



This is an electronic reprint of the original article. This reprint may differ from the original in pagination and typographic detail.

Zheng, Jianfang; Ala-Laurinaho, Juha; Räisänen, Antti

# On the One-Antenna Gain Measurement Method in Probe Station Environment at mm-Wave Frequencies

Published in: IEEE Transactions of Instrumentation and Measurement

DOI: 10.1109/TIM.2018.2890454

Published: 21/01/2019

Document Version Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:

Zheng, J., Ala-Laurinaho, J., & Räisänen, A. (2019). On the One-Antenna Gain Measurement Method in Probe Station Environment at mm-Wave Frequencies. *IEEE Transactions of Instrumentation and Measurement*, 68(11), 4510 - 4517. https://doi.org/10.1109/TIM.2018.2890454

This material is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.

# This is the accepted version of the original article published by IEEE.

© 2019 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

# On the One-Antenna Gain Measurement Method in Probe Station Environment at mm-Wave Frequencies

Jianfang Zheng, Juha Ala-Laurinaho, and Antti V. Räisänen, Life Fellow, IEEE

Abstract—In this paper, an antenna gain measurement method for millimeter wave (mm-wave) antennas in an on-wafer probe station environment is studied. The one-antenna gain measurement has been known since the 1940's. However, the authors believe that this extension of their previous work is the first time when the method is systematically studied in the on-wafer probe station environment. The main difference between the original one-antenna gain measurement and our method is that in the probe station environment the space is limited and, therefore, the reflecting plate dimensions are limited. We have studied the effect of the reflector size limitation through computations using physical optics (PO) and through measurements with a standard gain horn (SGH) and with a printed microstrip patch antenna. The necessary size of the reflecting plate naturally depends on the beamwidth of the antenna under test (AUT) and on the distance. Time gating has been applied in the retrieving calculation to filter out multiple reflections. According to this study, the one-antenna gain measurement in the W-band results in the correct antenna gain with very high accuracy for the highly directional SGH. For the patch antenna, the gain measured in the on-wafer probe station environment agrees well with the simulated one.

*Index Terms*—Antennas, gain measurement, millimeter wave (mm-wave), physical optics (PO), probe station, reflecting plate, standard gain horn, time gating.

#### I. INTRODUCTION

MILLIMETER-WAVES (mm-wave) have been applied in a wide range of applications, e.g., indoor highdata-rate communication systems, high-resolution automotive radars, and imaging systems [1]–[3]. These systems use small antennas that are usually on-chip or printed on flexible substrates and have tiny feeding points which cannot be connected by conventional coaxial lines. It is difficult to measure the radiation performance of these antennas, since they need an on-wafer probe station measurement set-up. Further, it is generally infeasible to build such a set-up for the conventional far-field gain measurements. Moreover, it is difficult to find an on-wafer reference antenna for the probe station calibration.

Manuscript received August 13, 2018; Revised date November 27, 2018, accepted December 13, 2018. This work is supported by the Academy of Finland through the DYNAMITE and LATERA projects. The Associate Editor coordinating the review process was xx xx. (*Corresponding author: Jianfang Zheng*).

The authors are with the Department of Electronics and Nanoengineering and MilliLab, School of Electrical Engineering, Aalto University, 00076, AALTO (Espoo), Finland (e-mail: jianfang.zheng@aalto.fi; juha.alalaurinaho@aalto.fi; antti.raisanen@aalto.fi).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier xxx

Traditional far-field antenna gain measurement techniques include the well-known three-antenna method, the two-antenna method, and the one-antenna method [4]–[7]. In the twoantenna method, the antenna gain can be obtained by measuring the transmission power between the two presumably identical antennas. If there is no antenna identical to the antenna under test (AUT), the three-antenna method can be utilized by measuring the transmission power between all possible two-pair combinations.

Furthermore, if there are no other proper antennas available, then the one-antenna gain measurement method devised by Purcell can be used [8]. In this method, the identical antenna in the two-antenna method is substituted with the image of the AUT, which can be realized with a reflecting plate. Pippard et al., as well as Lee and Baddour have implemented the one-antenna method by changing the distance between the reflecting plate and the antenna aperture [9], [10]. In these measurements, the operating frequencies were much lower than the mm-wave frequencies used in the current work, and the size of the reflecting plate was not critical. Coquet et al. have demonstrated one-antenna gain measurement also at mm-wave frequencies [11]; in their method the frequency is swept while the reflector distance from the antenna aperture is kept constant. Bhardwaj et al. have characterized circularly polarized antenna gain at mm-wave and THz frequency range [12]. On-wafer antenna gain measurement with near-field and far-field method have been reported in [13] and [14], respectively. In [15], a one-antenna gain measurement in onwafer probe station without reflector movement is shown.

In this work, we systematically study the optimal size of the movable reflecting plate, making it possible to measure antenna gain in the limited space of the probe station. Preliminary results of the one-antenna gain measurement in the onwafer probe station were reported in [16]. However, optimal reflecting plate size was not studied. Removal of the effect of multiple reflections through time-gating is studied in [17].

In this article, first the on-wafer probe station mm-wave antenna gain measurement method is introduced. Then, we study the selection of reflecting plate size through simulations. Reference measurements with standard gain horn (SGH) have been made to verify the presented method. Finally, a microstrip patch antenna is measured on the probe station with the proposed method.

# II. THEORETICAL BACKGROUND

#### A. One-Antenna Gain Measurement Method

Fig. 1 describes the one-antenna gain measurement set-up. When the antenna radiates towards the reflector, its image is created on the other side of the reflector plate. Therefore, the power reflected by the plate is equivalent to transmission from an identical antenna located at 2d.



Fig. 1. (a) Theoretical and (b) practical schematic of the one-antenna-method of gain measurement set-up.

Assuming that the reflecting plate is far enough from the AUT to fulfill the far-field condition, the ratio of the received and transmitted powers is obtained from Friis' formula:

$$\frac{P_{\rm r}}{P_{\rm t}} = G_{\rm t} \cdot G_{\rm r} \cdot (\frac{\lambda}{4\pi \cdot r})^2 \tag{1}$$

where  $G_t$  and  $G_r$  are the gains of the transmitting and receiving antennas respectively,  $\lambda$  is the wavelength, and r is the distance between the AUT and its image. In the one-antenna system, the gains of the transmitting and receiving antennas are equal ( $G_t = G_r = G$ ), and the antenna separation is twice the AUT to reflector distance (r = 2d). The power ratio is the square of the amplitude of the transmission coefficient  $S_{21}$ , which equals to the reflection coefficient  $S_{11}$  by the reflector. Therefore, we can rewrite (1) as:

$$\frac{1}{|S_{11\text{dif}}|} = \frac{8\pi}{G \cdot \lambda} \cdot d \tag{2}$$

where  $S_{11\text{dif}}$  is the difference of  $S_{11}$  in two cases: AUT with and without a reflector. In order to improve the accuracy of the method, the reflecting plate is translated in the z direction.  $1/|S_{11\text{dif}}|$  has a linear relationship with respect to d and from the slope  $8\pi/G\lambda$ , we can determine the antenna gain value.

The measurement procedure in practice is:

- 1) measure the reflection coefficient towards free space and record the original reflection coefficient  $S_{11\text{orig}}$ ;
- 2) put a reflecting plate on top of (in front of) the AUT and measure the reflection coefficient  $S_{11\text{meas}}$ . Then obtain the  $|S_{11\text{dif}}| = |S_{11\text{meas}} - S_{11\text{orig}}|$  in (2);
- move the reflector within a distance range, find the slope in (2), and determine the AUT gain.

Time gating must be used during the data processing to remove the effect of multiple reflections which improves measurement accuracy. Fourier transform (FFT) techniques were applied for the frequency domain reflection coefficient at each reflector position and the time-gated response over the reflector distance range was obtained. A proper window is used to filter out multiple reflections away. Finally, the transformed main reflection signal is transformed back to the frequency domain to calculate the antenna gain with the method above. MATLAB<sup>®</sup> built-in functions fft and ifft can be used for the data processing [18]. Since the bandwidth in the frequency domain defines the resolution in the time domain, it is recommended to measure the S-parameter over a wide frequency band. Therefore, there is a trade-off between time resolution and measurement time. More details on the FFT data processing for this measurement method are shown in Section IV.

#### B. Physical Optics Method

For the one-antenna-method measurement, it is necessary to choose the reflecting plate, which should be as small as possible and at the same time large enough in order to cover sufficiently the main beam of the antenna, and this way to enable the accurate gain measurement.

We use physical optics (PO) to evaluate the influence of the reflector size on the measurement. The PO approximation takes into account the diffracted field near the geometric boundaries (edge diffraction) [19], [20], so it is sufficiently accurate to estimate the effects of the reflective plate size applied in the one-antenna method. The calculation model is shown in Fig. 2. Here, we transform the one-antenna model to the two-antenna model with the identical antenna instead of the image and the slot instead of the reflecting plate. On each point on the slot (seen as the complement of the reflecting plate), the scattering field by the antenna is [21]:

$$\mathbf{E}_{\text{scat}}(x',y') = \int_{\mathbf{S}} \mathbf{E}_0 \cdot f(x,y) \frac{1+jkR}{2\pi R^3} e^{-jkR} \\ \times [\mathbf{u}_y(z'-z) - \mathbf{u}_z(y'-y)] d\mathbf{S} \quad (3)$$

where  $\mathbf{E}_0$  is the normalized field vector, f(x, y) is the field distribution function of the antenna aperture,  $R = \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2}$  is the distance from a point in the aperture to a point in the slot,  $k = 2\pi/\lambda$  is the free-space wave number,  $\mathbf{u}_y(z' - z) - \mathbf{u}_z(y' - y)$  defines the polarization (y-polarized), and **S** is the surface of the antenna aperture. In the image antenna, the received field at each point of the aperture is the integral of the field scattered from the slot:

$$\mathbf{E}_{\mathbf{r}}(x'',y'') = \int_{\mathbf{S}'} \mathbf{E}_{\text{scat}}(x',y') \cdot \frac{1+jkR'}{2\pi R'^3} e^{-jkR'} \\ \times [\mathbf{u}_y(z''-z') - \mathbf{u}_z(y''-y')] d\mathbf{S}' \quad (4)$$

where  $R' = \sqrt{(x' - x'')^2 + (y' - y'')^2 + (z' - z'')^2}$  is the distance from a point in the slot to a point in the image aperture, and **S**' is the aperture of the slot. Only *y*-polarized incident tangential field is taken into account in the integral. Finally, the total received field by the antenna image is the coupling integral over the antenna image aperture **S**'':

$$\mathbf{E}_{\text{total}} = \int_{\mathbf{S}''} \mathbf{E}_{\mathbf{r}}(x'', y'') \cdot f(x'', y'')^* \ d\mathbf{S}''.$$
(5)



Fig. 2. Model used to simulate the measurement.

Through this model, we can observe the distribution of the received power by the antenna image when changing the reflector size and its distance from the antenna aperture. It is worth noting that multiple reflections are neglected here.

# **III. SIMULATION**

### A. Ideally Aligned Reflector

To verify the one-antenna gain measurement method, we choose a WR-10 standard gain horn antenna (SGH) with dimensions of 14.48 mm  $\times$  11.18 mm ( $a \times b$ ) and a microstrip patch antenna with he aperture (patch) dimensions of 1.8 mm  $\times$  1 mm for the validation test. Before measurements, we employed the PO method (Section II-B) to simulate the influence of reflector size on measured gain values. MATLAB<sup>®</sup> is used to realize this calculation. In all simulations for the SGH and patch antenna, the length of the reflecting plate l is 100 mm and the width range is from 25 to 125 mm.

The far-field distance of the SGH is 112 mm at 80 GHz, so the reflecting plate was placed 56 mm away from the SGH to meet the far-field condition. However, reference [22] suggests that distances moderately less than  $2D^2/\lambda$  do not result in appreciable error. Therefore, in the simulation, the selected



Fig. 3. Electric field level (non-normalized) of (a) the SGH at 80 GHz and (b) the patch antenna at 80 GHz with a 20-mm reflector offset from the AUT center.

movement range of the reflecting plate spanned from 30 to 120 mm. We use a cosine aperture electric field distribution  $f(x, y) = \cos(\pi x/a)$ , |x| < a/2, |y| < b/2 for the SGH. The far-field distance of the microstrip patch antenna is much smaller than that of the SGH. Therefore, the movement range is 5-120 mm for the patch antenna simulation at 80 GHz. In practice, because of the spatial limitation due to the probe and the feeding cable or waveguide, the reflector cannot extend too far towards the probe side from the AUT, see Fig. 1(b). Therefore, for the patch antenna case the reflector has an offset of 20 mm in the y direction, whereas for the SGH, the reflecting plate was symmetrically placed. The aperture field distribution of the patch antenna is obtained from a simulation by commercial 3D full wave software ANSYS High Frequency Structure Simulator (HFSS) [23].

The simulated results of the received electric field level of the SGH and the patch antenna by the PO method are shown in Fig. 3. It demonstrates that , the received electric field level decreases with the increasing distance. Because at larger distance the main beam covers a wider area, the wider reflector results in a smoother response as a narrow reflector may fail to cover a large enough portion of the antenna beam and the effect of the edge diffraction is stronger.



Fig. 4. Influence of reflector width on the accuracy of one-antenna-method in antenna gain measurement of (a) the SGH and (b) the patch antenna with a 20-mm reflector offset from the AUT center. Slope determined over different movement range.

By choosing some specific distance range, we can calculate the gain level using the process presented in Section II-A. Here, we use two different distance ranges as examples, i.e. 30-50 mm and 50-90 mm. The analyzed results are shown in Fig. 4. For the SGH, when the distance range is 30-50 mm, in order to get a stable power (gain) level, we should use a reflector wider than 40 mm, and the variation is less than 0.01 dB (dotted line in Fig. 4(a)). However, when increasing the distance, i.e. to 50-90 mm, we need a wider reflector (more than 60 mm) to cover the main beam and maintain a stable gain value (black dashed line in Fig. 4(a)). In this movement range, if we chose a 25-mm wide reflector, we may obtain a 2.4 dB increase due to high edge diffraction. Similarly, for the patch antenna measurement set-up, when the movement range is 5-30 mm, a reflector width more than 40 mm produces a stable gain; however, we need an 100 mm wide reflector when the movement range is 50-60 mm.

#### B. Imperfectly Aligned Reflector

In practice, reflector alignment errors during measurement, e.g., tilt or/and offset are unavoidable. To explore the effects of these kinds of misalignment on the measurement accuracy, we assume several error cases related to the reflector in Fig. 2: (a) tilt around the reflector longer center line (y-axis); (b) offset horizontally (along x-axis); and (c) tilt with offset (case (a) and (b)). The tilt angles chosen for the study are  $2^{\circ}$  and  $5^{\circ}$ since the testing personnel should be able to perceive a larger tilt angle. The offset is considered only along the x-axis (w in Fig. 2), because the reflector length is much larger than the antenna aperture so that small offset in that direction has no apparent effect. The antenna for calculation is SGH, because it has a narrower beam and is expected to be more vulnerable to imperfectly aligned reflectors. The reflector distance range is 50-90 mm. Other parameters are the same as in Section III-A.



Fig. 5. Effects of the reflector imperfect alignment on the SGH measurement results.

The simulated results are shown in Fig. 5. Note that all curves are normalized and compared with the level of the perfectly aligned case. We can see that an offset of 5 mm has nearly no effect on the accuracy except when the reflector width is too small. A tilt of  $2^{\circ}$  will cause an error of 0.1 dB. Tilting  $5^{\circ}$  will increase the error to 0.7 dB. In conclusion, a small misalignment of the reflector causes a minor reduction in the measured gain.

#### IV. MEASUREMENT

#### A. SGH Measurement

In the SGH gain measurement, we arranged flat metal plates with three different widths (w = 25, 60, and 125 mm) in front of the antenna. All surrounding surfaces were obscured with microwave absorbers (Fig. 6). The measurement steps were described in Section II-A, and the reflector was displaced vertically in step of 0.5 mm.

Fig. 7 shows the time-domain response of the measured SGH reflection coefficient when the reflector width is 125 mm.



Fig. 6. Photo of the SGH measurement set-up.

The time-domain response is similar to the 25-mm and 60mm wide strips. The full movement range of the reflector spanned 10 mm to 130 mm from the SGH aperture. The antenna free-space reflection coefficient is removed, so there is no response at the time instant t = 0. It is clear that a strong signal line appears which represents the main reflection by the reflector. In addition, there are some small multiple reflections delineated by the different slopes with the increasing time. It is worth noting that when the reflector distance is less than 30 mm, there are some interfering signals with the main reflection. Therefore, when applying filtering, we should avoid this region, and instead, use some 'pure' signal region. In this case (w = 125 mm), we extract a 0.5 ns wide window to filter the time domain response, and the distance range is 50-90 mm (Fig. 7(b)). The time gate is shifting with the reflector distance to keep the main reflection signal. Similarly, for the w = 60 mm case, based on the time domain response of the measured results, we choose a distance range of 30-50 mm.

The retrieved SGH gain results by the one-antenna method and the conventional three-antenna method are shown in Fig. 8. In the three-antenna method measurement, we used another SGH and an open-ended waveguide (OEWG) antenna. The SGH has reference gain values ranging from 18 to 21 dBi in the frequency range of 75-105 GHz (blue solid line, data provided by the manufacturer [24]). The measured SGH gain curves revealed some pass band ripple due to finite wall thickness. Excellent agreement with the three-antenna method was observed with the one-antenna measurement method. Data from the complementary methods using the 60 mm (30-50 mm vertical displacement) and 125 mm (50-90 mm vertical displacement) width plates data diverged from theory  $\sim 0.1$  dB. When the reflector width is 25 mm, the retrieved gain has a 2-dB higher gain value (black solid line) at 80 GHz when the distance range is 50-90 mm, but it agrees better when the distance range is 30-50 mm (green solid line). These results agree well with the prediction in Fig. 4(a). Therefore, we believe the PO method can be a good tool and reference for choosing the proper reflector in the one-antenna measurement method.



Fig. 7. (a) SGH time domain response calculated from the measured frequency domain reflection coefficient (w=125 mm); (b) Gated time domain signal used for the SGH gain retrieval. The plate distance range is 50-90 mm.



Fig. 8. Gain measurement results of the SGH with different methods.

#### B. Patch Antenna Gain Measurement on Probe Station

A microstrip patch antenna working at the center frequency of 80 GHz was designed and fabricated. The substrate is Polyethylene Naphthalate (PEN) with a thickness of 125  $\mu$ m and measured dielectric constant  $\epsilon_r = 2.95$  and loss tangent tan $\delta = 0.004$  at 75 GHz. The patch metal has a sheet impedance value R of  $1.5\pm0.5 \Omega/sq$ , arising from the printing of silver nanoparticle ink on the substrate followed by sintering 120 minutes at 180 °C [25], [26]. With the help of ANSYS HFSS, we simulated the performance of the designed antenna. In simulation, we use  $R = 1.5 \Omega/sq$  and  $R = 2 \Omega/sq$  as references. The main parameters of the antenna are shown in Fig. 9(a).





Fig. 9. (a) Dimensions of the designed patch antenna; (b) antenna in the probe station measurement set-up.

Section III indicated a small reflector movement range and a wide reflector width for patch antenna measurement. Here, we use 60 mm and 80 mm wide copper plates with the full movement range of 4-64 mm in the measurement on the probe station (Fig. 9(b)).

Similar to that in Section IV-A, we use FFT to obtain the time responses of the patch antenna under reflectors of widths 60 mm and 80 mm (Fig. 10). It is clear that there are several multiple reflections. This is because the large metal (steel) chuck forms a large reflective area, which is difficult to cover with absorbers. Therefore, the multiple reflections between the AUT, the reflector and the measurement setup cannot be avoided. There are some measurement artefacts occurring at some reflector positions. Some interferences or distortions happen when the reflector is very close to the AUT

Fig. 10. Patch antenna time domain response calculated from the measured frequency domain reflection coefficient: (a) w = 60 mm; (b) w = 80 mm.

To reduce the influence of multiple reflections and distortions on the retrieved gain results, we use a 0.125 ns wide window to filter the time domain signal and get suitable sections for the gain retrieval (Fig. 11). The distance range is 20-30 mm.

The measured and retrieved results are shown in Fig. 12. The measured  $S_{11}$  of the AUT has a small frequency shift from the simulated one. The second resonance results from the whole test structure including also the CPW feed line, leading to a resonance in  $S_{11}$ , but it does not contribute to radiation. Correspondingly, the measured gain has a frequency shift as well. The retrieved gain values with two different reflector widths, i.e. 60 mm and 80 mm, agree well with the simulated ones.



Fig. 11. Gated time domain signal used for the patch antenna gain retrieval. (a) w = 60 mm; (b) w = 80 mm. The plate distance range is 20-30 mm.

#### V. DISCUSSION

In the model presented, we consider the antennas having broadside beams. For an antenna with beam steering or unknown radiation pattern, in order to measure the maximum gain, it is needed to characterize its radiation performance first, e.g., using the method presented in [27]. Then the reflecting plate is tilted towards the main beam direction and the proposed one-antenna gain measurement method can be used.

# VI. CONCLUSION

This article discussed the one-antenna gain measurement method which can be used in the probe station environment, where the application of the conventional gain measurement methods is difficult. The selection of the proper reflector size has been studied through physical optics and measurements with two different antennas. Time gating is used to filter out the multiple reflections in the gain retrieval process. Reference measurements with an SGH operating in the W-band show that with this method it is possible to measure accurately the gain of a directive antenna. A microstrip patch antenna operating



Fig. 12. Patch antenna reflection coefficient and gain retrieved from gated time domain signal. (a) reflection coefficient and (b) realized gain when w= 60 mm and w= 80 mm. The reflector distance range is 20-30 mm.

at 80 GHz fed by the on-wafer probe has also been measured in the probe station with the proposed method. The measured gain agrees well with the simulated ones although a frequency shift in the measured gain response is observed.

The work presented in this paper supports application of the one-antenna method for gain measurement of antennas working in mm-wave frequency range in a probe station environment.

## ACKNOWLEDGMENT

The authors would thank Mr. Jouko Aurinsalo and Mr. Ismo Huhtinen at VTT Finland for the material characterization measurement, Mr. Asko Sneck, Dr. Ari Alastalo and Dr. Tapio Mäkelä at VTT for the patch antenna fabrication, and Prof. Zachary Taylor for improving the language of this paper.

#### REFERENCES

- [1] IEEE Std 802.11ad-2012, IEEE Standard, 2012.
- [2] H. H. Meinel, "Evolving automotive radar—From the very beginnings into the future,"*The 8th European Conference on Antennas and Propa*gation, Hague, Netherlands, 2014, pp. 3107-3114.

- [3] A. Luukanen, R. Appleby, M. Kemp, and N. Salmon, "Millimeterwave and terahertz imaging in security applications," in *Terahertz Spectroscopy and Imaging*, vol. 171, K. Peiponen, A. Zeitler, M. Kuwata-Gonokami, Ed. Springer Series in Optical Sciences, Springer, Berlin, Heidelberg.
- [4] IEEE Standard Test Procedures for Antennas, ANSI/IEEE Std. 149-1979.
- [5] C. A. Balanis, Antenna Theory, New York: Wiley, 1997.
- [6] J. D. Kraus, Antennas, New York: McGraw-Hill, 1988.
- [7] W. L. Stutzman and G. A. Thiele, *Antenna Theory and Design*, New York: Wiley, 1998.
- [8] E. M. Purcell, "A method for measuring the absolute gain of microwave antennas," Radiation Laboratory, Massachusetts Institute of Technology, Report 41-9, January 3, 1943, 8 p.
- [9] A. B. Pippard, O. J. Burrell, and E. E. Cromie, "The influence of reradiation on measurements of the power gain of an aerial," *Journal of the Institution of Electrical Engineers - Part III A: Radiolocation*, vol. 93, no. 4, pp. 720-722, 1946.
- [10] R. Q. Lee and M. F. Baddour, "Absolute gain measurement of microstrip antennas under mismatched conditions," *Electronics Letters*, vol. 24, no. 9, pp. 521-522, 1988.
- [11] P. Coquet, K. Mahdjoubi, and C. Terret, "Automatic antenna gain measurement at high frequencies," *Electronics Letters*, vol. 28, no. 14, pp. 1339-1340, July 1992.
- [12] S. Bhardwaj, N. K. Nahar, and J. L. Volakis, "Novel phaseless gain characterization for circularly polarized antennas at mm-wave and THz frequencies," *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 10, pp. 4263-4270, 2015.
- [13] A. Jam and K. Sarabandi, "A submillimeter-wave near-field measurement setup for on-wafer pattern and gain characterization of antennas and arrays," *IEEE Transactions on Instrumentation and Measurement*, vol. 66, no. 4, pp. 802-811, 2017.
- [14] H. Gulan, S. Beer, S. Diebold, C. Rusch, A. Leuther, I. Kallfas and T. Zwick, "Probe based antenna measurements up to 325 GHz for upcoming millimeter-wave applications," In 2013 International Workshop on Antenna Technology (iWAT), pp. 228-231, IEEE.
- [15] G. Felic, "Antenna gain measurements in the V-band: A single-antenna method," *Electromagnetic Compatibility Symposium Adelaide*, Adelaide, Australia, 2009, pp. 98-101.
- [16] J. Zheng, J. Ala-Laurinaho, and A. V. Räisänen, "A simple method for on-wafer antenna gain measurement," 2017 Progress In Electromagnetics Research Symposium - Spring (PIERS), St Petersburg, 2017, pp. 1620-1624.
- [17] J. Ala-Laurinaho, J. Zheng, and A. V. Räisänen, "One-antenna gain measurement in a probe station," presented in the 2018 IEEE Conference on Antenna Measurements and Applications (2018 IEEE CAMA), Västerås, Sweden, September 3-6, 2018.
- [18] MATLAB R2018a, The MathWorks, Inc., Natick, Massachusetts, United States.
- [19] C. A. Balanis, L. Sevgi, and P. Y. Ufimtsev, "Fifty years of high frequency diffraction," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 23, no. 4, pp. 394-402, 2013.
- [20] P. Y. Ufimtsev, *Physical Theory of Diffraction*, 2<sup>nd</sup> ed., John Wiley & Sons, Inc., Hoboken, New Jersey, 2014.
- [21] T. Hirvonen, J. Tuovinen, and A. Räisänen, "Lens-type compact antenna test range at mm-wave," in *Proc. 21st European Microwave Conference*, Stuttgart, Germany, Sept. 1991, pp. 1079-1083.
- [22] S. Silver, *Microwave Antenna Theory and Design*, New York: McGraw-Hill, 1949.
- [23] ANSYS HFSS 2014, ANSYS, Inc., Canonsburg, Pennsylvania, United States.
- [24] Aerowave, [Online]. Available: http://www.aerowave.net/Catalog/28.pdf.
- [25] A. Sneck, T. Mäkelä, and A. Alastalo, "Reverse-offset for roll-to-roll high-resolution printing," *Flexible Printed Electron.*, vol. 3, no. 1, pp. 014001, 2018.
- [26] X. Wang, A. Díaz-Rubio, A. Sneck, A. Alastalo, T. Mäkelä, J. Ala-Laurinaho, J. Zheng, A. V. Räisänen, and S. A. Tretyakov, "Systematic design of printable metasurfaces: validation through reverse-offset printed millimeter-wave absorbers," *IEEE Transactions on Antennas and Propagation*, vol. 66, pp. 1340-1351, 2018.
- [27] Z. Du, V. Viikari, J. Ala-Laurinaho, A. Tamminen, and A. V. Räisänen, "Antenna pattern retrieval from reflection coefficient measurement with reflective loads," *Progress in Electromagnetics Research*, vol. 148, pp. 15-22, 2014.