Traceable terahertz power measurement from 1 THz to 5 THz

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Abstract: The metrology institute in Germany, the Physikalisch-Technische Bundesanstalt (PTB), calibrates the spectral responsivity of THz detectors at 2.52 THz traceable to International System of Units. The Terahertz detector calibration facility is equipped with a standard detector calibrated against a cryogenic radiometer at this frequency. In order to extend this service to a broader spectral range in the THz region a new standard detector was developed. This detector is based on a commercial thermopile detector. Its absorber was modified and characterized by spectroscopic methods with respect to its absorptance and reflectance from 1 THz to 5 THz and at the wavelength of a helium-neon laser in the visible spectral range. This offers the possibility of tracing back the THz power responsivity scale to the more accurate responsivity scale in the visible spectral range and thereby to reduce the uncertainty of detector calibrations in the THz range significantly.

OCIS codes: (040.2235) Far infrared or terahertz; (120.5630) Radiometry; (120.3930) Metrological instrumentation; (140.3070) Infrared and far-infrared lasers; (260.3090) Infrared, far.

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1. Introduction

The terahertz (THz) and sub-terahertz frequency range down to approximately 100 GHz are the longest wavelength ranges where optical methods can be used to measure the power of electromagnetic radiation. The adjacent lower frequency spectrum is attributed to radio

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frequency range and the local electric field strength is the more suitable measurand because it is rather the electrical field than its absolute square which describes the propagation of an electromagnetic wave at radio frequencies. The difference originates from the strong interference caused by the geometric boundary conditions which are important at the wavelength scale of radio frequencies. In contrast to that, THz and sub-terahertz radiation still propagates like a bundle of rays at laboratory dimensions even though beam diffraction has to be taken into account. The last point is the main difference to beams of optical radiation at shorter wavelengths in the range of a few micrometers which could be considered more or less as “pencil like” beams. Besides that, standing waves by interference of the diffracted or reflected radiation with the incoming beam have to be considered. This is crucial when the power of a THz laser beam is measured with an optical power meter because many absorbing materials such as optical black coating become transparent and the substrate below the coating reflects the transmitted part of the terahertz radiation. In addition, there is less diffuse but more specular reflection of any surfaces coated with an optical black coating because scattering scales inverse with increasing wavelength.

These problems had to be solved for the first calibration of a THz detector traceable to the International System of Units [1, 2]. As explained in ref [1], the final uncertainty of 7.3% at 2.52 THz achieved there is mainly caused by the limited THz absorption of the cavity absorber of the cryogenic radiometer used as primary detector standard. This instrument is an electrical substitution radiometer at low temperature which is part of the ultraviolet and near infrared calibration facility of PTB [3].

Based on this experiment a THz detector calibration facility has been set up at PTB dedicated for customer service. The calibrated THz detector became the original standard detector at 2.52 THz. A far-infrared molecular gas laser is used as monochromatic power source of this facility which is described in detail in the next section. Section 3 explains how the calibration capability is extended to other THz emission lines of this laser by a new standard detector. A physical model of the absorption of this detector is depicted in the proximate section. This section ends with the application of this model in the THz and the visible spectral range which allows tracing back the THz power responsivity scale to the accurate scale in the visible spectral range.

2. The THz detector calibration facility

Detector-based radiometry with laser radiation [4] was chosen as optical method for the first THz power measurement and for the dedicated THz power responsivity calibration facility as well. This method with a laser as time-stable monochromatic radiation source is well established for visible and infrared radiation but also suited for the long wavelengths of THz radiation. The main advantages of laser based calibration in THz range are: high spectral purity, low stray light and lowest possible beam divergence. The latter properties facilitate the focusing of the radiation in order to under-fill the detector aperture which is the crucial part of absolute THz power measurements.

Figure 1 shows the configuration for laser based spectral responsivity measurement by the THz detector calibration facility. The core instrument is an optically pumped THz laser. It is a far-infrared molecular gas laser which was commercially available until 2010 [5]. The laser system delivers an output power of multiple milliwatts continuous wave (cw) at frequencies between 1 THz and 5 THz at a variety of rotational emission lines of selected molecular gases at low pressures in the range of 10 Pa to 100 Pa. In detail, the molecules are optically pumped by an integrated grating tunable 50 W CO_2-laser. As a specific feature, the single frequency of the CO_2 pump laser can be locked to a built-in Fabry-Perot etalon in order to stabilize the pump laser frequency at the desired molecular transition from a rotational state of the ground vibrational manifold to a rotational state in an excited vibrational manifold. This process causes a population inversion between neighboring rotational states either in the excited manifold due to optical pumping, or in the ground manifold due to depletion of the lower

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state. For example operated with methanol as laser medium and CO_2 pump radiation at 9.7 µm, the methanol molecules lase between the J = 16 and J = 15 rotational levels emitting radiation at 2.52 THz which corresponds to a wavelength of 119 µm. This is exactly the same wavelength which was used for the original calibration experiment [1].

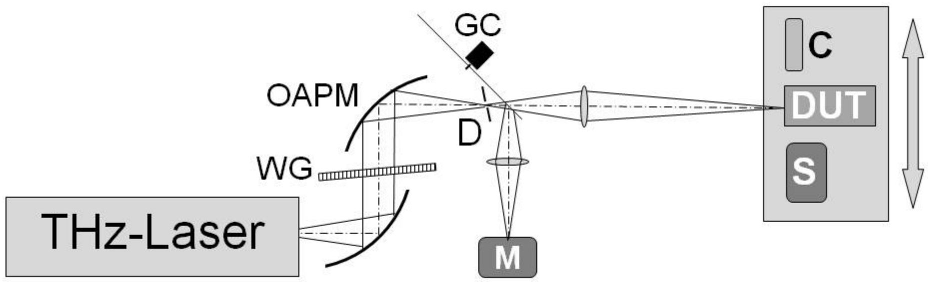

Fig. 1. Measurement setup of the THz calibration facility. The radiation emitted by the THz-laser is imaged by two off-axis parabolic mirrors (OAPM) through a wire grid polarizer (WG) onto the aperture of an iris diaphragm (D). The transmitted radiation is focused by a lens to the detector under test (DUT), to the standard detector (S) or to a THz camera (C) which are all mounted on top of a linear translation stage. The reflected radiation from the surface of a gold plated chopper blade (GC) is focused to a monitor detector (M) by another lens.

Due to diffraction of the long wavelength, the THz laser beam has a large divergence which requires a diameter of 75 mm for the first focusing mirror at 178 mm distance to the output-coupling hole of the THz laser. A 90 degree off-axis parabolic mirror (OAPM) with 178 mm focal length is used to produce a collimated beam. The next optical element along the beam path is a rotatable polarizer. The free-standing metal wire grid polarizer for THz radiation consists of an array of parallel 10 µm tungsten wires secured to a mounting frame with a wire spacing of 25 µm. The transmitted beam is focused by another OAPM into the aperture of an iris diaphragm acting as spatial filter. The diameter and position of the iris diaphragm are adjusted to achieve a Gaussian like beam profile (Fig. 2). The diaphragm is tilted off normal incidence by 10 degrees in order to avoid standing waves by any reflected radiation of its blade.

A chopper is placed at a short distance behind the diaphragm. The gold plated chopper blade has two slots and a diameter of 200 mm. The large chopper wheel and the small beam diameter at a short distance behind the focus result in a symmetric on-off power modulation with a small 0.5% ratio of rise time to modulation period at typical modulation frequencies in the range of 10 Hz to 50 Hz. As the chopper blade is coated with a gold layer and oriented at 45 degree the reflected THz beam can be used to monitor the power variation during the calibration process. An aspheric plane-convex Tsurupica lens with 30 mm clear aperture and 50 mm focal length is used to focus the reflected beam without clipping any THz radiation onto the absorbing surface (12 mm diameter) of the monitor detector. The transmitted beam is focused by another Tsurupica lens with 100 mm focal length onto the absorbing surface of the detector under test (DUT).

The detector at the focus position is mounted on top of a horizontal translation stage together with the standard detector and a THz camera. The displacement range of 400 mm of this translation stage is used to position these devices one after another into the focus of the THz laser beam and to measure the spatial variation of the sensitivity of the DUT in the horizontal direction. The mechanical design includes two lifting tables with 30 mm travel range which are used to vary the vertical position of these devices.

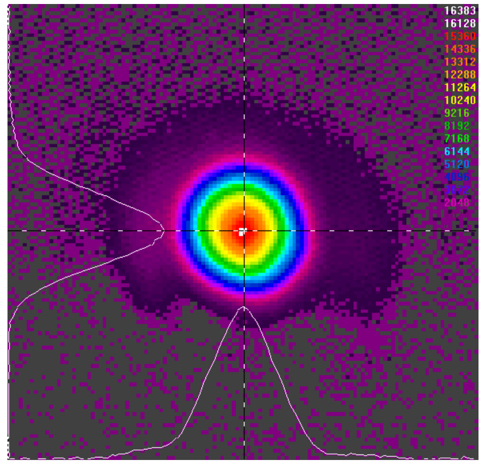

Fig. 2. A typical focal beam profile of the molecular gas laser at 2.52 THz. The sensitive area of the THz camera is 12 mm x 12 mm.

The calibration procedure is as follows: First the focal beam profile is recorded by the THz camera (Fig. 2). Then the power is measured by the standard detector. The monitor detector is recorded at the same time. Finally, the DUT is moved into the focus of the THz beam to the same position as the standard detector and the power reading of the DUT and the monitor detector are stored. The responsivity of the DUT is calculated as ratio of its power reading to the measured power. The signal of the monitor detector is used to correct any temporal drift of the laser output power during these measurements.

3. Expansion of the THz detector calibration facility to 1 THz to 5 THz

Currently the calibration service for THz detectors is restricted to 2.52 THz which is the frequency of the first power measurement traceable to the International System of Units. Beside this frequency the far-infrared molecular gas laser can be operated at a variety of molecular lines in the spectral range between 1 THz and 5 THz. In order to expand the calibration service to the other laser lines a THz detector with known spectral power responsivity in this large frequency interval is needed as a new standard detector. This is achieved by two steps:

First, a so called “gray” absorber is needed, i.e. a detector with a spectral responsivity weakly depending on frequency in this large spectral interval. The physical model described in the next section together with the characterization of the spectral reflectance and transmittance results in a known spectral absorptance of the detector.

As a second step, this well characterized detector is then calibrated at 2.52 THz against the original standard detector at the THz calibration facility. By this single point calibration its spectral absorptance is transformed into a spectral power responsivity which is traceable to the International System of Units. So the THz detector can be used as new standard detector from 1 THz to 5 THz.

This detector is a modified commercial laser power meter. It is a high sensitive thermopile detector, model 3A-P from Ophir Optronics Ltd., which uses a 0.6 mm thin disc of 12 mm diameter made of NG1 neutral density filter glass from SCHOTT AG as volume absorber. In contrast to the standard model an optically polished plane surface is used instead of a matt surface. In addition, the back side of the NG1 disc is coated with a thin gold layer which acts as mirror for the residual transmitted radiation in order to achieve a longer absorption path. This is depicted in Fig. 3. Both modifications make a simple physical model of the radiation losses applicable.

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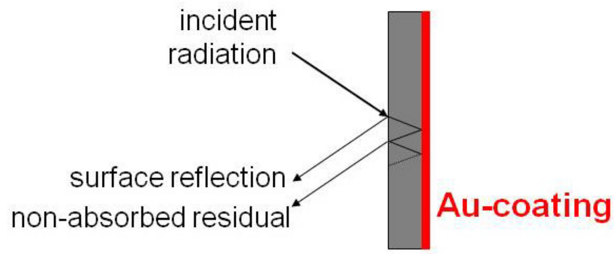

Fig. 3. Schematic of the radiation absorption process by a sectional drawing of the gold coated NG1 disc.

4. Physical model of the absorption of the new standard detector

The model describes the frequency depending absorptance $A(\nu)$ of the new standard detector in the THz region but also in the visible spectral region. Due to the optical quality of the NG1 material and the polishing of its surfaces, radiation scattering or diffuse reflection can be neglected. Only specular reflection has to be taken into account for the THz radiation which is not absorbed by the NG1 disc. The major losses originate from the first reflection when incident radiation impinges on its surface. Most of the penetrating radiation is absorbed by the NG1 material. However, at frequencies below 1 THz NG1 becomes transparent. But due to the gold coated back side all residual transmitted radiation is reflected and is partially absorbed on its way back to the first surface. Because of the lower refractive index of the air with respect to the NG1 only a minor part is transmitted out of the NG1 and most of the residual THz radiation is reflected again towards the reflective backside, is again partially absorbed and so on. Because the front and back side of the NG1 disc are parallel the non-absorbed residual radiation has the same direction as the first surface reflection as indicted by a parallel slim line in Fig. 3. The resulting interference of the parallel beams is of minor importance as long as there is a noticeable absorption by the NG1 disc which occurs for THz radiation above 0.7 THz (see section 4.1).

In any case all radiation which is not absorbed inside the NG1 disc is reemitted in the same direction of the front surface reflection. This is the only significant optical loss that has to be taken into account. The reflectance $R(\nu)$ is determined by a measurement of the ratio of the reflected and the incident radiation at any frequency ν. The absorptance of the NG1 volume absorber of the new standard detector is given according to the model:

$$A(\nu)=1-R(\nu). \tag{1}$$

As mentioned above this detector has been calibrated at the frequency ν_0 = 2.52 THz against the original standard detector at the THz detector calibration facility, i.e. its power responsivity $s(\nu_0)$ = 2.52 THz has been determined. Then the power responsivity $s(\nu)$ at a frequency ν can be calculated by taking the ratio of absorptance into account:

$$s(\nu)=\mathrm{s}(\nu_0)\cdot\frac{A(\nu)}{A(\nu_0)}=s(2.52\ \mathrm{THz})\cdot\frac{1-R(\nu)}{1-R(2.52\ \mathrm{THz})}. \tag{2}$$

Equation (2) holds for all frequencies ν_0 where the power responsivity is known and for all frequencies ν where the physical model is applicable, i.e. the frequencies where reflectance and transmittance of the absorber of the new standard detector are known. These frequencies may also be within the visible spectral range.

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4.1 Application of the model in the THz spectral range – Optical characterization of NG1

The optical properties of NG1 are well known from published data of its manufacturer SCHOTT AG in the visible, near infrared and mid infrared spectral range up to 5.2 µm which is the maximum wavelength of the published data of the manufacturer. The transmittance in the far infrared spectral range was measured in this work using a Fourier transform infrared (FT-IR) spectrometer, namely a VERTEX 80v vacuum FT-IR spectrometer from Bruker Corporation. The result for a 0.57 mm thick sample of the same batch as the gold coated NG1 disc absorber of the new standard detector is shown in Fig. 4.

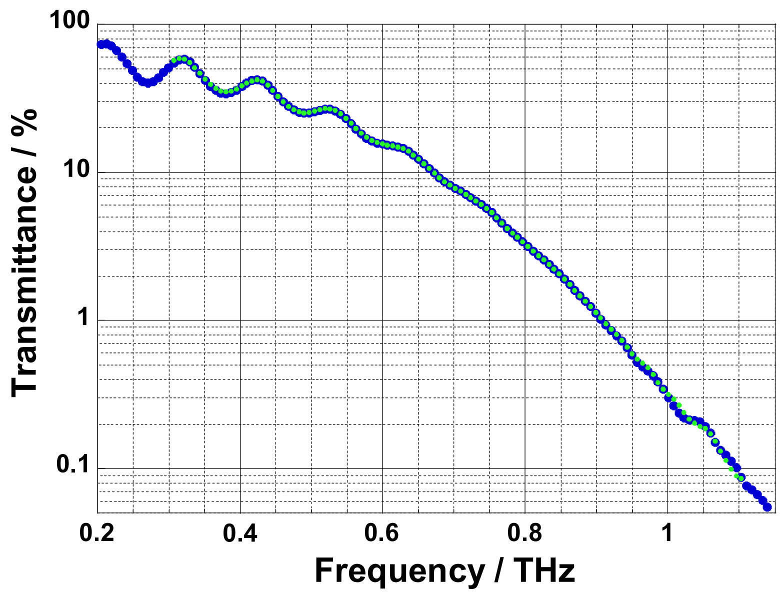

Fig. 4. Spectral THz transmittance of a 0.57 mm thick NG1 sample. Two different beam splitters (blue and green dots) were used inside the FT-IR spectrometer for the measurement at lower THz frequencies at 1 THz and below.

The spectral THz transmittance of Fig. 4 reveals the absorption coefficient of NG1 glass to be 9.5 mm^{-1} at 1 THz and to increase to more than 10 mm^{-1} for larger THHz frequencies of interest, i.e. the transmittance of a 0.57 mm thick NG1 sample is too low to yield a signal larger than the noise level of $1 \cdot 10^{-3}$ of the FT-IR spectrometer in the THz spectral range from 1 THz to 5 THz. Only at frequencies below 0.7 THz the transmittance is large enough to generate interference by the front and back side reflection of the polished surfaces of the NG1 disk. The interference causes the modulation of the transmittance which is clearly visible in Fig. 4 in the range from 0.2 THz to 0.6 THz. From the oscillation period of 105 GHz a refractive index of n = 2.51 at these lower THz frequencies can be determined. The Fresnel reflection losses at front and back side sum up to 1/3 peak to peak variation of this oscillation at the lowest frequencies. Summarizing this, the physical model is applicable from 0.7 THz to 5 THz.

In addition to the transmittance of an uncoated NG1 sample, the reflectance of a NG1 sample with the gold coating on its back side has to be measured as well. However, the diameter of 12 mm of the absorber disc is too small to measure the reflected signal without any losses due to clipping and diffraction of radiation at large wavelengths of the THz spectral range. NG1 discs of 40 mm diameter were ordered together with the 12 mm NG1 absorber discs and coated with gold in the same process run. The gold coated NG1 sample with 40 mm in diameter has the same thickness of 0.57 mm and will therefore have the same reflection as the gold coated NG1 absorber of the new standard detector.

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The reflectance was measured in the spectral range from 1 THz to 5 THz by two independent methods. In addition to measurements by the FT-IR spectrometer different emission lines of the molecular gas laser of the THz detector calibration facility in a slightly modified setup were used. The Tsurupica lens with 100 mm focal length was shifted towards the iris diaphragm to achieve a 200 mm longer focus distance by weaker focusing. The THz detector was moved to the new focus position and measured the full power at first. Then, in order to measure the reflected radiation, the large NG1 sample was placed with a small tilt of 4 degree at the original detector position on the translation stage and the THz detector was moved to the focus of the reflected radiation which is 200 mm in front of the sample. The correct position of the detector was checked with the THz camera. In addition, special care was taken to measure the power without any background due to the known offset drift of a thermopile detector by two precautions. First, the detector is not touched but only its fastening base when its position is changed between full power and reflection measurements. Second, the background reading of the thermopile is always measured immediately before and after each power measurement. All of this enables the determination of the reflectance and its uncertainty. By using the THz laser the absolute measurement uncertainty is not more than 0.5%. The measurement by means of the FT-IR spectrometer reveals consistent reflectance values with an uncertainty larger than 1%.

Within the spectral range of interest from 1 THz to 5 THz the losses due to the reflectance $R(\nu)$ of the NG1 sample vary between 18% and 10%. According to Eq. (1), the corresponding spectral absorptance $A(\nu)$ varies only between 82% and 90%. An absolute measurement uncertainty of 0.5% of $R(\nu)$ yields a relative uncertainty of $A(\nu)$ well below 1% for any frequency ν in the THz spectral range.

4.2 Application of the model in the visible spectral range – New traceability of the THz power responsivity scale

Among all other type of neutral density filter glasses NG1 has the lowest internal transmittance $\tau_i \cong 10^{-4}$ at a thickness of 1 mm for optical frequencies of the visible spectral range. Starting at the red edge of the visible spectrum NG1 gets more and more transparent towards increasing wavelengths. That is the reason why this material is commonly used as a volume absorber for high power pulsed Nd:YAG laser radiation in the near infrared spectral range. The absorptance of a 0.6 mm thick NG1 at 1.06 µm is about 90%. But 10% internal transmittance is sufficient to cause interference which prevents a reliable measurement of the reflectance. However at the helium-neon (HeNe) laser wavelength of 633 nm, the internal transmittance is only 0.6% which drops down to $3.6 \cdot 10^{-5}$ for the gold coated absorber. This high absorption inhibits any interference and the physical model of Eq. (1) is applicable also for visible light. This renders it possible to establish a new traceability chain and to reduce the uncertainty of the THz power responsivity scale by directly calibrating the new THz standard detector with visible radiation against a primary detector standard at the HeNe wavelength [7]. This approach avoids the problem of limited absorption of the cavity absorber of a cryogenic radiometer at the long wavelengths of THz radiation.

Due to the short wavelength of visible radiation the reflectance of NG1 could be measured with a HeNe laser not only for the sample 40 mm in diameter but for the gold coated 12 mm THz absorber inside the new standard detector as well. In both cases the result is $R_{HeNe} = (4.38 \pm 0.03)$ %. This low value is consistent with the refractive index of $n = 1.52$ in the visible spectral range published in the datasheet of NG1 of the manufacturer.

Finally the radiant power responsivity s_{HeNe} of the new standard detector is determined by means of a HeNe laser. Thanks to the optical quality of NG1 and the resulting good homogeneity within its aperture of 12 mm diameter, s_{HeNe} has an uncertainty as low as 0.2% and is traceable to the International System of Units because the calibration is performed at the laser radiometry working group of PTB responsible for the dissemination of radiometric units for laser radiometry in the optical wavelength range and adjacent spectral regions [8,9].

Replacing tracing back the radiant power at 2.52 THz by tracing it back by means of a HeNe laser, Eq. (2) can be rewritten as follows:

$$s(\nu) = \frac{s_{HeNe}}{0.9562} \cdot \left[1 - R(\nu)\right]. \tag{3}$$

The quantities in Eq. (3) can be determined with low uncertainty because s_{HeNe} and R_{HeNe} are based on accurate measurements in the visible spectral range. Therefore the THz power responsivity $s(\nu)$ of the new standard detector is known more accurate. The combined uncertainty of the new THz power responsivity scale $s(\nu)$ is 1.2% mainly caused by the uncertainty of the reflectance $R(\nu)$ at THz frequencies. As explained in the introduction the uncertainty of the old THz power responsivity scale at 2.52 THz based on the calibration of the original standard detector at 2.52 THz was 7.3% [1]. The thus improved accuracy of the THz power responsivity scale is more than a factor of six better than before.

A comparison of both scales, i.e. a measurement of the power of the laser radiation at 2.52 THz with both the original and the new standard detector, reveals perfect agreement of both scales: the power together with its uncertainty interval measured by the new standard detector was completely covered by the larger interval measured by the original detector.

5. Summary and conclusion

A THz detector calibration facility with a far-infrared molecular gas laser which is operated at a variety of molecular emission lines in spectral range spanning from 1 THz to 5 THz is described in this work. The extension of the existing calibration services at 2.52 THz to the whole operating range of the THz laser requires a suitable new standard detector for this large spectral range. Therefore, a NG1 neutral glass absorber of a commercial thermopile detector was modified by optical polishing both surfaces and coating its back side with gold. Furthermore the absorber was characterized with respect to its absorptance and reflectance from 1 THz to 5 THz.

A physical model is applicable which describes the spectral variation of the THz responsivity of this detector. The model can be applied for the visible optical frequencies as well. Due to the optical quality of the NG1 absorber plate and the resulting accurate measurement of its reflectance at the HeNe laser wavelength the low uncertainty of the visible radiant power scale could be transferred to the new THz standard detector. As a consequence, the uncertainty of the existing THz radiant power scale is reduced by more than a factor of six and the power responsivity of the new standard detector in the spectral range from 1 THz to 5 THz is now known with a standard uncertainty of only 1.2%. This enables the PTB as metrology institute of Germany to offer the accurate calibration of suitable THz detectors as worldwide unique official service.

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