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RF Conductivity Measurement of Conductive Zell Fabric

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Abstract

This study presents a conductivity measurement technique that is applicable at radio frequencies (RF). Of particular interest is the measurement of the RF conductivity of a flexible Zell fabric, which is often used to implement wearable antennas on clothes. First, the transmission coefficient is measured using a planar microstrip ring resonator, where the ring is made of a Zell fabric. Then, the fabric's conductivity is determined by comparing the measured transmission coefficient to a set of simulation data. Specifically, a MATLAB-based root-searching algorithm is used to find the minimum of an error function composed of measured and simulation data. Several error functions have been tested, and the results showed that an error function employing only the magnitude of the transmission coefficient was the best for determining the conductivity. The effectiveness of this technique is verified by the measurement of a known copper foil before characterizing the Zell fabric. The conductivity of the Zell fabric at 2 GHz appears to be within the order of 10^4 S/m, which is lower than the DC conductivity of 5×10^5 S/m.

Key Words: Conductivity, Material Characterization, Ring Resonator, Zell Fabric.

I. INTRODUCTION

In recent years, wearable antennas for body-worn communication systems have been studied extensively [1]. One way to realize such antennas is by using conductive fabrics [2]. Such fabrics are highly flexible, durable, and restorable, and they can be directly integrated onto clothing by ordinary sewing or embroidering techniques. To derive an appropriate antenna design, it is essential to have accurate information about the electrical properties of conductive fabrics, especially the conductivity (σ) at the antenna's operation frequency.

Commonly, the manufacturers of conductive fabrics provide the DC sheet resistances (R_s) measured by the well-known four-point probe or van der Pauw methods [3, 4]. The DC sheet resistance values range from 0.02 to 0.8 Ω/sq [5], implying that the DC conductivity ranges from $s=1.2\times10^4$ to 5×10^5 S/m based on the formula $s=1/(R_s\times t)$, where t is the thickness of the fabric. This study aims to measure the RF conductivity instead of the DC one to realize accurate modeling of wearable antennas.

Many studies have measured the RF permittivity of dielectrics. However, few studies have measured the conductivity of highly conductive materials at RF. In [6, 7], a planar resonator is used as a test fixture to measure the quality factor (Q-factor) with the conductor under test inserted in. Then, the conductor's σ is obtained from a closed-form equation of the Q-factor under the assumption that the dielectric and radiation losses are trivial. However, in practice, these losses may distort the resulting σ, and they should not be underestimated.

As an alternative, full-wave simulation data can be used to estimate the conductivity instead of the approximate closed-form equations.In a full-wave simulation tool, a structure identical to the material under test is modeled, and then, the simulation data is collected by varying the material properties

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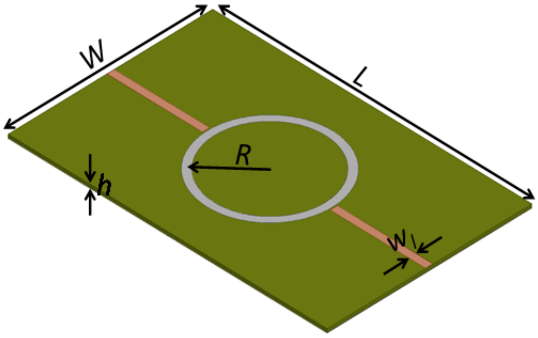

Fig. 1. Geometry of microstrip ring resonators. The ring is made of the material under test.

(e.g., σ). Subsequently, the measured and simulated data are compared in a root-searching algorithm to find the best fit. Recent reports have verified the effectiveness of this method for the measurement of the dielectric constant (ε_r) and loss tangent (tan δ) of an antenna substrate [8, 9].

In this paper, we present a conductivity measurement method by employing a planar ring resonator (shown in Fig. 1) and surrogate-based optimization (SBO) [10] as the root-searching tool. Section II provides an outline of the measurement process. Section III demonstrates the effectiveness of the proposed method by measuring a copper ring with known conductivity. Section IV discusses the conductivity measurement of the Zell fabric. The results appear to be within the order of 10^4 S/m, which is lower than the DC conductivity of the order of 10^5 S/m reported by the manufacturer.

II. Overview of Proposed Measurement Method

Fig. 2 shows a flowchart of the conductivity measurement process. A microstrip ring resonator with H=1.6 mm, W=90 mm, and L=140.3 mm is fabricated on a FR-4 substrate to measure the transmission coefficient (S_{21}). This resonator is fabricated to exhibit a resonance of around 2 GHz, which is the frequency of interest. The transmission lines between the ports and ring are made of copper, and the ring is made of the material under test. The main radius of the ring is R=25.9 mm, and the width of both the ring and the transmission lines is w_l=3.2 mm to conform to the 50-Ω impedance matching condition at 2 GHz. The coupling gap separating the feeding lines from the ring should have an appropriate size to avoid any effect on the fields of the resonant structure and to minimize losses. Specifically, the gap is set to 0.64 mm to support resonance around 2 GHz based on the ring resonator design equation found elsewhere [11].

Meanwhile, a resonator identical to the fabricated one is modeled in a full-wave simulation tool (Ansys HFSS). The conductivity of the ring in the simulation model is varied to

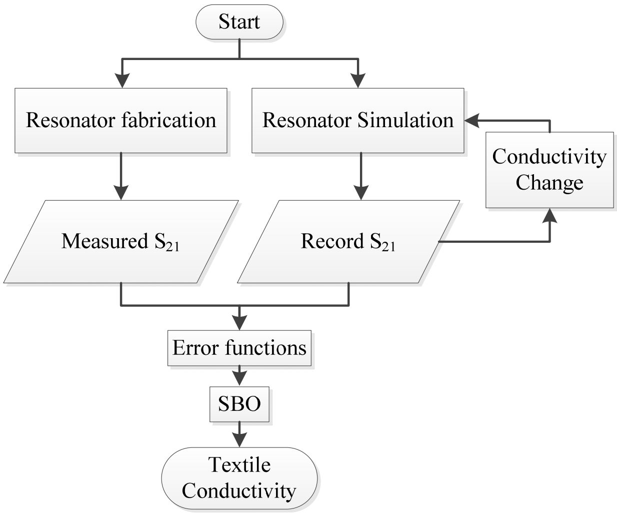

Fig. 2. Flow chart of the conductivity measurement process.

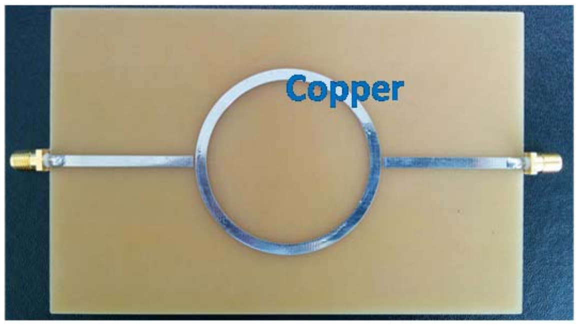

Fig. 3. Fabricated copper ring resonator

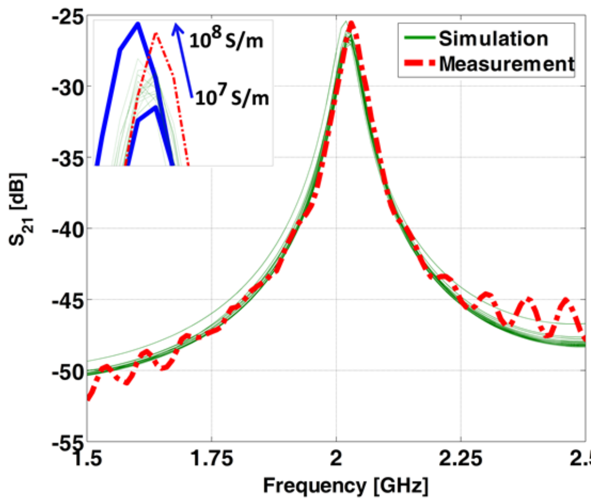

Fig. 4. Simulated and measured S_{21} of copper ring resonator (simulation from σ =10^7 to 10^8 S/m).

collect a set of S_{21} data, as shown in the right-hand-side branch in Fig. 2. The measured S_{21} and the set of simulated S_{21} values are then compared in an error function formulated using the magnitude and phase of S_{21}. The conductivity of the unknown fabric is determined when the error function becomes zero (or close to zero). We use SBO as the iterative comparator to efficiently search for a σ value that minimizes the error function. SBO is widely used to find solutions of nonlinear electromagnetic problems as it offers an efficient iterative scheme by intelligently choosing the best sampling and evaluation strategies. In this work, the MATLAB toolbox for SBO provided by Ghent University, Belgium [12] is used.

III. Measurement with Copper Ring Resonator

The proposed measurement method is first tested with a ring made of copper. Fig. 3 shows the fabricated copper ring resonator and Fig. 4, the measured and simulated S_{21} magnitudes. For the simulation data, S_{21} is collected by varying s of the ring from 10^7 to 10^8 S/m with an interval of $10^{0.0625}$ (i.e., 17 points are considered). As can be observed, the resonator is correctly designed to resonate around 2 GHz, and only a slight perturbation is observed in the simulation results as the copper conductivity is high enough.

The set of simulated S_{21} values is compared with the measured S_{21} value using an error function in the SBO process. The error function should be formulated carefully to obtain an accurate result. Initially, we used an error function composed of only the magnitude of S_{21}, namely,

$$EF_1 = \left| S_{21}^r - \tilde{S}_{21}^r \right|$$

where S_{21}^r, and $\tilde{S}_{21}^r$ are the magnitudes of the simulation and measurement at the resonant frequency. Fig. 5 shows the error function values along the sampled conductivity points and the interpolated Kriging model after the SBO process. The error function is minimum at $\sigma = 10^{7.24}$ (1.74×10^7 S/m). This retrieved conductivity is lower than the DC conductivity of pure bulk copper ($\sigma = 5.7 \times 10^7$ S/m) and is close to the conductivity of plated copper at microwave frequency [13, 14]. It is also known that the conductivity becomes lower as the frequency increases owing to the skin effect and surface roughness.

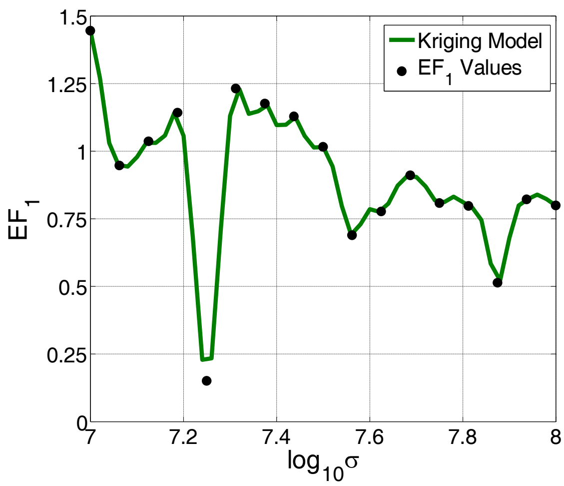

Fig. 5. Error function values and corresponding Kriging model from surrogate-based optimization (SBO) process.

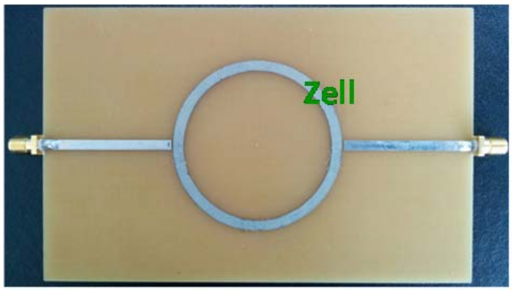

Fig. 6. Fabricated Zell ring resonator.

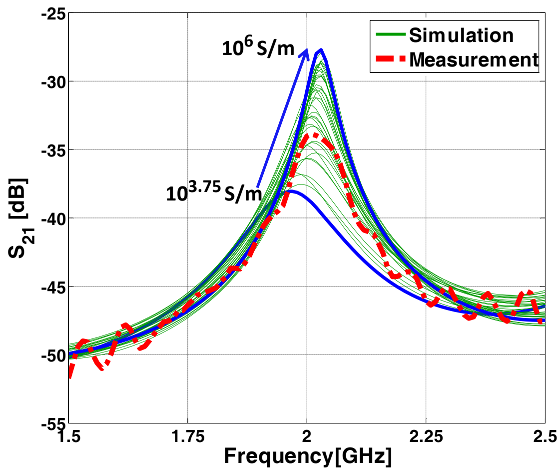

Fig. 7. Simulated and measured S_{21} values of Zell ring resonator.

IV. Measurement of Zell Fabric

After measuring the conductivity of copper using the proposed method, we measured the conductivity of the Zell fabric, a metalized nylon fabric. The Zell fabric under test has a thickness of 0.1 mm and DC surface resistance as low as 0.02 Ω/sq [5], corresponding to a DC conductivity of 5×10^5 S/m.

Fig. 6 shows the microstrip ring resonator with the ring made of Zell fabric. The Zell fabric ring is attached on the FR-4 substrate using fast-drying urethane glue. The glue has trivial influence on the resonator performance because its layer is very thin and its relative permittivity (3.2 at 23℃) is close to that of the FR-4 used. On the other hand, a ring resonator with the same dimension as that shown in Fig. 6 was modeled in the full-wave EM simulator, and S_{21} values were obtained by varying the conductivity of the ring from $10^{3.75}$ to 10^6 S/m. Specifically, 37 values were collected with an interval of $10^{0.0625}$ S/m. Fig. 7 shows the measured and simulated S_{21} magnitude data. The measurement is performed using Anritsu Vector Network Analyzer MS2038C, which as measurement uncertainty of 0.04 dB around 2 GHz.

As shown in Fig. 7, the simulated S_{21} peak is broader and lower for the ring with lower conductivity, and the measured data falls somewhere within the simulated conductivity range.

For the conductivity retrieval process, we test four different error functions in addition to EF_1 in the previous section. The other three are

$$EF_2 = \left| S_{21}^r - \tilde{S}_{21}^r \right| + a * \left| \angle S_{21}^r - \angle \tilde{S}_{21}^r \right|$$

$$EF_3 = \frac{1}{h-l+1}\left[\sum_{i=l}^{h} \left| S_{21i} - \tilde{S}_{21i} \right| \right]$$

$$EF_4 = \frac{1}{h-l+1}\left[\sum_{i=l}^{h} \left(\left| S_{21i} - \tilde{S}_{21i} \right| \right) + b * \sum_{i=l}^{h} \left(\left| \angle S_{21i} - \angle \tilde{S}_{21i} \right| \right) \right]$$

where $\angle S_{21}^r$, and $\angle \widetilde{S_{21}^r}$ are the phase of the simulated and measured S_{21} at the resonant frequency, respectively. In EF_3 and EF_4, the arithmetic mean of S_{21} is used by averaging S_{21} data over a 300-MHz bandwidth (i.e., 31 frequency points). Here, h and l are index numbers of the frequencies that are 150 MHz higher and lower than the resonant frequency, respectively. The constants a and b in EF_2 and EF_4 are scaling factors to compensate for the difference of order between the magnitude and phase, respectively.

The SBO toolbox compares the simulated and measured data using the abovementioned error functions to determine the conductivity of the Zell fabric. Fig. 8(a)–(d) show the resulting Kriging models when EF_1 to EF_4 are considered, respectively.

The error function minima for EF_1, EF_2, EF_3, and EF_4 are located at $\sigma = 10^{4.335}$ (2.16×10^4 S/m), $10^{4.38}$ (2.4×10^4 S/m), $10^{4.11}$ (1.29×10^4 S/m), and $10^{4.11}$ (1.29×10^4 S/m), respectively. The consistency among these error functions demonstrates that including the phase (e.g., EF_2) or averaging over a bandwidth (e.g., EF_3 and EF_4) does not alter the obtained conductivity value. This implies that formulating the error function using only the S_{21} magnitude (e.g., EF_3) is sufficient to evaluate the conductivity using the proposed method. Furthermore, it should be noted that the measured conductivity of the Zell fabric at 2 GHz shows an order difference from the DC conductivity given by the manufacturer (5×10^5 S/m) [5]. This may be due to the significant ohmic loss as well as the surface roughness seen at the microwave frequency.

V. Conclusion

In this paper, a new measurement technique for evaluating RF conductivity is described. The proposed method employs a microstrip ring resonator, full-wave simulation data, and SBO optimization technique to measure the conductivity of a conductive fabric at a microwave frequency. We first evaluated the conductivity of plated copper using the proposed method, and

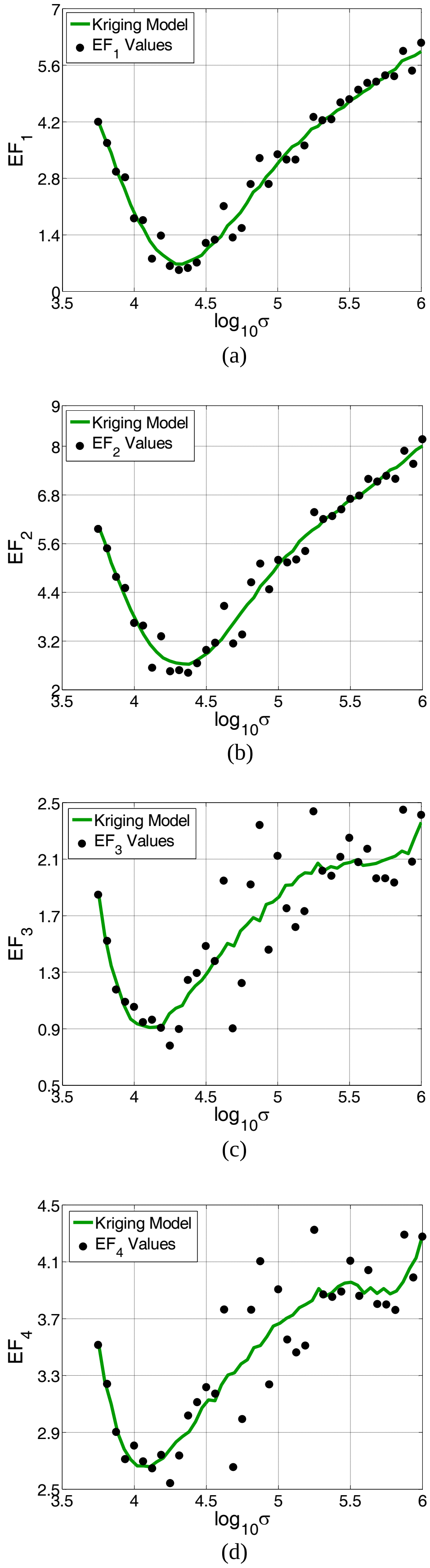

Fig. 8. (a–d) Error function values and corresponding Kriging models from surrogate-based optimization (SBO) process.

then, we applied it to measure the conductivity of a Zell fabric. For both cases, the conductivity values around 2 GHz were lower than the known DC conductivity. This is because high-frequency currents mostly flow along the surface owing to the skin effect and concurrent influence of the surface roughness of the conductor. Therefore, it is important to measure the high-frequency conductivity of newly introduced conductive materials to formulate an accurate model of antennas and RF components.

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