Efficiency Measurement for Multi-band and Broadband Antennas Using the Modified Wheeler Cap Method

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I. INTRODUCTION

Poor antenna efficiency is a primary factor contributing to the reduction of antenna gain; this includes cases where the antenna was designed to match other RF systems. Therefore, the accurate estimation and measurement of antenna efficiency is critical to the design of an antenna. One of the most widely used techniques for measuring antenna efficiency is the Wheeler cap method because of its simple measurement procedure and reasonable accuracy. In this method, the antenna is assumed to operate as a simple series or parallel RLC lumped element circuit model. When the antenna has one clean single resonance, this method will provide an accurate assessment of efficiency. However, the Wheeler cap method will result in unreliable measured efficiency when the antennas have more complicated operations such as: circularly polarized radiation, multiple resonances, or an ultra wide bandwidth.

In this paper, a modified Wheeler cap method is proposed using a high order circuit model to more accurately estimate the efficiency of antennas containing such complicated operations. To verify the proposed method, the efficiency of a microstrip antenna with triple resonances was measured. Additionally, the efficiency of an electromagnetic coupled monopole antenna, which has more complicated operating principles, was measured. Finally, the modified Wheeler cap method was compared with the conventional Wheeler cap method and the simulated results.

II. METHODOLOGY OF MODIFIED WHEELER CAP METHOD

Antenna efficiency is defined as the ratio of input power to radiated power [1]. Equivalently, it can be represented as the ratio of radiation resistance to total resistance, which is the sum of the radiation resistance and loss resistance. In the conventional Wheeler cap method, the antenna efficiency can be represented as

$$Eff = \frac{P_R}{P_R + P_L} = \frac{R_R}{R_R + R_L} = \frac{R_{free\ space} - R_{cap}}{R_{free\ space}} \quad (1)$$

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where P_R and R_R are the radiated power and radiation resistance, respectively; and P_L and R_L are the loss power and loss resistance, respectively. $R_{free\ space}$ is the input resistance in free space and R_{cap} is the input resistance of the antenna in the Wheeler cap. Here, the loss resistance is measured by shielding the antenna with the conducting cap [2]. Assuming that the antenna operates as a series RLC circuit, such as a simple monopole antenna, the efficiency is measured by comparing the input resistances of the antenna in free space and when shielded with the cap. Recently, it has been demonstrated that the parallel RLC circuit model is more appropriate when the efficiency of a standard microstrip antenna is measured [3]. However, if the antenna has more complicated operating principles, the conventional Wheeler cap method based on either the series or the parallel RLC circuit model does not yield an accurate efficiency.

In the modified Wheeler cap method, a high order circuit model was introduced to more accurately estimate the efficiency of an antenna having complicated operations. The loss resistance was measured in the same way as in the conventional Wheeler cap method. The high order circuit model must be built to represent the input impedance of the antenna in the cap and in free space. Ideally, L and C in the circuit are lossless passive components that only charge and discharge the electric and magnetic energy without any power loss. Therefore, the higher order circuit model could represent input impedance of the antenna for both in the cap and in free space with only different values of resistance R. Hence, all resistance could be separated into radiated resistance R_R and loss resistance R_L. The efficiency could be calculated by the power ratio of each R using Eq. (2)

$$Eff = \frac{P_R}{P_R + P_L} = \frac{\sum_{i=1}^{N} |I_i|^2 (R_{i,free\ space} - R_{i,cap})}{\sum_{i=1}^{N} |I_i|^2 (R_{i,free\ space})} \qquad (2)$$

where I_i is the current in the *i-th* mesh and N is the number of meshes.

III. RESLTS

To verify the proposed method, first the efficiency of the microstrip antenna with triple resonances was measured. The microstrip antenna had a patch size of 60 mm × 50 mm and used a FR4 (ε_r = 4.25, tanδ = 0.002) substrate of 1.6 mm thick. A probe feed was located at x = 15 mm and y = 12.5 mm. The measured return loss of the microstrip antenna is shown in Fig. 1. A high order circuit model was built using a transformer circuit. Using this method, an accurate high order circuit model could be obtained with only a few elements and could be straightforwardly constructed without the transformation process given in [4]. The three transformers were applied to model the triple resonances of the antenna; the high order circuit model is shown in the inset of Fig. 1. Parenthetical values are those that resulted when the antenna was shielded by a cap; whereas non-parenthetical values are element values in free-space. A few changes occurred in the capacitor values due to the parasitic capacitance between the cap and each of the antenna parts. Figure 2 shows the measured input impedance (solid line) and the computed one using the circuit model (dash line) when the antenna was in free space. The results of the input impedance with the Wheeler cap are shown in Fig. 3. Both the input resistance and reactance were satisfactorily represented with and without the Wheeler cap. A comparison between the measured efficiencies using the modified Wheeler cap method and the conventional Wheeler cap method is shown in Fig. 4. The efficiencies measured using the series model and parallel model are represented by a dotted line and a dash-dot line, respectively. The solid-line represents the efficiency of the proposed method using Eq. (2) with the circuit model in Fig. 1. The dashed-line represents the efficiency computed using the IE3D of the EM simulator. The efficiency of the high order circuit model showed excellent agreement with the simulation over a wide frequency range.

Additionally, the modified Wheeler cap method was applied to the electromagnetic coupled monopole antenna [5]. The antenna was optimized to operate at around 900 MHz. The optimized antenna had a size of 35 mm × 31 mm × 27 mm and had broad bandwidth characteristics as shown in Fig. 5. In this case, two transformers were applied for the high order circuit since it showed two dominant resonances within the frequency range of interest. The circuit element values were marked in the same way as in Fig. 1 and the resulting efficiency using the high order circuit model is shown in Fig. 6. The conventional Wheeler cap method provided unreliable results, but the modified Wheeler cap method showed good agreement with the simulation results.

IV. CONCLUSION

The conventional Wheeler cap method often results in an unreliable measurement of efficiency when antennas under test have more complicated operating principles. In this paper, a modified Wheeler cap method was proposed that used a high order circuit model to more accurately estimate the efficiency of antennas containing complicated operations. The proposed method was verified by measuring the efficiency of a microstrip antenna with triple resonances and a broad bandwidth monopole antenna with electromagnetic coupling. All results demonstrated that use of the proposed method shows an excellent agreement with simulations. These results indicated that even for antennas with a complicated operating principle, the Wheeler cap method with the higher order circuit can provide accurate measurements of antenna efficiency.

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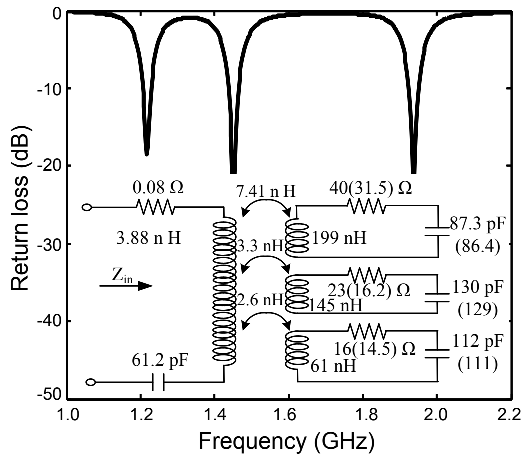

Fig. 1. Measured return loss and high order circuit model for the multi-band microstrip antenna.

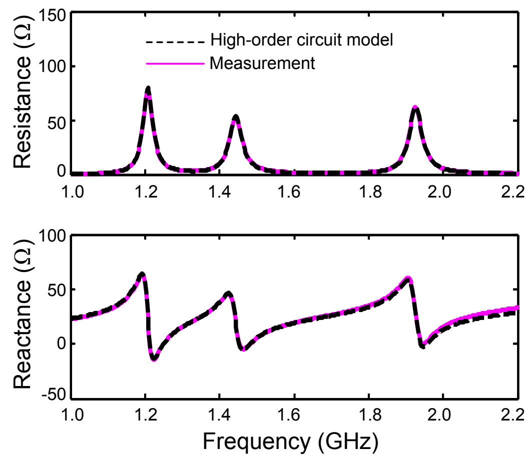

Fig. 2. Impedance of the antenna in free-space.

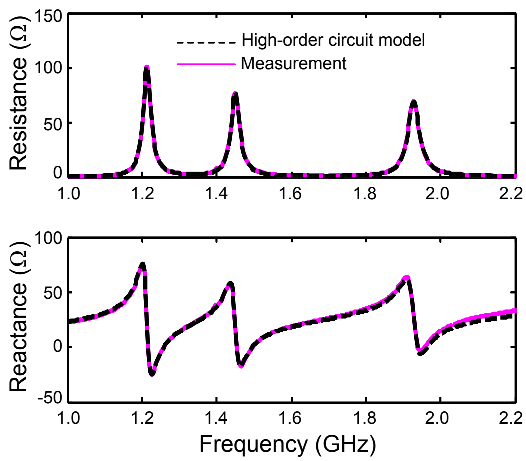

Fig. 3. Impedance of the antenna with the cap.

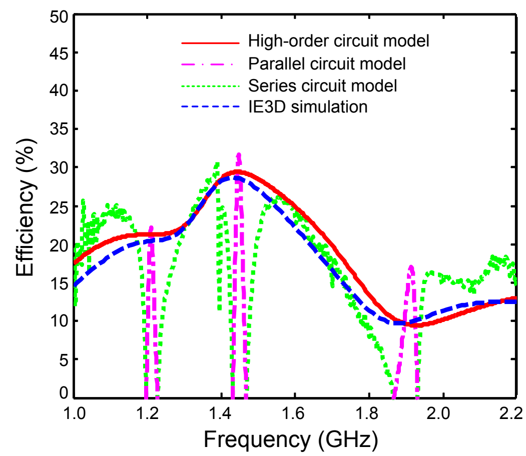

Fig. 4. Efficiency of the multi-band antenna.

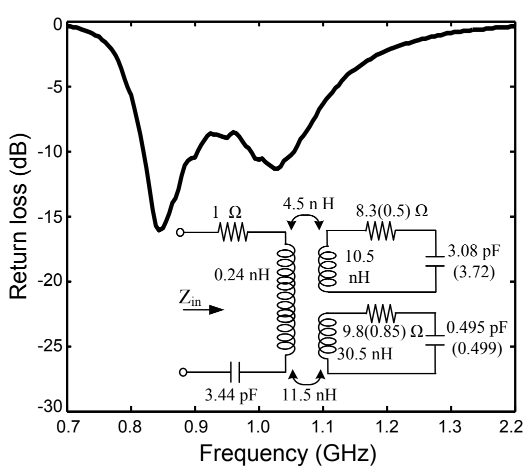

Fig. 5. Measured return loss and high order circuit model for the broad-band monopole antenna.

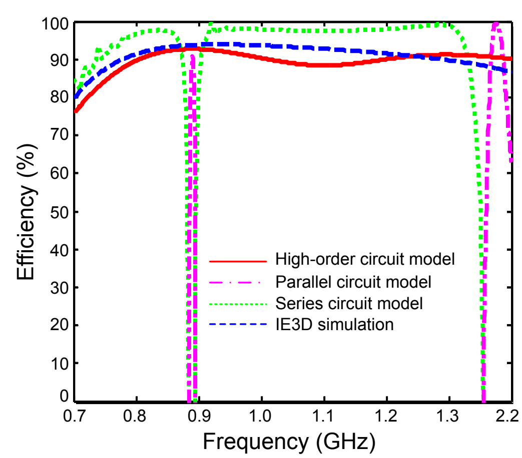

Fig. 6. Efficiency of the broadband monopole antenna.