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An Improved Method for Efficiency Measurement of All-Excited Antenna Array in Reverberation Chamber Using Power Divider

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***Abstract*—Reverberation chambers (RCs) are ideally suitable for antenna efficiency measurements. For the measurement of the efficiency of a passive all-excited antenna array in an RC, a power divider is normally used to excite all the ports of the array simultaneously. The presence of the power divider introduces additional insertion loss to the antenna array. How to calibrate the insertion loss accurately is a problem for such a measurement. In the existing method, the effect of the mismatch between the array elements and the power divider was not taken into consideration, which could result in inaccurate evaluation of the efficiency of the antenna array. In this paper, an improved method of measuring the antenna array efficiency is presented. It allows the de-embedding of the power divider which removes the insertion loss of the power divider, thus it obtains the efficiency of an antenna array more accurately. This is realized by introducing proper attenuators between antenna array elements and power divider ports. Simulations and measurements have been conducted to verify the proposed method. It is shown that this method is accurate even when the array elements are not well matched with the power divider, especially for wideband antenna arrays where good impedance matching of array elements is difficult to maintain. The advantages and limitations of this approach are also discussed. The proposed method should be very useful for accurate and efficient measurement of antenna array efficiency.**

***Index Terms*—Antenna array, antenna efficiency, power divider, reverberation chamber.**

I. INTRODUCTION

THE efficiency of an antenna array is an important indicative measure of the merits in a given design. Conventionally, the efficiency measurement of an antenna array is conducted in an anechoic chamber with the pattern integration method [1]. However, the measurement setup of this method is complicated and the measurement uncertainty is usually high (>10%) [1]. Over the past few years, the reverberation chamber (RC) is becoming a prevalent alternative facility for performing radiated power measurements of either an antenna or device under test [2]–[6]. It is very applicable to determine the efficiency of antennas. The RC can be characterized as an electrically large shielded metallic enclosure with typically an asymmetric rotating conducting paddle/stirrer to change the boundary conditions of the chamber [2], [7]. Thus, a statistically uniform environment is created inside the chamber and it offers a unique test facility.

In [8], the efficiency of an antenna array was measured with the reference antenna method in an RC. In this approach, to make the array work in an "all-excited" manner, a power divider is used to excite the feeding ports of the array elements simultaneously, that is, all the array elements are excited through a power divider by merely a single excitation source. Thus, the efficiency measurement of the entire array can be effectively treated in a manner similar to a single port antenna, which would simplify the measurement procedure and reduce the overall measurement time. Because of the introduction of the power divider that is external to the array under test, the consequent insertion loss has to be calibrated out. In [8], to measure the insertion loss of the power divider, we terminated all outputs except the one in impedance-matched loads and measured the transmission coefficient between the input and the one output; we then proceeded to measure each output in turn (the insertion loss was measured in the condition of 50 Ohm loads). It is correct for the antenna array that each element is well-matched but it could be a problem when some elements are not well-matched because the reflection from the array elements could contribute to the insertion loss of the power divider, which will result in an inaccurate evaluation of the array efficiency.

In this paper, the array efficiency can be obtained accurately using a power divider even when the elements of the array are not well-matched with the power divider. This is realized by introducing proper attenuators between the array elements and the power divider to alleviate the effect of the reflected power from the array to the insertion loss of the power divider. The theoretical investigation is detailed. Simulations and measurements are conducted to validate the effectiveness of the proposed method.

This paper is organized as follows. Section II contains the problem identification of the existing method for the efficiency measurement of an antenna array in an RC. Measurements and

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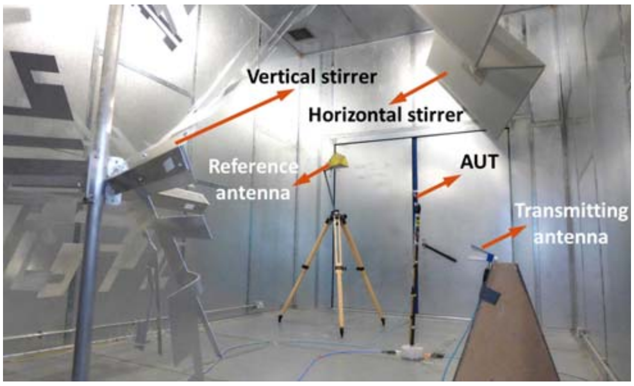
(a) AUT with a 5-dB attenuator



(b) Measurement setup in RC

Fig. 1. Measurement setup of the efficiency of a dipole antenna.

theoretical investigations are conducted to verify the problem. Section III presents the improved method. Both simulations and measurements are performed to justify the improved method. The measurement setup and experiment results of the measured efficiency are given. Section IV presents the measurement uncertainty analysis. Discussions and conclusions are given in the final section.

II. THE PROBLEM

It could be difficult to identify the problem of the existing method [8] from the measurement of an antenna array directly. However, it can be much easier and clearer to start the analysis from a single antenna and then extend it to an antenna array. Thus, the progressive steps in the problem-solving process will be made explicit.

A. Single Antenna Case

In the single antenna case, a sleeve dipole antenna was selected as an antenna under test (AUT). A 5-dB RF attenuator was connected to the AUT to introduce specific insertion loss, as shown in Fig. 1(a). Measurements were performed from 2.6 to 2.8 GHz in the RC at the University of Liverpool which has a size of 3.6 m × 4.0 m × 5.8 m. It has two mode-stir paddles: the vertical one is mounted in a corner, while the horizontal one is set close to the ceiling. In this measurement, the reference antenna method was adopted to obtain the radiation efficiency and the total efficiency of the AUT. Two double-ridged waveguide horn antennas were used as the transmitting antenna (SATIMO® SH 2000) and the reference antenna (Rohde & Schwarz® HF 906), respectively. The antennas were connected to a vector network analyzer (VNA) via cables running through the bulkheads of the chamber. During the measurement, the two stirrers were moved simultaneously and stepwise to 360 positions (1° for each step). At each mode stir position, a full frequency sweep was performed using the VNA and the *S*-parameters were collected. In this measurement, 10,001 points were sampled in the measured frequency range. The measurement setup is shown in Fig. 1(b). The measurement procedure is given as follows.

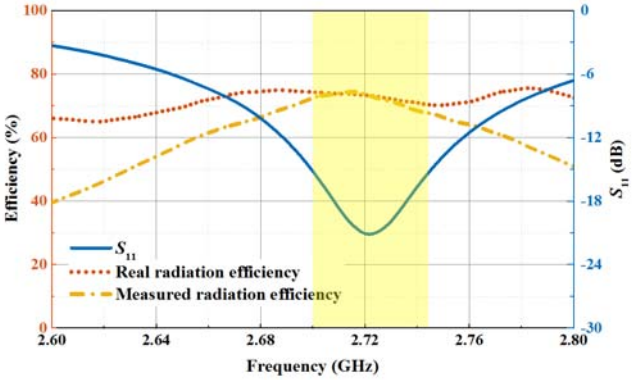


Fig. 2. Comparison of the measured radiation efficiency and real radiation efficiency of the sleeve dipole antenna with 5-dB insertion loss.

Step1: Calibrate the VNA including the cables according to the standard calibration procedure.
Step2: Place the AUT, the reference antenna, the transmitting antenna and the supports inside the RC to keep the chamber loss constant.
Step3: Connect the AUT to port 1 of the VNA and the transmitting antenna to port 2 of the VNA, terminate the reference antenna with a 50 Ω load and record the full *S*-parameters for each stir position.
Step4: Disconnect the AUT from port 1 of the VNA and terminate it with a 50 Ω load. Connect the reference antenna to port 1 of the VNA and the transmitting antenna is kept connecting to port 2 of the VNA. Record the full *S*-parameters for each stir position.

The radiation efficiency of the AUT (η_{aut}^{rad}) is then calculated using the reference antenna method [9]-[11]

$$\eta_{aut}^{rad} = \left[\frac{\langle |S_{12,s}^{aut}|^2\rangle}{\langle |S_{12,s}^{ref}|^2\rangle} \times \frac{1-|\langle S_{11}^{ref}\rangle|^2}{1-|\langle S_{11}^{aut}\rangle|^2} \times \frac{1}{IL}\right] \times \eta_{ref}^{rad} \qquad (1)$$

where η_{ref}^{rad} is the radiation efficiency of the reference antenna. The quantities $\langle |S_{12,s}^{aut}|^2\rangle$ and $\langle |S_{12,s}^{ref}|^2\rangle$ represent the stirred energy contributions of S_{12}^{aut} and S_{12}^{ref}, respectively [4].

$$S_{*,s} = S_* - \langle S_* \rangle \qquad (2)$$

where $*$ can be any *S*-parameter combination, $\langle\cdot\rangle$ means the average value of the *S*-parameter using any stirring method

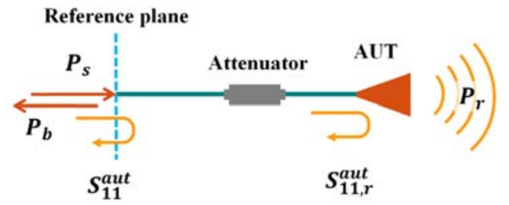


Fig. 3. The equivalent model.

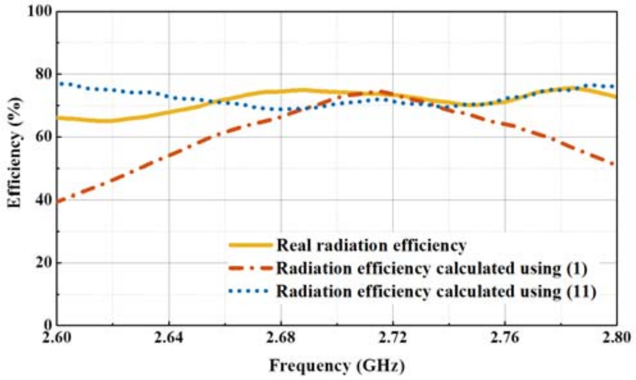


Fig. 4. The comparison of the measured radiation efficiency using (1) and (11) and the real radiation efficiency.

(mode stir, frequency stir, source stir, *etc*.). S_{12}^{aut} and S_{12}^{ref} are the transmission coefficients when the VNA port 1 is connecting to the AUT and the reference antenna, respectively. S_{11}^{aut} and S_{11}^{ref} are the reflection coefficients of the AUT and the reference antenna, respectively. IL is the insertion loss introduced by the attenuator (5 dB here). The measurement results are shown in Fig. 2. As can be seen, when the AUT is matched very well (S_{11} is approximately below -15 dB in this case), the measured radiation efficiency agrees well with the real radiation efficiency (the real radiation/total efficiency was measured with the conventional reference antenna method without the attenuator which should be accurate), shown as the shaded band. However, when the AUT is not well matched, considerable errors may occur (the maximum error is approximately 25% in this case). The reason can be explained as follows: when the AUT is very well matched, $S_{11}^{aut} \rightarrow 0$ and $(1-|\langle S_{11}^{aut}\rangle|^2) \rightarrow 1$, which means η_{aut}^{rad} is not easily influenced by S_{11}^{aut} . The contribution of S_{11}^{aut} to η_{aut}^{rad} is negligible. However, when the AUT is not well matched, the contribution of S_{11}^{aut} to η_{aut}^{rad} cannot be neglected. Actually, the measured S_{11}^{aut} is not the real reflection coefficient of the AUT because of the influence of the introduced insertion loss. Therefore, the radiation efficiency is not measured correctly. This is because the precondition of (1) is that the antenna is well matched with the attenuator. To show this problem quantitatively, we consider an equivalent model in Fig. 3, where P_s is the power supplied to the antenna, P_b is the power reflected back at the reference plane and P_r is the power radiated. The relationship between P_b and P_s can be expressed as

$$P_b = P_s \cdot IL \cdot \left|S_{11,r}^{aut}\right|^2 \cdot IL \qquad (3)$$

where IL is the insertion loss (in linear form) of the attenuator and $S_{11,r}^{aut}$ is the real reflection coefficient of the AUT in free space. (3) can be rewritten as

$$|S_{11}^{aut}|^2 = \left|S_{11,r}^{aut}\right|^2 \cdot IL^2 \qquad (4)$$

where

$$|S_{11}^{aut}|^2 = P_b/P_s \qquad (5)$$

is the measured reflection coefficient at the reference plane.

The radiated power P_r is linked to the supplied power P_s by

$$P_r = P_s \cdot IL \cdot \left(1-\left|S_{11,r}^{aut}\right|^2\right) \cdot \eta_{aut}^{rad} \qquad (6)$$

where η_{aut}^{rad} is the real radiation efficiency of the antenna. The corresponding transformation of (6) is

$$\eta_{aut}^{rad} = \eta_{aut}^{tot} \cdot \frac{1}{1-\left|S_{11,r}^{aut}\right|^2} \cdot \frac{1}{IL} \qquad (7)$$

where

$$\eta_{aut}^{tot} = P_r/P_s \qquad (8)$$

is the measured total efficiency at the reference plane.

For the reference antenna method, we have

$$\eta_{aut}^{tot}/\eta_{ref}^{tot} = \langle\left|S_{12,s}^{aut}\right|^2\rangle/\langle\left|S_{12,s}^{ref}\right|^2\rangle \qquad (9)$$

where

$$\eta_{ref}^{tot} = \left(1-\left|\langle S_{11}^{ref}\rangle\right|^2\right) \cdot \eta_{ref}^{rad} \qquad (10)$$

Substituting (4), (7), (9) and (10) into (1) gives

$$\eta_{aut}^{rad} = \left[\frac{\langle\left|S_{12,s}^{aut}\right|^2\rangle}{\langle\left|S_{12,s}^{ref}\right|^2\rangle} \times \frac{1-\left|\langle S_{11}^{ref}\rangle\right|^2}{1-|\langle S_{11}^{aut}\rangle|^2/IL^2} \times \frac{1}{IL}\right] \times \eta_{ref}^{rad} \qquad (11)$$

Thus, the modified equation is mathematically derived. As can be seen from (11), when there is no insertion loss ($IL = 1$) or the insertion loss is negligible ($IL \rightarrow 1$). (11) is equivalent to (1). However, when the insertion loss is large, there is big difference between (1) and (11). That is, when the insertion loss is large, if we still use (1) to calculate the efficiency of the AUT, considerable errors will occur. The comparison of the calculated radiation efficiency using (1) and (11) and the real radiation efficiency is shown in Fig. 4. We can see that the radiation efficiency calculated using (11) seems closer to the real radiation efficiency in most of frequency span than that calculated using (1). But it does not agree well with the real

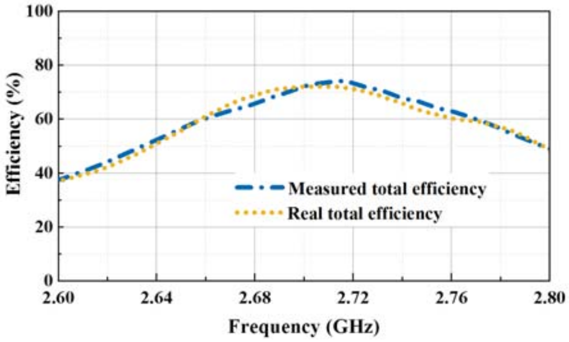


Fig. 5. Comparison of the real total efficiency and the measured total efficiency.

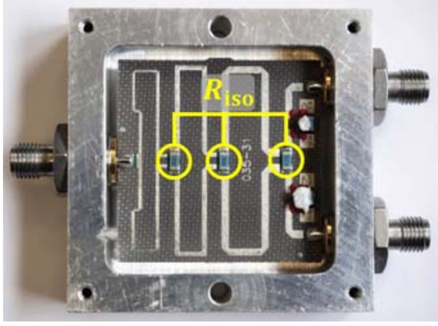


Fig. 6. A typical 2-way Wilkinson power divider in microstrip line format.

radiation efficiency as expected. At some frequency bands, say, 2.60–2.64 GHz, there is still significant error between the measured radiation efficiency and the real radiation efficiency. This error is caused by the imperfection of the transition section between the antenna and the attenuator or the attenuator and the cable. To be more specific, when the AUT is connected with the attenuator, the reflection coefficient measured at the reference plane is very small. Thus, it is easily affected by the mismatch caused by the imperfection of the transition section. A small mismatch of the transition section may cause a big variation of the reflection coefficient measured at the reference plane. Therefore, it would be very difficult to calibrate the influence of the insertion loss to S_{11} of the AUT in practice. Thus, in reality, the radiation efficiency is hard to be measured accurately when there exists insertion loss between the AUT and the feeding port. However, S_{12} is not easily affected by the small mismatch of the transition section because this mismatch is negligible compared with the insertion loss caused by the attenuator. Therefore, the total efficiency can be measured correctly because the total efficiency η_{aut}^{tot} depends only on S_{12}^{aut} while not on S_{11}^{aut}, as indicated in (12). The comparison of the real total efficiency and the measured total efficiency are shown in Fig. 5. We see that the results are in reasonable agreement.

$$\eta_{aut}^{tot} = \left[\frac{\langle \left|S_{12,s}^{aut}\right|^2 \rangle}{\langle \left|S_{12,s}^{ref}\right|^2 \rangle} \times (1 - \left|\langle S_{11}^{ref} \rangle\right|^2) \times \frac{1}{IL}\right] \times \eta_{ref}^{rad} \quad (12)$$

B. *Antenna Array Case*

When measuring the efficiency of an antenna array, to make the array work in an “all-excited” manner, a power divider is normally adopted to excite the feeding ports of the array elements simultaneously [8], [12], i.e., all the array elements are excited through a series of power dividers by merely a single excitation source. Thus, the efficiency measurement of the entire array can be effectively treated in a manner similar to a single port antenna. The power divider is such a network with the property of appearing lossless when the output ports are matched and only the reflected power from the output ports is dissipated [13]. The reflected power will be consumed by the isolation resistance (R_{iso}) in the power divider, as can be seen in Fig. 6. Therefore, the insertion loss of the power divider depends on the impedance of the external device. When the elements of the antenna array are well matched, very small amount of power will be reflected from each element and the insertion loss of the power divider can be neglected. However, when the elements are not well matched, a large amount of power will be reflected from each element and then dissipated on the R_{iso}, thus the insertion loss can be very large. Even worse, unlike the single antenna case, the insertion loss of the power divider caused by the reflection from the antenna array cannot be quantified because we do not know how much power has been dissipated on R_{iso}. Therefore, the measurement problem caused by the insertion loss will become more complicated. Neither the radiation efficiency nor the total efficiency can be measured accurately when the elements of the antenna array are not well matched.

III. IMPROVED METHOD

From the above analysis, we know that it is difficult to quantify the insertion loss of the power divider when the external device is not well matched. In this case, we may try to minimise the dissipated power on R_{iso} of the power divider, i.e., minimise the reflected power from the antenna array. In this section, we propose to introduce an attenuator of a proper value between each array element and each power divider port. Actually, by introducing an attenuator, the effects of mismatch between the array elements and the power divider ports could be minimized. Thus, the use of the attenuator allows transferring the power that should have been dissipated on R_{iso} to the attenuator. To validate this idea, field-circuit co-simulation is employed in CST (Computer Simulation Technology) Microwave Studio in the frequency range of 2.0-3.5 GHz. A two-dipole array is adopted as an antenna under simulation, as can be seen in Fig. 7. In the two-dipole array, one element is 53.4 mm long and the other is 46.5 mm long. The spacing between these two elements is set to be 25.4 mm. The material for making the array is PEC (perfect electric conductor). The reflection coefficients, the phase of the reflection coefficients and the transmission coefficients of the array are shown in Fig. 8. As we can see, S_{11} and S_{22} are interlaced (both in amplitude and phase), which ensures that there will be power loss on the R_{iso}. Another thing that should be noted is that S_{21} and S_{12} are very small (below -15 dB), which means the mutual coupling between the two dipole elements is negligible. In practice, the mutual coupling between elements is an importance issue that needs to be carefully considered in an

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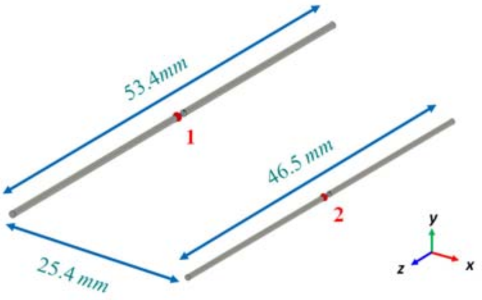

Fig. 7. The two-dipole array used for simulation in CST.

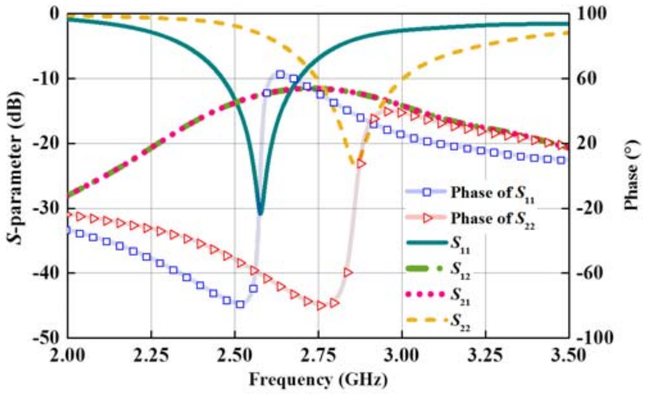

Fig. 8. The simulated *S*-parameters of the two-dipole array.

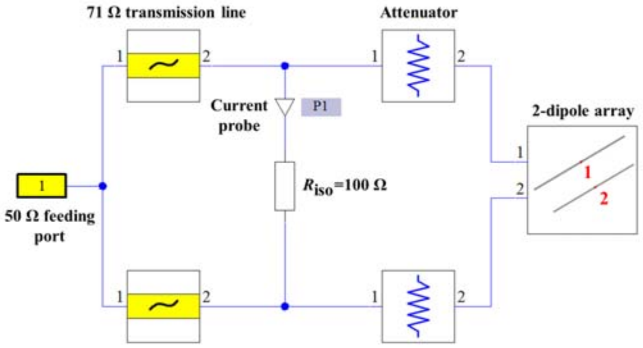

Fig. 9. Schematic of the circuit.

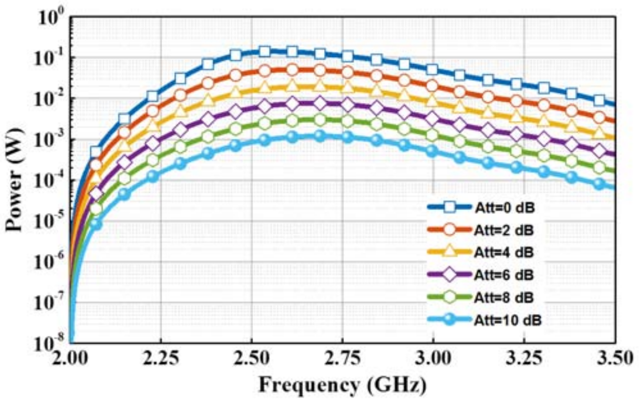

Fig. 10. Simulated power consumed on the isolation resistance of the power divider for 1 W input power with different attenuators.

antenna array. In this section, the impact of the mutual coupling to the validity of the proposed method is studied as well and will be discussed later. The schematic of the field-circuit co-simulation model is given in Fig. 9. To obtain the power loss on the R_{iso}, a current probe P1 is introduced to monitor the current on the R_{iso}. The feeding power from port 1 is 1 W. The attenuation of the attenuators is tuned stepwise from 0 dB to 10 dB (2 dB per step). The power consumed on the R_{iso} is shown in Fig. 10. Two things can be identified from this figure. First, because of the mismatch of the array elements, there exists power loss on R_{iso} (when the attenuation is zero, the power consumed is not zero). Second, with the increase of the attenuation, the power consumed on R_{iso} will decrease as expected. When the attenuation is 10 dB, the power consumed on the R_{iso} will be always below 0.002 W, that is, only less than 0.2% power will be consumed by R_{iso}.

From the above simulation analysis, we can see that the attenuator can help to reduce the power loss on the R_{iso}. Because the attenuation value is exactly known, the insertion loss caused by the attenuator can be calibrated out for the total efficiency measurement. However, the radiation efficiency measurement is still a problem because the effect of the imperfection of the transition section between the antenna and the attenuator or the attenuator and the cable is hard to remove, as discussed in Section II. In the following part, we will demonstrate that the radiation efficiency can be measured accurately using the proposed method.

To demonstrate the effectiveness of the proposed method, measurement was performed in our RC. A 2-way 0° power divider (Mini-Circuits® ZAPD-4-S+) with a voltage standing wave ratio (VSWR) < 1.33:1 from 2.0-4.2 GHz was employed in this study. The spacing of the two output ports is 25.4 mm. The AUT in this study is a two-dipole array consisting of two parallel dipole elements with the spacing of 25.4 mm. The *S*-parameters of the two dipole elements are shown in Fig. 11. The power divider is connected to the AUT to feed the two dipole elements with equal weights, as can be seen from Fig. 12. The measurement was conducted in the frequency range of 2.0-3.5 GHz. The reference antenna method is adopted in this measurement. The measurement setup and measurement procedure are the same as detailed in Section II (A). The comparison of the measured total efficiency of the two-dipole array with the conventional method and with the proposed method is shown in Fig. 11. We can see that, in the frequency range of 2.0-2.6 GHz and 3.1–3.5 GHz, there is not much difference of the amplitude and phase between S_{11} and S_{22}. Therefore, very little power will be consumed on the R_{iso}. Thus, the total efficiency measured with the conventional method and with the proposed method agrees well. However, in the frequency range of 2.6-3.1 GHz, there is a significant difference of the amplitude or phase between S_{11} and S_{22}, i.e., a considerable amount of power will be consumed by R_{iso}. In this case, the *IL* in (12) cannot be accurately obtained. The *IL* of the power divider measured (using the method in [8]) is not valid because it is accurate only when the power divider ports are terminated with impedance-matched loads, i.e., no reflection

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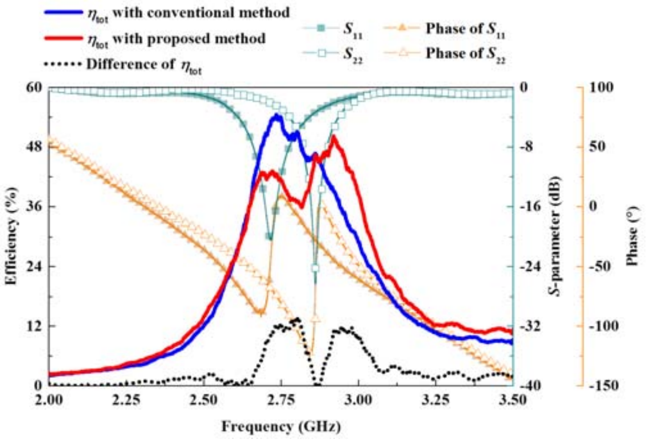

Fig. 11. Comparison of the measured total efficiency of the two-dipole array with the conventional method and with the proposed method.

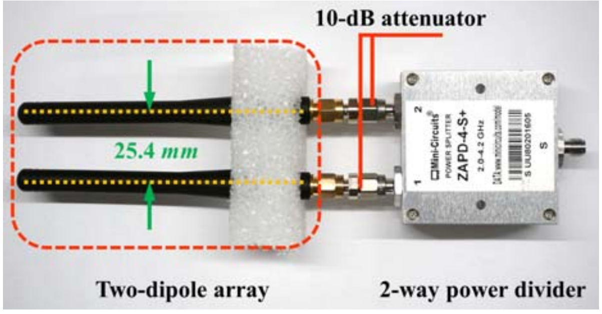

Fig. 12. The two-dipole array connected with the 2-way power divider.

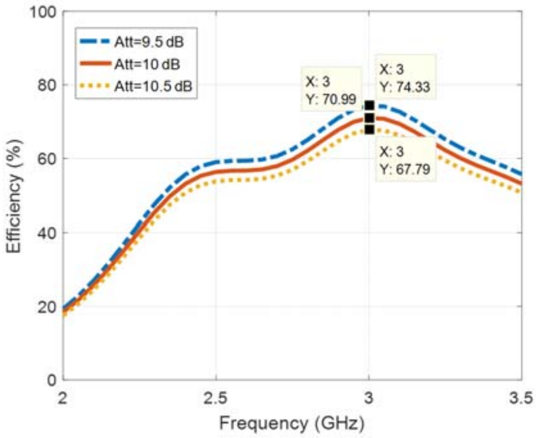

Fig. 13. The total efficiency of the two-dipole array in CST with different attenuation values.

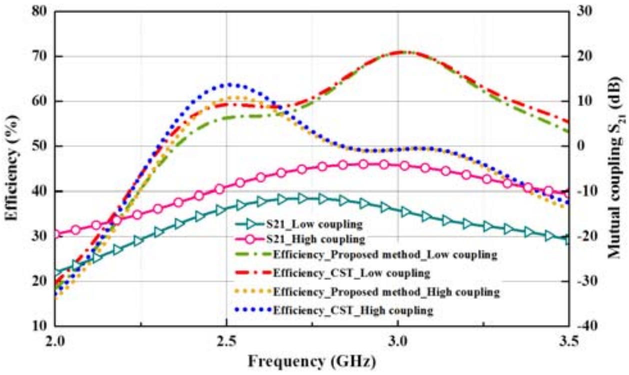

Fig. 14. The two-dipole array total efficiency predicted by CST and that obtained from the field-circuit model using our proposed method with low and high mutual coupling.

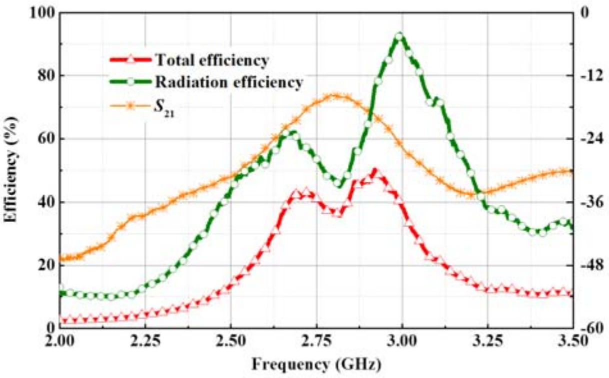

Fig. 15. The comparison of the radiation efficiency and the total efficiency of the two-dipole array and the mutual coupling of the two dipole elements.

occurs. Thus, considerable errors may occur if the conventional method is adopted. Conversely, for the proposed method, the IL is dominated by the attenuators and the contribution of the power divider to the IL can be neglected. Besides, the reflected power from the array elements will be attenuated by the attenuators as well. Hence, the IL of the power divider including the reflection effect will have little influence on IL in (12). As we can see in Fig. 11, the total efficiency measured using the conventional method has obvious errors compared with that measured using the proposed method in the frequency range of 2.6-3.1 GHz where the amount of the power consumed on R_{iso} is big. The maximum error can reach 15% at about 2.76 GHz, which cannot be neglected in practice.

One thing should be noted is that there is always some uncertainty on the attenuation value of the attenuator. That is, the actual attenuation value is not always exactly the same as the nominal value. The attenuator used in the experiment has about ± 0.5 dB deviation in the frequency range of dc to 3.0 GHz [14]. To show the impact of the deviation of the attenuation value on the efficiency of the antenna array, the field-circuit co-simulation was conducted in the above-mentioned two-dipole array model in CST. The total efficiency of the two-dipole array was calculated with the attenuation value of 9.5 dB, 10 dB and 10.5 dB, respectively. The results are shown in Fig. 13. As can be seen, only a very small difference can be observed for the total efficiency of the array calculated with different attenuation values in the full frequency span. The maximum difference is only about 4% which is small. Thus, the impact of the uncertainty from the attenuation value of the attenuator can be neglected. Another point that may be concerned is the impact of the mutual coupling between antenna elements on the validity of the proposed method. To investigate this issue, a simulation is done using CST. In this simulation, the spacing between the two elements of the dipole array (as shown in Fig. 7) is set to be 5.0

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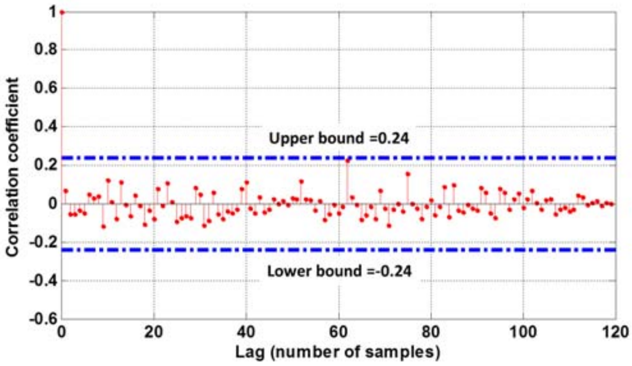

Fig. 16. The autocorrelation coefficient of the received power samples and the lag at which the correlation is lost (@ 2.0 GHz).

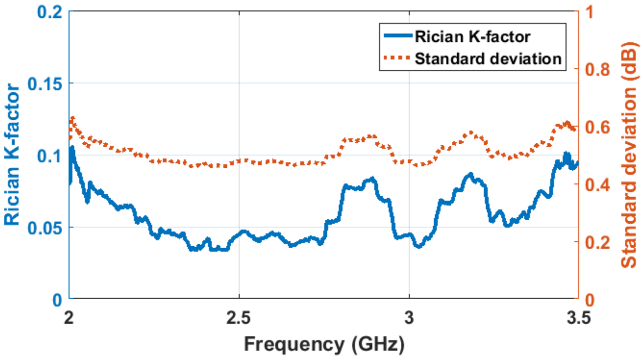

Fig. 17. Rician *K*-factor and standard deviation.

mm, which results in significant increase in the mutual coupling of the two dipole elements. Thus, a new dipole array with higher mutual coupling is created. As can be seen from Fig. 14, the mutual coupling of the new dipole array exceeds -10 dB from 2.5 GHz to 3.45 GHz and can reach about -3 dB at 2.9 GHz. The array total efficiency predicted by CST (used as a benchmark here) and that obtained from the field-circuit model using our proposed method are plotted and compared in Fig. 14. The total efficiency of the array with low mutual coupling (the array shown in Fig. 7 and Fig. 8) is also plotted for reference here. It can be seen that no matter the mutual coupling is high or low, the efficiency obtained from our proposed method does not have big difference from the benchmark. The maximum difference is only about 3% for both high coupling and low coupling scenarios, which is very small. That is, the mutual coupling does not influence the validity of the proposed method. The proposed method is general for the efficiency measurement of antenna arrays regardless of the mutual coupling.

Once we have known the total efficiency, the radiation efficiency can be calculated by excluding the impedance mismatch effect of the antenna elements. The radiation efficiency can then be expressed as

$$\eta_{rad} = \frac{\eta_{tot}}{1-\frac{1}{2}\left(|S_{11}|^2+|S_{22}|^2\right)} \tag{13}$$

The array radiation efficiency, the array total efficiency and the mutual coupling S_{21} of the two dipole elements are shown in Fig. 15. As we can see, the radiation efficiency is reasonable and the mutual coupling between array elements is negligible.

Generally, for an antenna array with N elements, the total efficiency can be obtained using (12) and the radiation efficiency will become

$$\eta_{rad} = \frac{\eta_{tot}}{1-\frac{1}{N}\sum_{i=1}^{N}|S_{ii}|^2} \tag{14}$$

where i is the element number.

IV. Measurement Uncertainty

To quantify the measurement uncertainty, we have adopted the method proposed in [15]. As demonstrated in [15], the direct coupling can be a major source of uncertainty inherent during over-the-air measurements in an RC. Therefore, the direct coupling (normally expressed as the Rician *K*-factor) should be as small as possible. Furthermore, the uncertainty model presented in [15] combines the random non-line-of-sight (NLOS) process and the random line-of-sight (LOS) process, and the combined standard deviation can be written as

$$\sigma = \frac{\sqrt{\sigma_{NLOS}^2 + K^2\sigma_{LOS}^2}}{\sqrt{1+K^2}} \tag{15}$$

where $\sigma_{NLOS} = 1/\sqrt{N_{NLOS,ind}}$, $\sigma_{LOS} = 1/\sqrt{N_{LOS,ind}}$ and K=average Rician *K*-factor, comprising the samples obtained from mechanical stirring, source stirring and polarization stirring. $N_{NLOS,ind}$ and $N_{LOS,ind}$ are the NLOS independent samples and LOS independent samples, respectively. The Rician *K*-factor is calculated as follows:

$$K = \frac{|\langle S_{12}^{aut}\rangle|^2}{\langle |S_{12}^{aut} - \langle S_{12}^{aut}\rangle|^2\rangle} \tag{16}$$

The standard σ is presented in dB scale by averaging the dB values of $(1+\sigma)$ and $(1-\sigma)$, i.e.,

$$\sigma_{dB} = \frac{10\{\log(1+\sigma)-\log(1-\sigma)\}}{2} = 5\log\left(\frac{1+\sigma}{1-\sigma}\right) \tag{17}$$

$N_{NLOS,ind}$ is computed by applying the standardized circular autocorrelation to a 1-D array written using the received power samples during one rotation cycle [16]. The critical value r suggested by the standard [7] is applied.

$$r = \frac{1}{e}\left(1-\frac{7.22}{n^{0.64}}\right) \tag{18}$$

where n is the number of the checked samples (120 in our case). The autocorrelation coefficient of the received power samples at the lowest frequency 2.0 GHz is shown in Fig. 16. As can be seen, it is always below the critical value for the lag number from 1 to 199, which means the 120 samples are independent. For $N_{LOS,ind}$, we calculated via

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$$N_{LOS,ind} = N_{ap} \cdot N_{ant,ind} \tag{19}$$

where N_{ap} is the number of antenna positions, and $N_{ant,ind}$ is the number of independent antennas used in the chamber. In our case, $N_{ap} = N_{ant,ind} = 1$. The measured Rician *K*-factor and standard deviation in decibel format are shown in Fig. 17. We can see that any contribution toward the uncertainty from LOS coupling is small and the overall uncertainty inherent in the measurements is acceptably low.

V. DISCUSSIONS AND CONCLUSIONS

In this paper, an improved measurement-based method to obtain the efficiency of an all-excited antenna array in an RC has been presented. When measuring the efficiency of an antenna array in an RC, to make the array work in an "all-excited" manner, a power divider is normally employed to excite the feeding ports of the array elements simultaneously, that is, all the array elements are excited through a series of power dividers by merely a single excitation source. Thus, the efficiency measurement of the entire array can be effectively treated in a manner similar to a single port antenna, which would simplify the measurement procedure and reduce the overall measurement time. However, the introduction of the power divider will inevitably bring in insertion loss which needs to be quantified and calibrated out. In our previous work, the calibration of the insertion loss of the power divider was implemented by terminating all outputs in impedance-matched loads and measured the transmission coefficient between the input and the output port. By repeating this procedure for each output port, the *S*-parameters from the input to all output ports can be obtained. The total insertion loss is calculated by summating the measured transmission coefficient of each port. It is correct if each element of the antenna array is well matched. However, if some elements of the array antenna are not well matched, a considerable error may occur. The reason is, when the element is not well matched, a non-ignorable amount of the power fed to the element will be reflected back to the power divider and then dissipated on the R_{iso}. The power dissipated on the R_{iso} is very difficult to quantify. Therefore, we cannot exactly know the insertion loss of the power divider.

In this study, we have minimized the power dissipated on the R_{iso} of the power divider by introducing 10-dB attenuators between array elements and power divider ports. The attenuators would alleviate the reflection from the array antenna to the power divider and thus reduce the dissipated power on the attenuator. Moreover, because the attenuation of the attenuator is known, thus we can calibrate it out accurately. Simulations and measurements have been done to validate the proposed method. The results show that this method is effective to measure the efficiency of an antenna array especially for an antenna array that some elements of it are not well matched. It is advantageous especially for wideband antenna arrays where good impedance matching of array elements is difficult to maintain.

There are some points that need to be emphasized. Firstly, the attenuation of the attenuators used in the measurement should be large enough. Otherwise, when the attenuator is loaded with the mismatched antenna, the attenuation value will be changed [13]. In our case, a 10-dB attenuator is suitable. Theoretically, the bigger the attenuation, the less sensitive the attenuation to the impedance of the mismatched antenna, and consequently, the more accurate the measured results will be. However, considering the dynamic range of the VNA, the attenuation cannot be too large to ensure the accurate measurement of the *S*-parameters. Therefore, the attenuation value should be carefully selected before the measurement. Secondly, the proposed method is time-saving as the whole array is treated in a manner similar to a single port antenna, and also we do not need to calibrate the insertion loss of power divider. This is advantageous especially for arrays of large number of elements. However, no verification of this method has been performed for such arrays, and it is left as a topic for future work.

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