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COMMENT

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On the reliability of power measurements in the terahertz band

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In order for terahertz devices to reach technological maturity, robust characterization methods and reliable metrics for comparison between studies must be defined. In this comment, the authors describe the challenges faced in obtaining robust power measurements in the terahertz regime, and summarize recent efforts to establish standards for this field.

Towards the end of the 1980s, the appearance of the titanium-sapphire laser among other technological developments pushed the study of radiation into the far-infrared or terahertz (THz) band of the electromagnetic spectrum[1]. In those early days, this spectral region also started being referred to as "the terahertz gap" owing to the lack of appropriate sources and detectors for this type of radiation[2]. From the low-frequency end, its neighbor, the microwaves, benefited from the use of the comparatively mature electronic technology that saw enormous progress over the twentieth century. On the high-frequency end, also the comparatively mature infrared technology provides very powerful sources and sensitive detectors. The reasons for this gap of applications originate from the very fundamental principles by which the microwave and optical technologies operate. On the one hand, classical microwave generation and detection are based on direct electronic oscillation or the use of nonlinearities in semiconductor devices. These devices struggle to operate at frequencies higher than about 100 GHz because the carrier-transit times in such devices can only be shortened at the cost of its physical dimensions, which in turn implies a reduction of the power they can handle. On the other hand, optical technologies become noisy at longer wavelengths since the photon energies involved approach the thermal energy of particles at room temperature. Hence, quantum systems that could otherwise, be used for photodetection are continuously excited by the surroundings and not only by the radiation to be measured.

Three decades ago, the field of terahertz research was in its infancy. Sensitive photometric and radiometric devices for terahertz frequencies did not yet exist, and the only powerful monochromatic sources available, alcohol-vapor lasers, were hard to operate and maintain. Hence, these light sources were relatively rare. However, over the last 3 decades, terahertz technology has seen enormous progress, and many interesting applications have emerged. Terahertz radiation is now used both to probe fundamental interactions in novel materials and to perform non-destructive inspection for purposes as diverse as industry, medicine, biology and cultural heritage[3]. Crucially, the output power and number of monochromatic[4], tuneable[5] and broadband[6] sources have expanded considerably. The number of free-space and waveguide

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devices for the manipulation of this type of radiation has increased far more than we could review here.

One issue that is often discussed at conferences and during peer review of terahertz research is the ability to make reliable and traceable power measurements that would allow comparison between a variety of experiments in laboratories around the world. In many cases, power levels are quoted either in arbitrary units, or in actual physical units obtained from equipment that in many cases have not been calibrated properly. The reason for this is that using broadly accepted measurement methods implies the use of well calibrated instruments, which are not generally available, and requires relatively strict experimental designs and a systematic measurement uncertainty analysis taking into account all statistical and systematic error contributions which, in turn, results in reports of the performance of devices such as emitters and detectors, that cannot be fairly compared.

In this comment, we provide a brief overview of the state-of-affairs in the metrology of terahertz power, and discuss the foreseeable evolution and implications of these types of measurements.

One standard for all

The central task—to measure the radiant power across the terahertz spectral range traceable to the International System (SI) of Units—has been the core of the activities at the terahertz radiometry group at the national metrology institute of Germany, Physikalisch-Technische Bundesanstalt (PTB). Although the determination of power at terahertz frequencies has been an issue of interest to the entire community for a relatively long time, the number of laboratories with reliable detectors that can produce traceable measurements is still relatively limited. One of PTB's most important contributions is the calibration of the spectral responsivity of THz detectors from 700 GHz to 5 THz[7]. We have found that the lowest uncertainty for these kinds of measurements is achieved with a far-infrared molecular gas laser, which is optically pumped by a frequency-stabilized CO_2-laser and that emits tuneable monochromatic radiation from rotational transitions of the molecular gas.

The service of calibration has been proposed as a potential solution to the lack of reliably pre-calibrated off-the-shelf measurement systems in the many terahertz laboratories around the world. It is a strategy to improve the reliability and the ability to compare measurements from different laboratories, which is still an issue these days. There are two reasons for this: First, it is not a common practice to have instruments calibrated specifically for terahertz radiation, and second, the capacity to provide calibration services for this band is still restricted to very few places worldwide.

Free-space detectors

Triggered by uniformity limitations of commercial THz detectors with optically black radiation absorbers, PTB, together with a manufacturer of laser power meters developed a new type of pyroelectric thin-film detector based on a polyvinylidene fluoride (PVDF) film[8]. The novelty is a special metal coating on both surfaces, which are used as read out electrodes for the pyroelectric signal. The equivalent parallel circuit of their sheet conductivities is set to half the vacuum impedance. In this way, both electrodes act together as a semi-transparent metal absorber resulting in a frequency-independent absorbance of 50%, especially for lower sub-THz frequencies. This innovation resulted in a constant responsivity over a large aperture high enough to measure the THz power of tens of μW of a pulsed TDS system[9].

Recently, such a pyroelectric thin-film detector was used in an international pilot comparison for measuring radiant power in the THz spectral range. The comparison was organized by PTB in a new manner and involved the comparison of measurements carried out using devices provided by at the national metrology institutes of China, the USA, and Germany for two laser lines, 2.52 THz and 0.762 THz[10]. The measurements revealed good agreement within the stated uncertainties of the three participating countries.

Detectors for waveguided "low"-frequencies

In contrast to the recently implemented free-space THz power measurement capabilities, radio frequency (RF) power measurements in coaxial and hollow metallic waveguides are well established. Here, the output power of an active device is directly measured by connecting a calibrated, well-matched power sensor to its standardized output connector or flange. Traceability to the International System of Units is achieved by direct current (DC) power substitution. Different sensor types[11] such as thermistor power sensors, thermoelectric power sensors, and the dry-load calorimeter principle are used. The DC power applied to keep a self-balancing measurement bridge balanced or to achieve the same heating in the power sensor is a measure for the absorbed RF power.

The main contributions to the uncertainty are the RF losses in the waveguide leading from the connector or flange to the sensor element, non-ideal equivalence between RF and DC heating, temperature instabilities and nonlinearities of thermopiles used in the power sensors. Calibration of a power sensor in a microcalorimeter[12] allows to account for the RF waveguide losses dominating the measurement uncertainty at mm-wave frequencies. Taking all error contributions into account, expanded measurement uncertainties in the order of 1% at 100 GHz are achieved both for thermistor and thermoelectric power sensors[13]. So far, this primary power calibration is available up to 110 GHz at PTB. Work on extending the calibration capabilities into the upper waveguide bands is ongoing.

In a comparative experiment[14], it has been confirmed for the WR-10 band (75 GHz–110 GHz) that the power measured inside the waveguide equals that radiated into free-space via an antenna measured with a pyroelectric thin-film detector[8] calibrated at 1.4 THz with an optically calibrated detector. Further work to extend this link between the power scales to higher frequencies is ongoing.

Outlook

Over the last 5 years, important efforts have fructified in the introduction of new absorbers, which in turn have allowed improving the accuracy of traceable power measurements across the band between 0.7 and 5 THz in free-space. In addition, the reliability of waveguided power measurement methods for radiation in the mm-wave band has improved by the use of microcalorimetry.

We foresee that with the introduction of these novel techniques and devices, in addition to the ability to calibrate existing radiometric devices, the power measurements in this spectral region will become much more consistent in the coming few years. This will eliminate the inconsistencies that still come up in the literature.

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Competing interests

The authors declare no competing interests.

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