ON THE WHEELER CAP MEASUREMENT OF THE EFFICIENCY USING THE HIGH-ORDER CIRCUIT MODEL

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1. Introduction

Generally, as the size of an antenna is reduced, its radiation efficiency drops rapidly. An additional decrease in antenna efficiency takes place when an antenna is built on a lossy dielectric medium. Decreased antenna efficiency is a primary factor contributing to the reduction of antenna gain, even when an antenna is designed to be well matched with an RF system. Therefore, the accurate estimation and measurement of antenna efficiency is critical to the improvement of antenna characteristics. There are some well-known techniques for measuring antenna efficiency such as the Directivity/Gain method, Q method, and Wheeler cap method. The Directivity/Gain method requires a highly accurate measurement of antenna gain in an anechoic chamber, a process that results in significantly long measurement time [1]. The Q method requires two identical antennas to be built with the different materials [2]. The Wheeler cap method is the most common small antenna efficiency measurement technique due to its simple procedure and reasonable accuracy [3, 4]. In the Wheeler cap method, the antenna is assumed to operate as a simple series or parallel RLC lumped circuit model, and it provides an accurate assessment of efficiency when the antenna has one clean single resonance. The Wheeler cap method, however, often offers unreliable efficiency measurement results when the antenna has more complicated operations such as circularly polarized radiation, multiple resonances in proximity, or strong electromagnetic coupling.

In this paper, we propose an enhanced Wheeler cap method using a high order circuit model to more accurately estimate the efficiency of antennas containing such complicated operations. To verify the proposed method, we measure the efficiency of microstrip antenna with a circular polarization (CP). We also measure the efficiency of microstrip antenna with triple resonances. Finally, we compare the enhanced Wheeler cap method with the conventional Wheeler cap method and the simulated results.

2. Methodology using a high order circuit

If the impedance characteristic of an antenna can be represented as an ideal lumped RLC circuit, the inductor (*L*) and the capacitor (C) in the circuit only charge and discharge the electric and magnetic energy without any power consumption. Thus, all power is dissipated by resistances in the circuit. According to demonstrations performed by Wheeler [3] and Smith [2], it is possible to effectively remove the radiation resistance of the antenna by perfectly shielding it with a conducting Wheeler cap sized at or less than λ/6. Efficiency can then be determined by separately estimating the resistances due to radiation and loss. In the Wheeler cap method, if the antenna operates as a series RLC circuit, such as a simple monopole, then the antenna efficiency can be characterized by using Eq. (1).

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

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where P_R and P_L represent the power consumed by radiation and loss, respectively, while R_R and R_L are the radiation resistance and loss resistance in the circuit model. $R_{free\ space}$ is the measured input resistance in the free space and R_{cap} is the input resistance that results from placing the conducting Wheeler cap on the antenna. If the antenna operates as a parallel RLC circuit model, such as a microstrip antenna with thin substrate, then the antenna efficiency can be determined by characterizing conductances (G) in the antenna, as shown in Eq. (2).

$$Eff = \frac{P_R}{P_R + P_L} = \frac{G_R}{G_R + G_L} = \frac{G_{free\ space} - G_{cap}}{G_{free\ space}} \tag{2}$$

However, if the antenna has a more complicated operation than a series or parallel RLC circuit, such as an antenna with circular polarization, multiple resonances in proximity, and strong electromagnetic coupling, then the conventional Wheeler cap method may offer an unreliable measurement of efficiency.

We propose a modified Wheeler cap method using a high order circuit model to more accurately estimate the efficiency of antennas containing such complicated operations. While the conventional Wheeler cap method assumes the operating principle of the antenna to be a simple series or parallel RLC model, our method employs a more accurate model to characterize antenna operation. Thus, our method can provide reliable measurements of antenna efficiency for antennas with highly complicated operations, even for antennas with broad bandwidth. The procedure for the proposed Wheeler cap method starts from the building of a high order circuit model that more precisely describes the free space impedance characteristic of a given antenna in terms of frequency. Then, each element of the circuit model is determined to match with the impedance that results from putting the antenna with a Wheeler cap. This enables the discrimination of multiple radiation resistances R_{Ri} and loss resistances R_{Li}. As the impedance characteristic, in terms of frequency, is modeled more accurately, antenna efficiency can be measured with greater precision. Finally, the total power dissipation ratio between the radiation and loss can be obtained by solving the current I_i flowing through R_{Ri} and R_{Li} in the high order circuit, as shown in Eq. (3).

$$Eff = \frac{P_R}{P_R + P_L} = \frac{\sum_{i=1}^{N} |I_i|^2 R_{Ri}}{\sum_{i=1}^{N} |I_i|^2 (R_{Ri} + R_{Li})} \tag{3}$$

3. Efficiency measurement results

To verify the proposed method, we first measure the efficiency of microstrip antennas with CP. The CP microstrip antenna has a patch size of 78 mm × 81 mm and uses a FR4 (ε_r = 4.25, tanδ = 0.002) substrate that is 1.6 mm thick. A probe feed is located at x =19.5 mm, y = 20.5 mm. This antenna shows double resonances closely spaced in frequency and has an axial ratio of about 3 dB near the resonance frequency. The circuit model of the CP microstrip antenna with each value of circuit element is shown in Fig. 1. Parenthetical values are those that result when the antenna is perfectly shielded by a Wheeler cap and non-parenthetical values are element values in free-space. Antenna resistance decreases after cap installation because shielding of the antenna prevents far field radiation, which results in a reduction of radiating resistances. A few changes in capacitor values occur due to parasitic capacitance between the cap and each of the antenna parts. Compared to (1) and (2) the proposed method provides the efficiency affected by the current flowing through the higher order circuit as in (3). Thus, not only the resistance (R) but the reactance values (L, C) are very important since the changes in frequency of the current are dependent on the R, L and C elements, which results in efficiency that can be described in terms of frequency. The measured input impedance of the antenna and the simulated result using the circuit model in Fig. 1 are shown in Fig. 2(a). The results of the impedance with the Wheeler cap are shown in Fig. 2(b). Both the input resistance and reactance represent well with and without the Wheeler cap.

A comparison between measured efficiency using the enhanced Wheeler cap method and the conventional Wheeler cap method is shown in Fig. 3. The efficiencies measured using the series model and parallel model are represented by a dash-dot line and a dotted line, respectively. The solid-line represents the efficiency of the proposed method using Eq. (3) with the circuit model in Fig. 1 and the dashed-line represents the efficiency computed using the IE3D of the EM simulator. The efficiencies of the circuit model and the simulation show excellent agreement, while the efficiency obtained by using the conventional Wheeler cap method gives totally unreasonable result in the operating frequency.

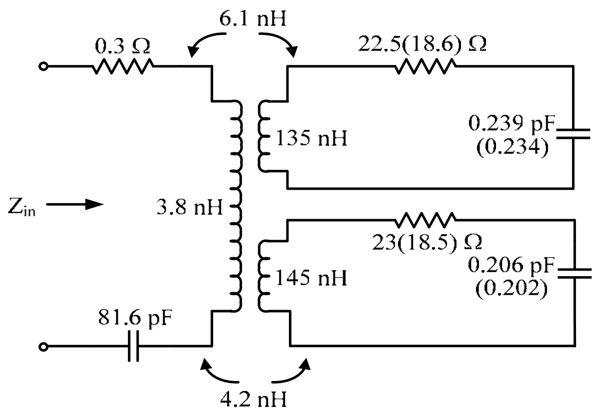

Fig. 1. Circuit modeling for the CP microstrip antenna

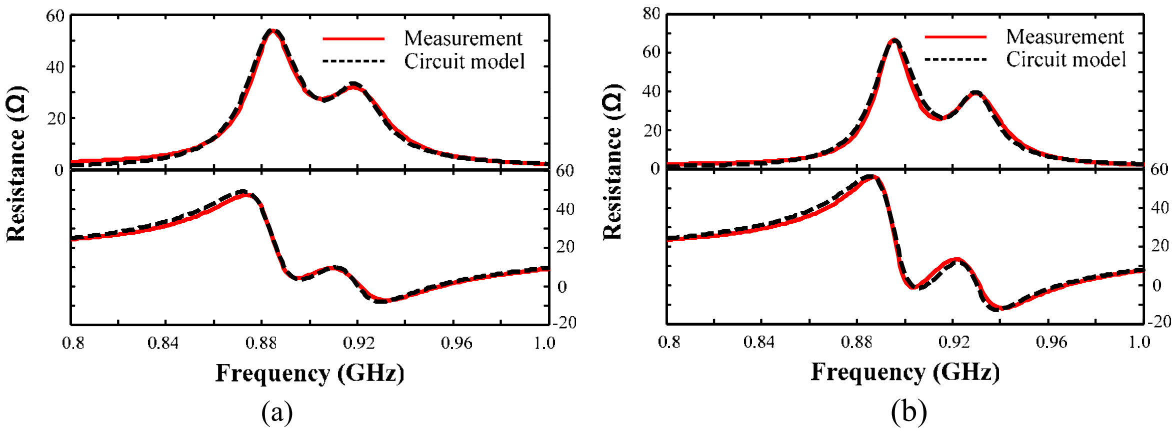

Fig. 2. Simulation using the circuit model and measurement (a) in the free space and (b) with the Wheeler cap.

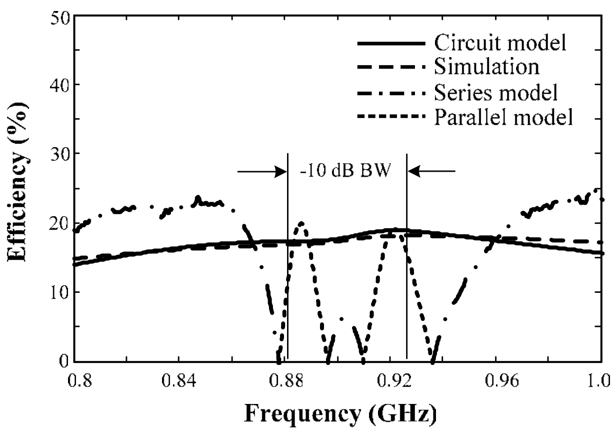

Fig. 3. Efficiency of the CP microstrip antenna

The enhanced Wheeler cap method was also applied to the even more challenging problem of a microstrip antenna with triple resonances. This antenna was built with same substrate as the CP antenna and has a patch size of 60 mm × 50 mm. A probe feed is located at x = 15 mm and y = 12.5 mm. Fig. 4. shows the high order circuit model for the given microstrip antenna with triple resonances; passive element values are marked in the same way as in Fig. 1. The three transformers are applied to more correctly model the triple resonances of the antenna. The return loss of the antenna and the efficiencies measured using the higher order circuit model and the simulation are shown in Fig. 5. The frequency range of interest is quite wide, ranging from 1.0 GHz to 2.2 GHz, and the efficiency of the circuit model again shows excellent agreement with the simulation over such a wide frequency range. This result clearly shows that the proposed method can provide an accurate measurement of efficiency over a broad frequency range if the circuit model exactly describes the impedance characteristics of the antenna in terms of the frequency.

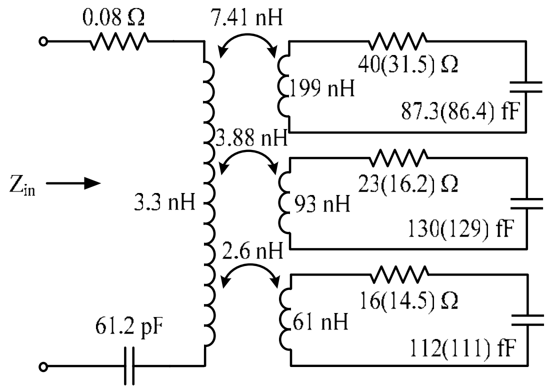

Fig. 4. Circuit modeling for triple-band antenna

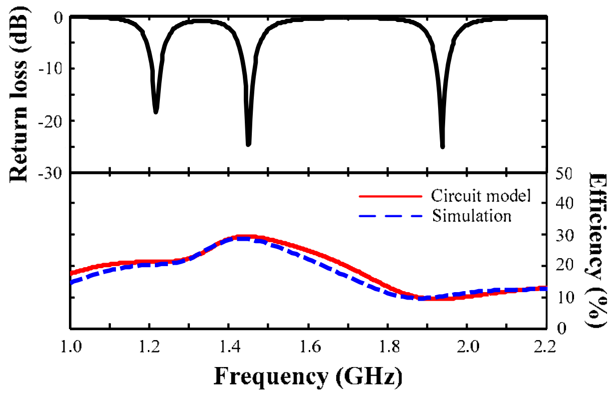

Fig. 5. Return loss and efficiency of the triple-band antenna

4. Conclusion

The conventional Wheeler cap is very useful due to its simplicity and convenience in the efficiency measurement procedure, and it usually gives a reliable measurement of efficiency in the vicinity of the operating frequency. However, if the antenna has a complicated operating principle, then the conventional Wheeler cap often offers an unreliable measurement of efficiency. In this paper, we proposed a modified Wheeler cap method using the high order circuit model to more accurately estimate the efficiency of antennas containing such complicated operations. We have verified the proposed method by measuring the efficiency of microstrip antennas with a circular polarization and triple resonances. All results ascertained using the proposed method show excellent agreement with simulations. These results indicate 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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