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Pushing the Boundaries of Antenna-Efficiency Measurements towards 6G in a mm-Wave Reverberation Chamber

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***Abstract*—With 6G around the corner, the push for higher-frequency over-the-air testing of antennas is inevitable, where antenna efficiency is one of the key performance metrics. Reverberation chambers can be an ideal tool for performing antenna-efficiency measurements at mm-Wave frequencies, due to its flexibility in placement, and ability to perform rapid and repeatable measurements. However, to the authors' best knowledge, no work on antenna efficiency above 47 GHz has been published so far. In this work, we show for the first time results of antenna efficiency using the two-antenna method up to 60 GHz, by using a novel mm-Wave reverberation chamber. We also evaluate chamber loss where we predict that larger systems, such as phased-array systems, can be measured inside this chamber as well, and that the current operational frequency range can be extended much further than 60 GHz for antenna-efficiency measurements.**

***Index Terms*—Antenna Efficiency, Chamber Loss, mmWave, Reverberation Chamber, Wireless Testing**

Fig. 1. Novel mm-wave reverberation-chamber with a setup for 20-40 GHz.

I. INTRODUCTION

Reverberation chambers (RC) are widely used to characterize antenna or device properties such as the antenna radiation efficiency, the total isotropic sensitivity (TIS) and the total radiated power (TRP) [1]. They are ideal candidates for those types of measurements due to their flexibility in device under test (DUT) form factor and placement in the working volume of the chamber. Moreover, these measurements can often be performed significantly faster in an RC in comparison to an anechoic chamber (AC) due to the inherent integration over angles in the RC.

With spectrum real-estate becoming more sparsely available, the push for higher frequencies to obtain more bandwidth is inevitable [2]. Research on devices in 6G bands is well on its way, which creates a need to construct new characterization methods for active array antennas operating in bands towards 100 GHz [3]. Historically, RCs have mainly been used for measurements at sub-6 GHz frequencies, but recent trends show mm-wave chambers that operate up to 60 GHz [1], [4]–[8]. However, to the author's best knowledge, no antenna-efficiency results have been published above 47 GHz [1]. Since an RC can accurately characterize antenna and device properties in its package [9], it has a promising future to measure the efficiency of antennas-on-chip, antennas-in-package, and complete antenna arrays.

In this work, we push the boundaries of the reverberation-chamber operating frequencies towards 6G. The lowest operating frequency of the RC is dictated by the maximum size of the chamber, but the highest frequency depends on the losses in the full measurement system (including leakage), and the measurable range of the instrumentation. At high frequencies, or for high-loss antennas, the system losses will have become so high that the behavior of the RC can no longer be distinguished from noise [10]. Especially with a phased-array system, the system contains many other components than only the antenna, such as the ICs, cooling block etc. This can add significant losses to the measurement, making them even more susceptible to noise. Therefore, a dedicated mm-Wave RC is required.

We use a novel reverberation-chamber where we show, for the first time, preliminary antenna-efficiency and chamber-loss results up to 60 GHz. The RC we introduce is shown in Fig. 1 and has a volume of 0.231 m^3. We will show different setups up to 60 GHz and analyze the chamber transfer function for these setups to evaluate whether the chamber can be pushed to operate at frequencies towards 100 GHz.

II. METHODS

A. Chamber Transfer Function

One of the most significant losses in a reverberation-chamber setup is the chamber loss, which naturally increases with frequency until it becomes outside of the measurable range [11]. The chamber loss is given by the chamber transfer function G_{Ref} as [12]

Fig. 2. Setup for 50-60 GHz.

$$G_{\text{Ref}} = \frac{\langle |S_{21}|^2 \rangle_N}{\eta_1^{\text{tot}} \eta_2^{\text{tot}}}, \tag{1}$$

where η_1^{tot} and η_2^{tot} are the total efficiencies of both antennas, and where $\langle \cdot \rangle_N$ is the ensemble average over N independent mode-stirring samples.

B. Antenna Efficiency

In this work, we use the two-antenna method as presented in [13] to estimate the antenna efficiency. It is based on the assumption that the quality factor (Q) as computed in the time domain (τ_{RC}) does not contain the losses due to the antennas' efficiencies, while its frequency-domain counterpart does. Therefore, dividing the two yields the antenna efficiencies. We refer the reader to [13] for the full derivation, where the total efficiency of each antenna computed with the two-antenna method is given by

$$\eta_i^{\text{tot}} = \sqrt{\frac{8\pi V f^2}{c^3 \tau_{\text{RC}}} \langle |S_{ij,s}|^2 \rangle_N \sqrt{\frac{\langle |S_{ii,s}|^2 \rangle_N}{\langle |S_{jj,s}|^2 \rangle_N}}}, \tag{2}$$

where $\langle |S_{ij,s}|^2 \rangle_N$ is the variance of the stirred-energy component given by $S_{ij,s} = S_{ij} - \langle S_{ij} \rangle_N$, where i and j correspond to the VNA ports that the antennas are connected to (in this case port 1 and 2 and vice versa). V is the chamber volume in m^3, f the frequency in Hz, and c the speed of light in m/s. We use the efficiencies computed with (2) to estimate G_{Ref} using (1). The radiation efficiency is estimated by correcting for the antenna mismatch (given by $|\langle S_{ii} \rangle|^2$).

C. Experimental Setups

We evaluate the results for frequencies up to 60 GHz using two different setups corresponding to the frequency ranges of 26.5-40 GHz and 50-60 GHz. The 40-50 GHz band is not shown here since this was out of the operating range of our antennas under test. If the chamber performs well for both frequency ranges, it can be expected to do the same in the 40-50 GHz band. For each frequency range, a vertical and a horizontal Z-folded paddle were used as mode-stirring mechanisms. Both were stepped over 10 positions (36 ° angular spacing) to obtain 100 low-correlated mode-stirring samples. All measurements were performed using a Vector Network Analyzer (VNA), using a frequency spacing of 200 kHz, an IF bandwidth of 1 kHz and a dwell time of 10 μs. The VNA output power was 0 dBm and the reference plane of the calibration was brought up to the antenna connectors for all setups using two different SOLT calibration kits. During post-pocessing, a 100 MHz averaging bandwidth was used for frequency stirring. Different antennas, cables, and feedthroughs were used for both setups.

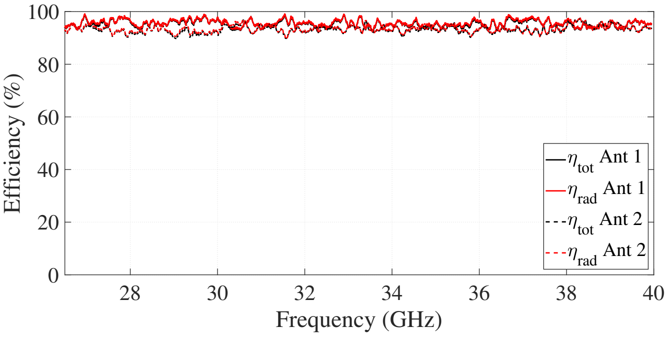

Fig. 3. Estimated efficiencies of two SGH antennas for the 26.5-40 GHz band. Since the antennas are of the same type, a similar efficiency result is expected.

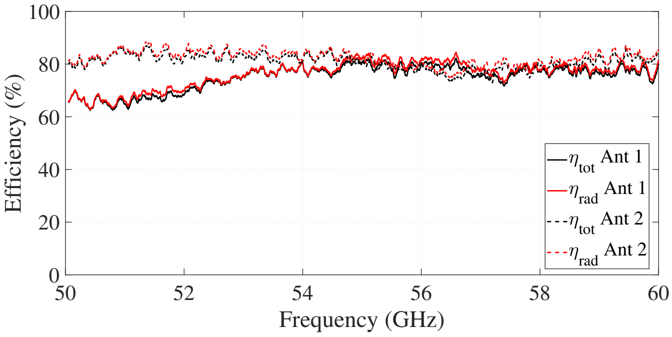

Fig. 4. Estimated efficiencies of two SGH antennas for the 50-60 GHz band. Since the antennas are of the same type, a similar efficiency result is expected.

1) 26.5-40 GHz: Fig. 1 shows the setup for 26.5-40 GHz, where we used two standard-gain horn antennas of the same type with a gain of 20 dBi. Two 2.92 mm coaxial cables were connected to the VNA using a feedthrough panel (lower right in Fig. 1).

2) 50-60 GHz: To characterize the 50-60 GHz band the setup shown in Fig. 2 was used. The setup contained two 1.85 mm feedthroughs with 1.85 mm coaxial cables connected to two standard-gain horn (SGH) antennas of the same type (20 dBi gain).

Next, we evaluate the antenna efficiency and chamber-transfer function for both setups for a single position of the antennas, which are shown in Fig. 1 and 2. Both antennas were pointed towards different stirrers at an angle to yield a low K-factor.

III. RESULTS

Fig. 3 shows the efficiency results for both horn antennas used in the setup shown in Fig. 1, which are expected to have a high efficiency (80 % or higher). Since the antennas

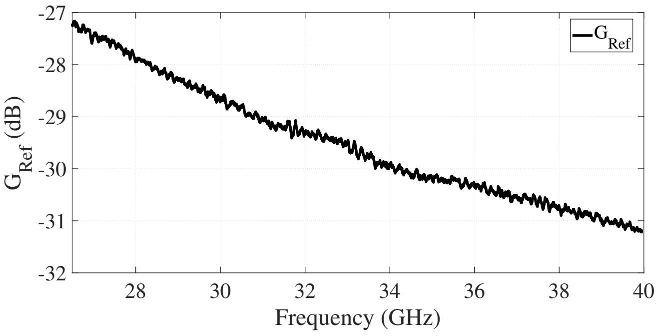

Fig. 5. Chamber loss G_{Ref} for the 26.5-40 GHz band.

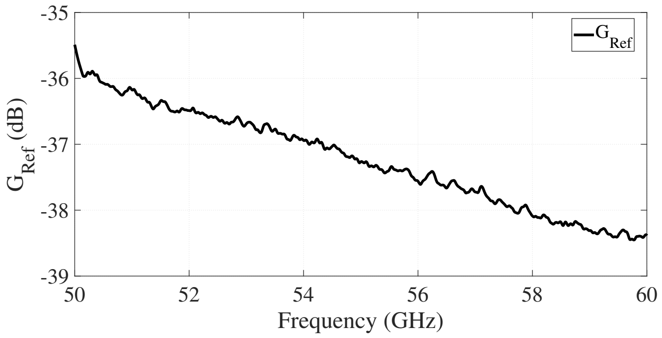

Fig. 6. Chamber loss G_{Ref} for the 50-60 GHz band.

were of the same type, the efficiency is expected to be similar (within 10 %), which can also be seen in the results. Because two antennas of the same type were used in the 50-60 GHz band, a similar antenna-efficiency estimate is also expected in this band. This is the case for the majority of the band (see Fig. 4), but with a (approximately 20 %) difference in the 50-54 GHz band. Since only one position was measured, no conclusion can be drawn yet on whether this is the physical antenna behavior, or a chamber effect. The latter effect could be an overestimated enhanced backscattering constant, which has been observed before with the two-antenna method [14]. There is also a larger variation across frequency, which may be attributed to a higher uncertainty due to increased losses [12]. Nonetheless, the efficiency results for both antennas are within 10 % deviation, which shows potential for accurate antenna-efficiency measurements in this chamber for frequencies up to 60 GHz.

The chamber loss for both setups are shown in Fig. 5 and 6, calculated using the previously shown efficiency results using (1). As expected, the chamber loss increases over frequency. These results show, compared to other reverberation chambers operating at these frequencies, that the chamber used in this work has a significantly lower chamber loss [5], [8], [11]. With the settings used in these setups, the noise floor of the VNA was approximately at -100 dBm. Therefore, the operating range of the mm-Wave reverberation chamber can probably be extended much further than 60 GHz, which will be part of future research. It also shows that, for these settings, larger systems can be placed inside the chamber while remaining within the measurable range. The chamber loss in the 40-50 GHz range that was not measured in this work is expected to be between -31 dB and -36 dB, due to the exponentially decaying behavior of the chamber-transfer function.

IV. CONCLUSION

We have shown, for the first time, preliminary results of antenna efficiency up to 60 GHz. Using the non-reference two-antenna method, the results show that the estimated efficiency is similar for antennas of the same type. We also showed that the chamber loss at 60 GHz is not lower than -40 dB, which is far above the noise floor of the VNA. This shows that there is potential for larger systems, such as phased-array systems, to be placed inside the chamber while staying inside of the measurable range. In future research, we will push the boundaries of antenna-efficiency measurements up to 90 GHz, including more chamber-performance metrics to show the functionality of the chamber for such purposes.

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