for the linkage of the system of units to the single photon regime for the European Metrology Research Project "towards quantum based photon standards." His current research interests include traceability for few photon metrology using carbon nanotube devices, standards for THz radiant power measurement, applications of radiometry to space-based observations, and low power pulse energy measurement.

John Lehman received the B.S. degree in mechanical engineering from the University of Colorado, Boulder, CO, USA, the M.Eng. degree in mechanical engineering from the University of Idaho, Moscow, ID, USA, and the Ph.D. degree in applied physics from the University of Kent, Canterbury, U.K.

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