Generalized Statistics of Antenna Efficiency Measurement in a Reverberation Chamber

Ieee Transactions on Antennas and Propagation (ISSN: 0018-926X)

Citation for the published paper:
Chen, X. (2014) "Generalized Statistics of Antenna Efficiency Measurement in a Reverberation Chamber". Ieee Transactions on Antennas and Propagation, vol. 62(3), pp. 1504-1507.

http://dx.doi.org/10.1109/tap.2013.2295420

(article starts on next page)

Generalized Statistics of Antenna Efficiency Measurement in a Reverberation Chamber

Xiaoming Chen

Abstract—**Statistics of the measured antenna efficiency using the reverberation chamber (RC) technique (proposed in IEC 61000-4-21) has been derived by assuming that the measurements of the antenna under test (AUT) and the reference antenna have the same independent sample number. This work generalizes the statistics of the measured antenna efficiency by allowing the AUT measurement and the reference measurement to have different numbers of independent samples. The derived statistics are verified by simulations as well as RC measurements. Moreover, practical issues about how to allocate the total measurement time to the AUT and reference measurements for different cases are discussed.**

Index Terms—**Antenna efficiency, measurement, reverberation chamber (RC).**

I. Introduction

Reverberation chambers (RCs) have been used for measuring antenna efficiencies [1]–[8]. While different approaches of measuring antenna efficiencies exist [2]–[5], this work focuses on the standard approach of measuring antenna efficiency [1], which involves separate measurements of the AUT and the reference antenna, because the standard approach is general and widely used, e.g., [6], [7].

A statistical RC measurement is incomplete without analysis of the measurement uncertainty. The statistics of the measured antenna efficiency has been derived in [8] based on the assumption that both AUT and reference measurements have the same number of independent samples. However, in practice, the independent sample numbers for the AUT and reference measurements may differ. For example, when there are many AUTs to be measured, in order to save measurement time, one may perform a common reference measurement with more samples than the individual AUT measurements [7]. Another example is that a physically large AUT mounted on the turn-table platform will circle with a smaller radius and therefore tend to have a smaller number of independent samples [9], compared with the reference measurement. Hence this work focuses on the statistics of the measured antenna efficiency when the AUT measurement and the reference measurement have different numbers of independent samples. The derived statistics are verified using numerical simulations as well as RC measurements. Based on the derived statistics, practical issue about how to allocate the total measurement time to the AUT and reference measurements is discussed.

II. Statistics of Measured Antenna Efficiency

The standard approach of measuring the antenna efficiency in an RC is to first measure the average power transfer function $P_{\rm ref}$ between a reference antenna (with known antenna efficiency $e_{\rm ref}$) and a fixed antenna; then measure that between the AUT and the fixed antenna, $P_{\rm AUT}$. During the measurements, both the reference antenna and the AUT must be placed in the RC in order to keep the same RC loading. (In case there are many AUTs, e.g., [7], all of them needed to be placed in the RC.) Based on the measurements, the total radiation efficiency (referred as antenna efficiency in this work) of the AUT is estimated as

$$\hat{e}_{\rm AUT} = \frac{\hat{P}_{\rm AUT}}{\frac{\hat{P}_{\rm ref}}{e_{\rm ref}}} \tag{1}$$

where $\hat{e}_{\rm AUT}$ denotes the estimated antenna efficiency $e_{\rm AUT}$, and $\hat{P}_{\rm AUT}$ and $\hat{P}_{\rm ref}$ are the estimated average power transfer functions of $P_{\rm AUT}$ and $P_{\rm ref}$, respectively. Note that the antenna efficiency of the fixed antenna is cancelled out in (1).

Denoting the net average power transfer functions as $\hat{G}_{\rm AUT} = \hat{P}_{\rm AUT}/e_{\rm AUT}$ and $\hat{G}_{\rm ref} = \hat{P}_{\rm ref}/e_{\rm ref}$, respectively, (1) can be rewritten as

$$\hat{e}_{\rm AUT} = \frac{e_{\rm AUT}\hat{G}_{\rm AUT}}{\hat{G}_{\rm ref}}. \tag{2}$$

Note that $e_{\rm AUT}$ is the true value of the antenna efficiency and $\hat{e}_{\rm AUT}$ is the estimation of $e_{\rm AUT}$. Let N_1 and N_2 be the numbers of independent samples of the AUT measurement and the reference measurement, respectively,

$$\hat{G}_{\rm AUT} = \frac{1}{N_1}\sum_{i=1}^{N_1} G_{{\rm AUT},i}$$
$$\hat{G}_{\rm ref} = \frac{1}{N_2}\sum_{i=1}^{N_2} G_{{\rm ref},i}. \tag{3}$$

Note that $E[\hat{G}_{\rm AUT}] = E[G_{{\rm AUT},i}] = E[\hat{G}_{\rm ref}] = E[G_{{\rm ref},i}] = G_0$, where E denotes the expectation. Since $G_{{\rm AUT},i}$ and $G_{{\rm ref},i}$ are independent and identically distributed (i.i.d.) random variables that are exponentially distributed [10], $\sum_{i=1}^{N_1} G_{{\rm AUT},i}$ and $\sum_{i=1}^{N_2} G_{{\rm ref},i}$ follow Gamma distributions, respectively, i.e., $\sum_{i=1}^{N_1} G_{{\rm AUT},i} \sim {\rm Gamma}(N_1, G_0)$ and $\sum_{i=1}^{N_2} G_{{\rm ref},i} \sim {\rm Gamma}(N_2, G_0)$ [11]. Since $e_{\rm AUT}$ is a constant, we are interested in the distribution of the random variable $\sum_{i=1}^{N_1} G_{{\rm AUT},i}/\sum_{i=1}^{N_2} G_{{\rm ref},i}$ only.

The probability density function (pdf) of ${\rm Gamma}(N_i, G_0)$ ($i = 1, 2$) is

$$p(x) = \frac{x^{N_i-1}\exp(-x/G_0)}{G_0^N \Gamma(N_i)} \tag{4}$$

where Γ is the Gamma function. Since N_i is an integer, $\Gamma(N_i) = (N_i - 1)!$, where ! represents the factorial operator. The pdf of $\sum_{i=1}^{N_1} G_{{\rm AUT},i}/\sum_{i=1}^{N_2} G_{{\rm ref},i}$ is

$$f(x) = \frac{\Gamma(N_1+N_2)}{\Gamma(N_1)\Gamma(N_2)}\frac{x^{N_1-1}}{(1+x)^{N_1+N_2}} \tag{5}$$

the derivation of which is given in the Appendix.

Once the pdf of $\sum_{i=1}^{N_1} G_{{\rm AUT},i}/\sum_{i=1}^{N_2} G_{{\rm ref},i}$ is known, one can readily calculate the mean and the variance of $\hat{e}_{\rm AUT}$,

$$E[\hat{e}_{\rm AUT}] = \frac{N_2}{N_2-1}e_{\rm AUT},$$
$$var[\hat{e}_{\rm AUT}] = \frac{N_2^2(N_1+N_2-1)}{N_1(N_2-2)(N_2-1)^2}e_{\rm AUT}^2 \tag{6}$$

respectively. As can be seen, the standard approach (1) is asymptotically unbiased (and it is biased with small N_2); and its variance goes to zero as N_i ($i = 1, 2$) goes to infinity. Note that the estimation bias of the standard approach (1) depends only on the independent sample

Manuscript received August 28, 2013; revised October 16, 2013; accepted December 13, 2013. Date of publication December 19, 2013; date of current version February 27, 2014.

The author is with the Department of Signals and Systems, Chalmers University of Technology, Gothenburg 41296, Sweden (e-mail: xiaoming.chen@chalmers.se).

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

Digital Object Identifier 10.1109/TAP.2013.2295420

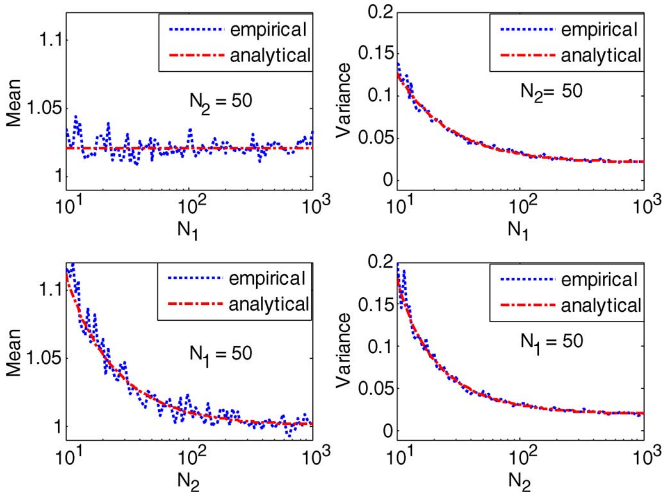

Fig. 1. Empirical and analytical mean and variance of the standard approach (1) for the case $e_{\rm AUT} = 1$.

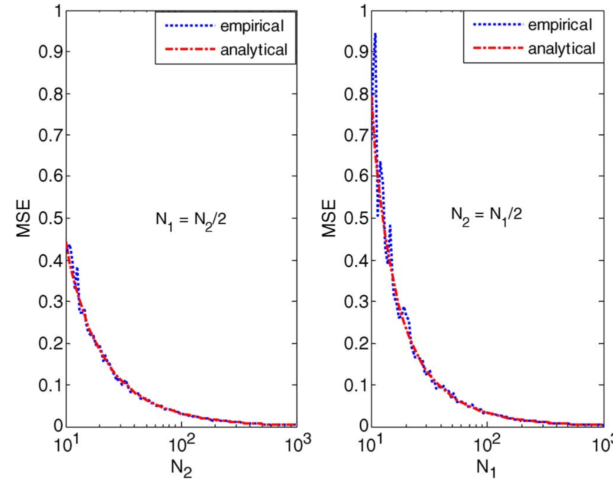

Fig. 2. Empirical and analytical MSE of the standard approach (1) for the case $e_{\rm AUT} = 1$.

number of the reference measurement N_2. This observation is verified by simulations in Section III.

The mean square error (MSE), i.e., $E[(\hat{e}_{\rm AUT} - e_{\rm AUT})^2]$, of the standard approach (1) can be readily derived from (6),

$$mse[\hat{e}_{\rm AUT}] = \frac{N_2^2(N_1+N_2-1)+N_1(N_2-2)}{N_1(N_2-2)(N_2-1)^2} e_{\rm AUT}^2. \quad (7)$$

When $N_2 = N_1 = N$, (7) boils down to [8]

$$mse[\hat{e}_{\rm AUT}] = \frac{2(N+1)}{(N-2)(N-1)} e_{\rm AUT}^2. \quad (8)$$

Since the MSE includes both variance and bias, it is used in both simulations and measurements in the following sections.

III. Simulations

In this section, we use simulations to verify the derived statistics of the standard approach (1) with different numbers of independent samples of the AUT measurement and the reference measurement. For simplicity and without loss of generality, we assume $e_{\rm AUT} = 1$ throughout this section.

We numerically generate 1000 realizations for $\hat{G}_{\rm AUT}$ and $\hat{G}_{\rm ref}$. This can be done by averaging N_1 and N_2 i.i.d. exponential random variables, respectively, for each realization [11]. As a result, we have 1000 realizations of $\hat{e}_{\rm AUT}$ for each set of N_1 and N_2, based on which the empirical mean, variance, and MSE are obtained. Fig. 1 shows the comparison between the empirical mean (variance) and the derived analytical mean (variance); and Fig. 2 shows the comparison between the empirical MSE and the derived analytical MSE.

As can be seen, there are good agreements between the analytical and empirical statistics. Moreover, it can be seen from the upper left graph in Fig. 1 that the estimation bias only depends on N_2 (and is independent of N_1). From both Figs. 1 and 2, it can be seen that, for fixed $N_1 + N_2$ (and therefore fixed measurement time[1]), it is beneficial to have $N_2 > N_1$ than to have $N_1 > N_2$; for fixed N_1, increasing N_2 improves both the estimation bias and variance. Therefore, for fast comparisons of tens of AUTs, e.g., [7], it is a good practice to perform a common reference measurement with more samples than the individual AUT measurements.

By letting $N = (N_1 + N_2)/2$ (assuming $N_1 + N_2$ is a even number) and comparing (7) and (8), one can easily conclude that, for measuring the antenna efficiency of a single AUT with fixed $N_1 + N_2$ (i.e., fixed total measurement time of the AUT and reference measurements), it is more accurate to allocate equal time to the AUT measurement and the reference measurement. To illustrate this point, the MSEs of different sets of N_1 and N_2 are compared with the corresponding N in Table I.

[1]The measurement time of the antenna efficiency in an RC is proportional to the total number of samples $N_1 + N_2$.

TABLE I
Comparison of MSE With Different Numbers of Independent Samples

Independent sample number	MSE
$N_1 = 80$, $N_2 = 100$	0.0234
$N = (80+100)/2 = 90$	0.0232
$N_1 = 150$, $N_2 = 300$	0.0101
$N = (150+300)/2 = 225$	0.0090
$N_1 = 300$, $N_2 = 600$	0.0050
$N = (300+600)/2 = 450$	0.0045
$N_1 = 600$, $N_2 = 1000$	0.0027
$N = (600+1000)/2 = 800$	0.0025

IV. Measurements

In order to further verify the derived statistics of the standard approach (1), extensive measurements were performed from 1 to 3 GHz in an RC. The RC used had two mode-stirring plates, a turn-table platform (on which a wideband discone antenna, used as the reference antenna, is mounted), and three half-bow-tie antennas mounted on three orthogonal walls (referred to as wall antennas hereafter). During the measurement, the turn-table platform was moved stepwise to 20 platform-stirring positions; at each platform-stirring position the two plates were moved simultaneously and stepwise to 50 positions. At each stirrer position and for each wall antenna, a full frequency sweep was performed by a vector network analyzer (VNA), during which the scattering parameters (S-parameters) were sampled. Hence, for each measurement, we have 3 wall antennas, 50 plate-stirring positions, and 20 platform-stirring positions. The same measurement sequence is repeated twelve times, each time with a different height/orientation of the reference antenna. The heights and orientations are chosen to ensure independent measurements. In post-processing, arbitrary pairs of antenna heights/orientations are chosen as the AUTs and the reference antennas, respectively, for estimating $e_{\rm AUT}$; and we introduce 0-, 3-, and 6-dB attenuator to the AUT (whose negative value in dB is $e_{\rm AUT}$). We choose six pairs of distinct measurements to obtain six independent antenna efficiency estimates, which are used for evaluating the MSE of the standard approach (1). In order to see the RC loading effect on the antenna efficiency measurement, the measurement procedure was repeated for two loading configurations: *load 0* (unloaded RC), *load 1* (a head phantom that is equivalent to a human head in terms of Electromagnetic absorption). In order to extend the study to the case of different numbers of independent samples of the AUT and reference

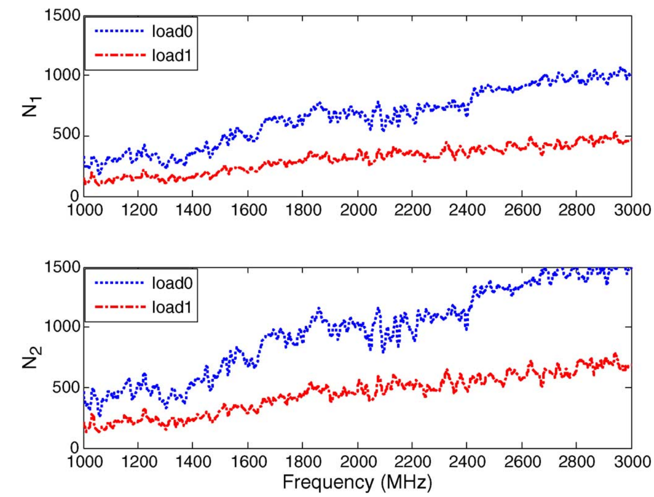

Fig. 3. Estimated numbers of independent samples of the AUT measurement (upper) and the reference measurements (lower).

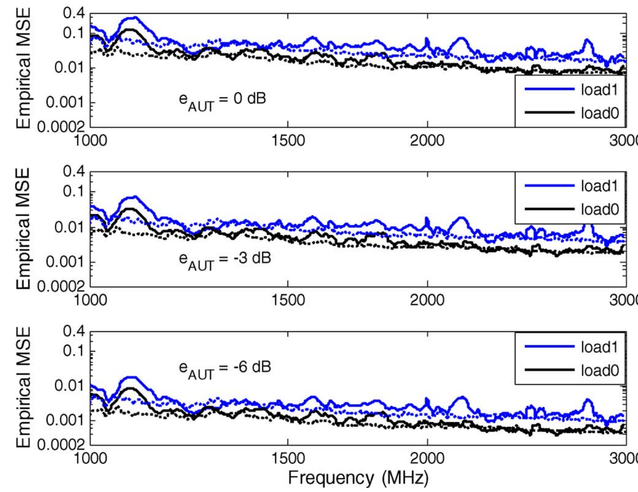

Fig. 4. Empirical MSE of $\hat{e}_{\mathrm{AUT}}$ based on independent measurements (solid) and the analytical MSE (7) (dotted).

measurement, we choose two wall antennas from the AUT measurement so that the sample number of the AUT measurement is two thirds of that of the reference measurement.

Note that, in practice, the measured samples in an RC may be correlated and that one needs to estimate the independent sample numbers of the AUT and reference measurements in order to apply the derived statistics to the antenna efficiency measurement. Different estimators of the independent sample number can be found in the literature, e.g., [12]–[15]. In this work, we use the DoF method [9] to estimate the independent sample number because it is more suitable for the measurement setup in this work [8]. Fig. 3 shows the estimated numbers of independent samples of the AUT measurement, N_1, and the reference measurements, N_2.

Fig. 4 shows the empirical MSE of $\hat{e}_{\mathrm{AUT}}$ (for $e_{\mathrm{AUT}} = 0, -3$, and -6 dB) estimated based on independent measurements and the analytical MSE (7) with N_1 and N_2 estimated from the AUT and reference measurements, respectively. Note that, for clear exhibition, the empirical MSE is plotted using the following dB-transformation [9]:

$$mse_{\mathrm{dB}} = 5\log_{10}\frac{(1+mse)}{(1-mse)} \tag{9}$$

and that a 40-MHz frequency smoothing is applied to the empirical MSE curves before plotting. As can be seen, there are good agreements between the analytical MSE (7) and the direct MSE estimate (based on the independent measurements). Note that it is time-consuming to directly estimate the MSE of the measured antenna efficiency by performing many independent measurements. However, using the analytical expressions of the derived statistics with estimated N_1 and N_2, the measurement uncertainty can be characterized based on one antenna efficiency measurement. It can also be seen that the MSE of $\hat{e}_{\mathrm{AUT}}$ decreases with decreasing e_{AUT}. This observation can be readily explained from the analytical MSE (7).

V. Conclusion

This work extend the statistical analysis of antenna efficiency measurement when N_1 (i.e., independent sample number of the AUT measurement) and N_2 (i.e., independent sample number of the reference measurement) are equal [8] to that with unequal N_1 and N_2. The derived analytical statistics are verified by simulations and RC measurements. Results show that the estimation bias of the measured antenna efficiency only depends on N_2 (and is independent of N_1); for fast comparisons of many AUTs, it is a good practice to perform a common reference measurement with more samples than the individual AUT measurements in that, for fixed N_1, increasing N_2 improves both the estimation bias and variance; for antenna efficiency measurement of a single AUT with fixed $N_1 + N_2$, it is more accurate to allocate equal time (sample number) to the AUT and reference measurements.

Appendix

Derivation of (5)

For notational convenience, we denote $X = \sum_{i=1}^{N_1} G_{\mathrm{AUT},i}$, $Y = \sum_{i=1}^{N_2} G_{\mathrm{ref},i}$, $Z = X/Y$, and the pdf of Z as f_Z. Thus, (4) is denoted as f_X or f_Y hereafter. In order to derive f_Z, we need an auxiliary equation $\mathrm{U} = \mathrm{Y}$. Hence the group of equations for the multivariate transformation is

$$\begin{cases} Z = g_1(X,Y) = \frac{X}{Y} \\ U = g_2(X,Y) = Y \end{cases} \tag{10}$$

whose inverse map is

$$\begin{cases} X = g_1^{-1}(Z,U) = ZU \\ Y = g_2^{-1}(Z,U) = U. \end{cases} \tag{11}$$

The Jacobian transform is

$$J = \begin{vmatrix} \frac{\partial g_1^{-1}}{\partial z} & \frac{\partial g_2^{-1}}{\partial z} \\ \frac{\partial g_1^{-1}}{\partial u} & \frac{\partial g_2^{-1}}{\partial u} \end{vmatrix} = u. \tag{12}$$

The joint pdf of Z and U is [11]

$$f_{Z,U}(z,u) = f_{X,Y}\left(g_1^{-1}, g_2^{-1}\right)|J| = f_{X,Y}(zu,u)u. \tag{13}$$

Since X and Y are independent, (13) becomes

$$f_X(zu)f_Y(u) = \frac{z^{N_1-1}u^{N_1+N_2-2}\exp\left(-\frac{zu+u}{G_0}\right)}{G_0^{N_1+N_2}\Gamma(N_1)\Gamma(N_2)}. \tag{14}$$

Substitute (14) into (13),

$$f_{Z,U}(z,u) = \frac{z^{N_1-1}u^{N_1+N_2-1}}{G_0^{N_1+N_2}\Gamma(N_1)\Gamma(N_2)}\exp\left(-\frac{zu+u}{G_0}\right). \quad (15)$$

In order to obtain f_Z, we integrate both sides of (15) over u,

$$\begin{aligned} f_Z(z) &= \int_0^\infty f_{Z,U}(z,u)du \\ &= \frac{z^{N_1-1}\int_0^\infty u^{N_1+N_2-1}\exp\left(-\frac{(z+1)u}{G_0}\right)du}{G_0^{N_1+N_2}\Gamma(N_1)\Gamma(N_2)} \\ &= \frac{\Gamma(N_1+N_2)}{\Gamma(N_1)\Gamma(N_2)}\frac{z^{N_1-1}}{(1+z)^{N_1+N_2}}. \end{aligned} \quad (16)$$

REFERENCES

[1] Int. Electrotech Comm., Geneva, IEC 61000-4-21: EMC, Part 4: Testing and Measurement Techniques; Section 21: Reverberation Chamber Test Methods, 2001.

[2] G. L. Fur, P. Besnier, and A. Sharaiha, "Time reversal efficiency measurement in reverberation chamber," *IEEE Trans. Antennas Propag.*, vol. 60, no. 6, pp. 2921–2928, Jun. 2012.

[3] P. Hallbjörner, "Reflective antenna efficiency measurements in reverberation chambers," *Microw. Opt. Technol. Lett.*, vol. 30, no. 5, pp. 332–335, 2001.

[4] H. G. Krauthäuser and M. Herbrig, "Yet another antenna efficiency measurement method in reverberation chambers," in *Proc. IEEE Int Symp. Electromagn. Compat.*, Jul. 25–30, 2010, pp. 536–540.

[5] C. L. Holloway, H. Shah, R. J. Pirkl, W. Young, J. Ladbury, and D. A. Hill, "Reverberation chamber techniques for determining the radiation and total efficiency of antennas," *IEEE Trans. Antennas Propag.*, vol. 60, no. 4, pp. 1758–1770, Apr. 2012.

[6] S. J. Boyes, Y. Huang, and N. Khiabani *et al.*, "Repeatability and uncertainty evaluations of on-body textile antenna efficiency measurements in a reverberation chamber," in *Proc. Loughborough Antennas Propag. Conf.*, Loughborough, UK, Nov. 12–13, 2012, pp. 1–5.

[7] Ó. Quevedo-Teruel, E. Pucci, and E. Rajo-Iglesias, "Compact loaded PIFA for multifrequency," *IEEE Trans. Antennas Propag.*, vol. 58, no. 3, pp. 656–664, Mar. 2010.

[8] X. Chen, "On statistics of the measured antenna efficiency in a reverberation chamber," *IEEE Trans. Antennas Propag.*, vol. 61, no. 11, pp. 5417–5424, Nov. 2013.

[9] X. Chen, "Experimental investigation of the number of independent samples and the measurement uncertainty in a reverberation chamber," *IEEE Trans. Electromagn. Compat.*, vol. 55, no. 5, pp. 816–824, Oct. 2013.

[10] J. G. Kostas and B. Boverie, "Statistical model for a mode-stirred chamber," *IEEE Trans. Electromagn. Compat.*, vol. 33, no. 4, pp. 366–370, Nov. 1991.

[11] G. Grimmett and D. Stirzaker, *Probability and Random Processes*, 3rd ed. Oxford, U.K.: Oxford Univ. Press, 2001.

[12] R. J. Pirkl, K. A. Remley, and C. S. L. Patané, "Reverberation chamber measurement correlation," *IEEE Trans. Electromagn. Compat.*, vol. 54, no. 3, pp. 533–544, 2012.

[13] C. Lemoine, P. Besnier, and M. Drissi, "Estimating the effective sample size to select independent measurements in a reverberation chamber," *IEEE Trans. Electromagn. Compat.*, vol. 50, no. 2, pp. 227–236, 2008.

[14] G. Gradoni, V. Mariani Primiani, and F. Moglie, "Reverberation chamber as a multivariate process: FDTD evaluation of correlation matrix and independent positions," *Progr. Electromagn. Res.*, vol. 133, pp. 217–234, 2013.

[15] H. G. Krauthauser, T. Winzerling, and J. Nitsch, "Statistical interpretation of autocorrelation coefficients for fields in mode-stirred chambers," in *Proc. Int. Symp. Electromagn. Compat.*, Chicago, IL, USA, Aug. 12, 2005, pp. 550–555.

64 × 64-Element and 32 × 32-Element Slot Array Antennas Using Double-Layer Hollow-Waveguide Corporate-Feed in the 120 GHz Band

Dongjin Kim, Jiro Hirokawa, Makoto Ando, Jun Takeuchi, and Akihiko Hirata

***Abstract*—This communication proposes high gain antennas having broad bandwidth characteristic for the 120 GHz band. The proposed antennas are fabricated by diffusion bonding of laminated thin copper plates which have the advantages of high precision and low loss characteristic even in a high frequency region such as the 120 GHz band. For stable fabrication using diffusion bonding, we propose a feeding structure which has a double layer. A 32 × 32-element array antenna shows more than a 38 dBi antenna gain with over 60% antenna efficiency and 15 GHz bandwidth (119.0-134.0 GHz) and a 64 × 64-element array shows a higher than 43 dBi antenna gain with over 50% antenna efficiency and 14.5 GHz bandwidth (118.5–133.0 GHz), respectively.**

***Index Terms*—Data transmission, diffusion bonding, double-layer structure, full corporate feeding, high gain.**

I. INTRODUCTION

High gain and high efficiency antennas are essential for the high speed wireless link systems in outdoor point-to-point relays. The reflector antenna and the dielectric lens antenna satisfy high gains and high efficiency simultaneously; however it is difficult to realize a thin planar structure because these antennas require a focal length [1]. Microstrip array antennas and array antennas with low temperature co-fired ceramic (LTCC) technology [2]–[5] have very low profiles and provide both broadband characteristics and low cost of fabrication, however, generally accompanied by low antenna efficiency due to large losses of the microstrip substrate and LTCC.

Hollow-waveguide slot array antennas are advantageous for larger or higher gain antennas with high efficiencies since they are not subject to dielectric or radiation losses [6]. Further, broad band characteristics can be achieved in waveguide slot array antennas with a multi layer feeding structure [7]–[9]. We have proposed double layer slot array antennas where the feeding circuit is located in the bottom layer underneath the radiating waveguides in the top layer with a diffusion bonding technique. These antennas are very attractive for wireless link systems because of very low losses and broad bandwidth characteristics and have a very low profile structure. A 16 × 16-element array antenna of this kind achieves 80% antenna efficiency with more than 33 dBi over a 4.8 GHz bandwidth at 60 GHz [10]. This antenna was redesigned for the 120 GHz band with considerations of several design limitations caused by the extremely small antenna parameters due to the very short

Manuscript received May 14, 2013; revised August 10, 2013; accepted November 29, 2013. Date of publication January 10, 2014; date of current version February 27, 2014. This work was supported in part by the Strategic Information and Communications R&D Promotion Programme, the Ministry of Internal Affairs and Communications.

D. Kim, J. Hirokawa, and M. Ando are with the Department of Electrical and Electronics Engineering, Tokyo Institute of Technology, Tokyo 152-8552, Japan (e-mail: djdjkim@antenna.ee.titech.ac.jp).

J. Takeuchi and A. Hirata are with NTT Microsystem Integration Laboratories, NTT Corporation, Atsugi-shi, Kanagawa 243-0198, Japan.

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

Digital Object Identifier 10.1109/TAP.2013.2296318