Comparison of Waveguide and Free-Space Power Measurement in the Millimeter-Wave Range

R. Judaschke, M. Kehrt, and A. Steiger

Acknowledgement: The comparison is part of the ongoing European project “Traceability for electrical measurements at millimetre-wave and terahertz frequencies for communications and electronics technologies” (18SIB09 TEMMT). This project has received funding from the EMPIR programme co-financed by the participating States and from the European Union's Horizon 2020 research and innovation program.

Full Citation of the original article published by IEEE:

R. Judaschke, M. Kehrt and A. Steiger, "Comparison of Waveguide and Free-Space Power Measurement in the Millimeter-Wave Range," 2019 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Paris, France, 2019, pp. 1-2.

Available at:
https://doi.org/10.1109/IRMMW-THz.2019.8874235

This is an author-created, un-copyedited version of the article R. Judaschke, M. Kehrt and A. Steiger, "Comparison of Waveguide and Free-Space Power Measurement in the Millimeter-Wave Range," 2019 44th IRMMW-THz, Paris, France, 2019, pp. 1-2.

Comparison of Waveguide and Free-Space Power Measurement in the Millimeter-Wave Range

R. Judaschke, M. Kehrt, and A. Steiger
Physikalisch-Technische Bundesanstalt (PTB), Braunschweig und Berlin, Germany

***Abstract*—A comparison of waveguide-based and free-space power measurements was carried out in the millimeter-wave range at PTB. The measurements revealed good agreement at 100 GHz of both power scales within their uncertainties. This confirms the consistent realization of SI traceable electronic and photonic power measurements at the national metrology institute of Germany.**

I. Introduction

TRACEABLE high-frequency power measurements are performed in coaxial and rectangular waveguides up to about 100 GHz by means of calorimeter-calibrated thermistors and thermoelectric sensors [1] whereas novel pyroelectric detectors are used to measure electromagnetic radiation propagating in free space in the sub-millimeter and THz range [2]. By their special coated electrodes which acts as radiation absorbers, these pyroelectric THz detectors feature a close-to-constant spectral responsivity in the wide range from 50 GHz to 5 THz. At PTB, such pyroelectric detectors are calibrated traceable to the International System of Units (SI) by means of a molecular gas laser using optical methods at frequencies above 1 THz [3].

Both methods of absolute power measurement are completely independent with respect to their metrological principle. Up to now, no comparison has been carried out whether both methods deliver the same result, i.e. if the power of an electromagnetic wave measured inside a guided-wave structure by a waveguide sensor equals the power detected by optical methods after the wave has been transferred into free-space via an antenna which is attached to the waveguide.

II. Experiment

The equivalence of high-frequency power measurements inside a waveguide and in free-space was verified in the rectangular waveguide WR-10 band between 75 GHz and 110 GHz. The measurements were taken in two spatially separated planes of a quasi-optical/waveguide measurement setup (Fig. 1).

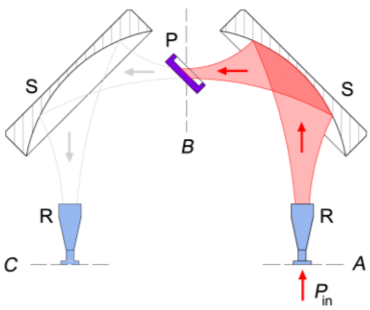

Fig. 1. Symmetric quasi-optical setup with two corrugated horn antennas (R) and two large elliptical mirrors (S). The pyroelectric THz detector (P) is placed in the central focal plane *B*. It is orientated under 45 degree with respect the optical axis.

First, the incident power P_{in} inside a rectangular waveguide (not shown in Fig.1) is determined in plane A by connecting a waveguide sensor instead of the horn antenna (R). In a second step, the electromagnetic wave is transformed into a Gaussian beam via a corrugated horn antenna (R) followed by an elliptical mirror (S) placed in front of the antenna to produce a well-defined small beam waist in the symmetry plane B. The measured beam profile at 105 GHz is shown in Fig. 2.

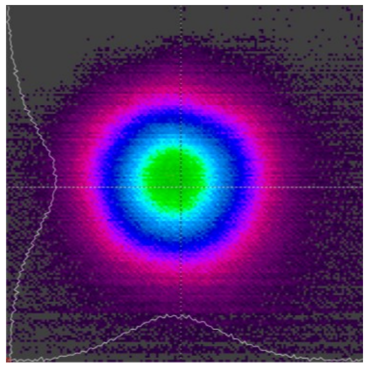

Fig. 2. Two-dimensional image (12 mm x 12 mm) of the focal beam profile at 105 GHz measured with pyroelectric camera. The nearly Gaussian spatial distribution is depicted by the superimposed curves of one-dimensional horizontal and vertical central power distribution.

At the focal beam waist, the free-space power is measured by means of a calibrated pyroelectric detector P with an aperture diameter of 34 mm. The detector is oriented under 45 degree with respect to the optical axis of the quasi-optical beam to avoid standing waves caused by surface reflection on the surface of the THz detector. This tilt is very important to completely absorb the surface reflection of 25 % of the radiation [2] outside the beam path by a foam absorber. The attenuation losses occurring between the two measurement planes A and B were determined by transmission measurements in a mirror-symmetrically expanded two-port setup between plane A and plane C by using a calibrated vector network analyzer. The experimental arrangement is depicted in Fig.1 as well, however with the pyro-electric detector removed.

A photo of the experimental setup consisting of RF multiplier source (Q), horn antenna (R), elliptical mirror (S) and pyroelectric detector (P) is shown in Fig. 3. The second mirror was removed to allow an easy mounting of the detector while the second horn antenna is still mounted on the base plate. To detect small power drifts of the RF source during the comparison, a monitoring waveguide sensor (M) is permanently attached via a directional coupler between RF source and horn antenna. This sensor indirectly measures the actual incident power inside the waveguide during both the free-space power measurements with the pyroelectric detector and waveguide measurements while the calibrated waveguide sensor W terminates the waveguide instead of the horn antenna.

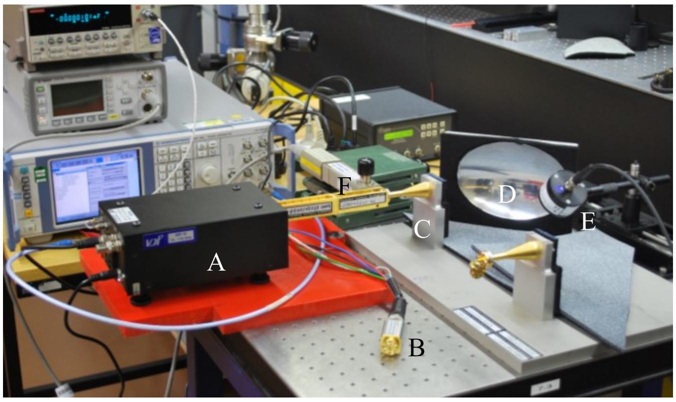

Fig. 3. Photo of the experimental setup with the RF source (Q), the calibrated waveguide sensor (W), the horn antenna (R) connected to the source via waveguides, the elliptical mirror (S), the 45°-tilted pyroelectric detector (P) and the monitor sensor (M) attached via a directional waveguide coupler.

III. RESULT

Fig. 4 shows the measured ratio of incident waveguide power and attenuation-corrected free-space power.

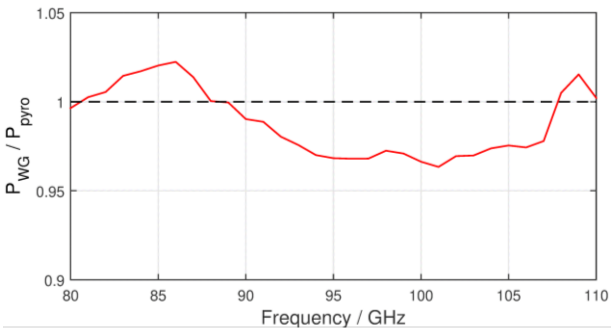

Fig. 4. Measured ratio of incident waveguide power in waveguide plane *A* and attenuation-corrected free-space power measured by the pyroelectric sensor in plane *B*.

Considering the uncertainties of both power measurements and the transmission losses between the measurement planes, a very good agreement between the two methods was found in the frequency range between 80 GHz and 110 GHz. It is important to note that the incident RF power in waveguide plane A is directly determined at these frequencies traceable to the International System of Units (SI) by using calorimeter-calibrated power sensor standards [1]. On the other hand, the calibration of the pyroelectric THz detector is performed by laser radiometry at 1.4 THz against another THz standard detector of PTB [3]. Due to flat frequency response of the pyro-electric detector, it is justified to take the calibration value at 1.4 THz at a more than 10 times lower frequency of the present comparison. Moreover, the radiant power responsivity of the THz standard detector is traced back to the SI with low uncertainty at visible laser frequencies by electrical substitution inside a cryogenic radiometer [4]. In total, this illustrates the huge frequency difference of more than three orders of magnitude for tracing back radiant power in this comparison besides the physical difference of electromagnetic wave propagation inside a waveguide and in free-space propagation.

IV. SUMMARY

To our knowledge, this is the first time that a comparison of traceable waveguide-based and free-space power measurement has been performed. Furthermore, the proof of equivalence of electronic and photonic power scales opens the promising possibility of tracing back high-frequency power measurements in higher-frequency waveguide bands up to the THz range by using these special pyroelectric THz detectors as reference standard in free-space.

ACKNOWLEDGEMENT

The comparison is part of the ongoing European project “Traceability for electrical measurements at millimetre-wave and terahertz frequencies for communications and electronics technologies” (18SIB09 TEMMT). This project has received funding from the EMPIR programme co-financed by the participating States and from the European Union's Horizon 2020 research and innovation program.

REFERENCES

[1]. R. Judaschke, K. Kuhlmann, T. Reichel, W. Perndl, “Millimeter-Wave Thermoelectric Transfer Standard”, *IEEE Transactions on Instrumentation and Measurement*, vol. 64, pp. 3445-3450, 2015.

[2]. A. Steiger, W. Bohmeyer, K. Lange, and R. Müller, “Novel pyroelectric detectors for accurate THz power measurements”, *Technisches Messen*, vol. 83, pp. 386-389, 2016.

[3]. A. Steiger, M. Kehrt, C. Monte, and R. Müller, “Traceable THz power measurement from 1 THz to 5 THz,” *Optics Express*, vol. 21, pp. 14466-14473, 2013.

[4]. L. Werner, J. Fischer, U. Johannsen, and J. Hartmann, “Accurate determination of the spectral responsivity of silicon trap detectors between 238 nm and 1015 nm using a laser-based cryogenic radiometer,” *Metrologia,* vol. 37, pp. 279-284, 2000.