Application of Dual-Mode Ruby Dielectric Resonator for Characterization of Copper Foils in High-Frequency Circuits

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Abstract — **Achieving high electrical performance in mmWave PCBs often compromises copper foil reliability. This study introduces a novel measurement approach using Ruby Dielectric Resonators (RuDR) operating at 13 GHz and 21 GHz to assess copper foil conductivity without substrate interference. By focusing on direct loss measurements, these resonators provide accurate data on the effects of surface roughness on foil performance, crucial for 5G applications. The RuDR resonator, used in this study, highlights a decreasing exponential relationship between conductivity and surface roughness, confirming the significance of surface texture. The findings guide the development of high-performance materials for next-generation mmWave technologies.**

Index Terms — **copper foils, dielectric resonators, non-destructive testing, effective conductivity, surface roughness, 5G applications**

I. Introduction

In the advancing field of millimeter wave (mmWave) technologies, achieving high electrical performance in printed circuit boards (PCBs) is critical but often comes at the cost of compromising the reliability of the copper foil materials used in these boards. This compromise between electrical conductivity σ and structural integrity presents a significant challenge in the development of mmWave components, particularly as demand grows for higher performance in 5G and other high-frequency applications. Recognizing the importance of addressing this issue, the iNEMI [1] consortium has undertaken a thorough investigation into the surface roughness and loss properties of copper foils from various manufacturers, highlighting the crucial role these factors play in determining the overall effectiveness of mmWave PCBs [2].

This paper discusses a novel approach to evaluating the electrical performance and reliability in copper foils with the use dual-mode dielectric resonator heads. Specifically, we apply a Ruby Dielectric Resonator (RuDR), designed for assessing the effective conductivity σ or surface resistance R_s of copper foil samples. Unlike traditional methods that require complex test circuits such as strip-line segments [3], our resonator-based instruments allow direct measurements of copper losses without the interference of PCB substrates. This approach simplifies the evaluation process, making it more compatible with the industrial needs for fast testing.

We draw on the long-term experience in microwave material characterization, documented in e.g. [3][4]. The novelty in our present approach resides in designing the new resonators with the use of advanced full-wave electromagnetic modeling techniques, and specifically, the conformal Finite-Difference Time-Domain (FDTD) method in the Bodies-of-Revolution formulation [5][6]. This approach not only allows geometrical flexibility and high accuracy of the model and thereby in the measurement results, but also provides deep insights into the electromagnetic behavior of the materials under test. In [7], the resonator technique has been applied to initial screening of copper foils from three different manufacturers, with the foils being annotated in general terms as “low roughness” or “high roughness”. A systematic study of a quantitative relationship between foils conductivity and different surface roughness parameters has been initiated in [8]. While in [9] RuDR has been applied at a single frequency of 13 GHz, here we extend the study to a dual-mode operation, at 13 GHz and 21 GHz, making it a more relevant and practical solution to the challenges faced by circuit designers at higher frequencies. The study is conducted for representative samples of foils manufactured by CFL [10] In this paper, the results are reported for 72 samples of foils.

The significance of the proposed testing methods extends beyond the laboratory, providing copper foil manufacturers with tools to enhance product quality and accelerate the development of new materials optimized for mmWave applications. In fact, this work forms a part of a project under the European Partnership on Innovative SMEs (EUREKA-Eurostars) [11]. It bridges the gap between fundamental scientific research and practical industrial application, showcasing the potential of these novel measurement techniques to drive improvements in PCB manufacturing and the broader 5G perspective.

II. MEASUREMENT SETUP

The measurement setup involves a cylindrical resonator RuDR, which is connected to a vector network analyzer (VNA), specifically the Keysight Streamline P5008B model. This VNA plays a crucial role in capturing S-parameters regarding the resonator's performance under various conditions. The connection between the RuDR and the VNA is established through coaxial cables, ensuring stable and low-loss signal transmission. The VNA is further connected to a laptop via a USB cable, allowing for data acquisition, analysis, and visualization in real time. The complete measurement setup is illustrated in Fig. 1. Depending on the specific parameters set on the VNA, the acquisition time can vary slightly; however, a single measurement cycle—including the placement of a sample and configuration of the application—typically takes less than one minute, highlighting the system's efficiency.

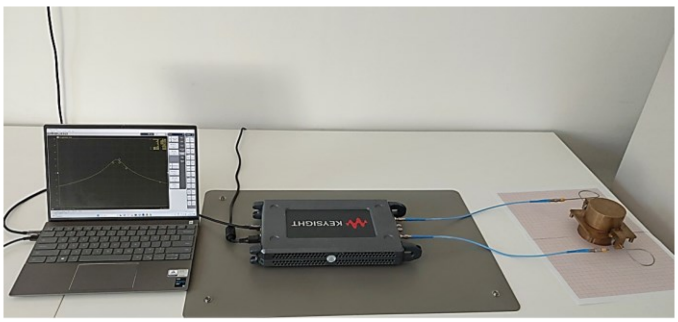

Fig. 1 Dual mode Ruby Dielectric Resonator measurement setup which also includes VNA and laptop with dedicated software.

A. Dual-Mode Ruby Dielectric Resonator

The RuDR is an advanced measurement device specifically designed for the precise characterization of electrically thick conductive layers, such as copper foils, by focusing on minimizing dielectric losses rather than metallic losses. In conventional resonators, dielectric losses are often a secondary concern, as the primary interest lies in metallic losses. However, the RuDR reverses this paradigm, emphasizing ultra-low dielectric losses using a ruby resonator, which allows for a highly accurate assessment of the conductive layers' properties. The resonator operates in a dual-mode setup at TE011 and TE021 modes, corresponding to resonant frequencies of approximately 13.8 GHz and 20.4 GHz. These modes enable dual-frequency measurements, enhancing reliability of the extracted data and relevance to wider-frequency-band applications.

The core of the RuDR consists of a ruby dielectric resonator embedded within a metallic cavity, where the top and bottom walls are replaceable and made from the conductive layers under test. Ruby, known for its exceptionally low dielectric loss [12], forms the resonator's head and minimizes internal losses, allowing the primary losses measured to be those associated with the conductive samples. This configuration is particularly suitable for electrically thick layers, fulfilling the condition $h_s > 3\delta$, where h_s is the thickness of the foil and δ denotes
the skin depth. By maintaining this condition, the RuDR ensures that the characterization is focused on bulk properties rather than surface anomalies.

The measurement process involves connecting the RuDR to VNA via RF coaxial cables. Two identical samples of the conductive material, each with a minimum lateral size of 23 mm x 23 mm, are placed on the dielectric head and carefully pressed down using weights to ensure uniform contact and flatness, reducing measurement uncertainties that can arise from non-uniform sample placement. This setup allows the VNA to precisely measure the resonant frequency and Q-factor for each mode of operation. The resonant frequency provides insights into the distribution of the electromagnetic field within the resonator, while the Q-factor—a measure of energy loss—indicates how efficiently the resonator stores energy versus how much it dissipates.

To extract the effective conductivity σ and surface resistance R_s of the material, the resonant frequency and Q-factor measurements are processed using specialized software. The resonator's total unloaded Q-factor, which reflects the combined losses in the structure, is defined by the equation:

$$Q^{-1} = Q_C^{-1} + Q_p^{-1} = \frac{R_s}{G_b} + Q_p^{-1}, \qquad (1)$$

where Q_c represents the combined conductive losses of the sample and the structure, Q_p denotes the dielectric and other parasitic losses, R_s is the surface resistance of the conductive layer, and G_b is the geometrical factor related to the distribution of fields in the resonator. The surface resistance R_s, which is directly tied to the sample's effective conductivity σ, can be further defined by the relationship [5]:

$$R_s = \left(\frac{0.5\omega \cdot \mu_0}{\sigma}\right)^{\frac{1}{2}}, \qquad (2)$$

where ω is the angular frequency, μ_0 is the permittivity of free space, and σ is the material's conductivity. The effective conductivity σ impacts the resonator by causing shifts in the resonant frequency and reductions in the Q-factor, reflecting increased energy losses due to the sample's conductive properties.

The dual-mode operation not only broadens the measurement spectrum but also enhances the reliability of data by allowing for cross-verification between the two modes. This approach to resonance measurement ensures that the dielectric contributions are minimized and the losses of interest—those in the metallic layers—are isolated and accurately quantified, making the RuDR a highly effective tool for studying conductive materials in high-frequency environments.

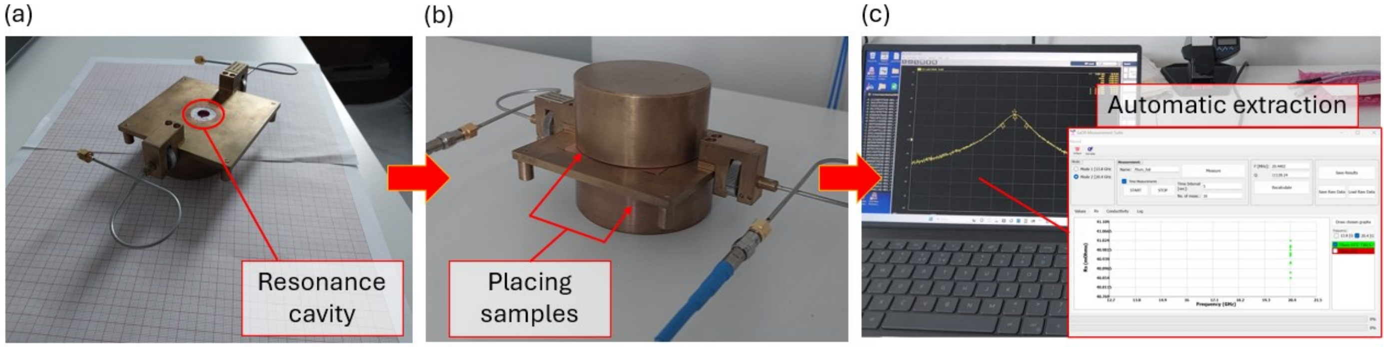

Fig. 2 The measurement procedure involves three main steps: (a) preparing a sample to fill the resonance cavity, (b) placing samples above and below the cavity (indicated by red arrows) and pressing them with brass cylinders, and (c) connecting the setup via RF coaxial cables to a VNA to extract material parameters using automated software.

III. Measurement Preparation and Results

The copper foils analyzed in this study were produced using standard industrial manufacturing processes at Circuit Foil Luxembourg [10]. The foils were delivered in two thicknesses: 35 µm and 70 µm. Instead, each foil is identified by its thickness and various roughness parameters measured using a noncontact laser interferometry (providing Sz, Sa, and Sdr values, as defined in [13]). The initial set of samples included 24 types of foil, with three sheets of each type, representing different combinations of foil base, applied treatment, and thickness (35 µm or 70 µm). Each sheet was provided in A4 paper format, from which 60 x 60 mm samples were cut, yielding a total of 72 copper foil samples for analysis.

In the first phase of the study, foil loss was measured using a RuDR at 21 GHz. Foil measurements at 13 GHz were taken and published in the [9]. For each measurement, two nominally identical samples, cut from the same foil sheet, were required and mounted as illustrated in Fig. 2 to form the two bases of the cylindrical ruby resonator. The samples were securely pressed by metallic blocks. The RuDR test fixture was connected to a VNA, which determined the Q-factor from the 3 dB bandwidth and resonance frequency. A dedicated software application then converted this data into effective conductivity σ values using full-wave modeling. The same procedure for different resonator is presented here [14]. Each of foil was measured 16 times via application function which do single measurement every 5 seconds. For further consideration we will use an average values of conductivities.

The effective conductivity σ was measured on the electrolyte side of each foil for both thicknesses (35 µm and 70 µm). These conductivity σ values were then correlated with surface roughness R_s parameters, showing a decreasing exponential relationship in all cases, as illustrated in Fig. 3. To better visualize this trend, an exponential curve was fitted to the entire set of measurements. The physics of the RuDR suggests that the foil thickness does not influence conductivity σ. Although a few data points deviate from the fitted curve, it is important to note that conductivity σ is not only affected by surface roughness R_s; other factors, such as the grain size of the copper foils, also play a role. The impact of grain size is currently being investigated as part of the 5GFoil project.

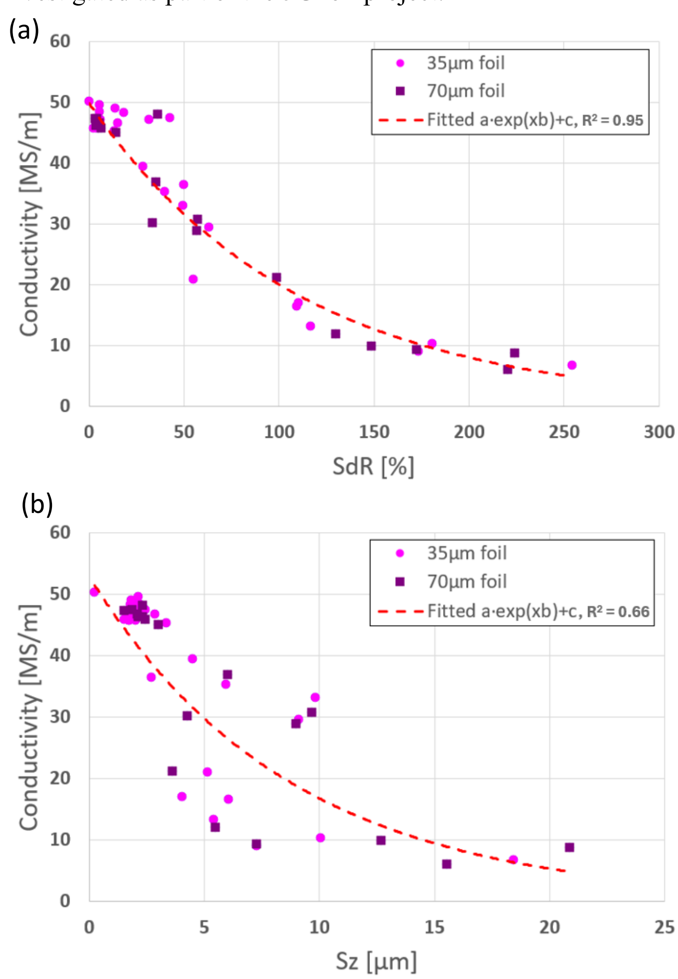

Fig.3 Correlation between effective conductivity σ (measured at 21 GHz in the RuDR test-fixture and surface roughness parameters: (a) SdR - Developed Interfacial Area Ratio, (b) Sz - Maximum Height

IV. CONCLUSIONS

This study validates the RuDR as an effective tool for precise characterization of copper foils used in microwave and mmWave PCBs. The RuDR technique streamlines the measurement of effective conductivity σ and surface resistance R_s by directly assessing conductive properties without complex test circuits or substrate interference. Operating at dual frequencies of 13.8 GHz and 20.4 GHz, the RuDR provides reliable data that directly correlates foil conductivity σ with surface roughness, highlighting a decreasing exponential trend. The results confirm that SdR parameter significantly affects conductivity σ, while foil thickness (as long as it exceeds several times the penetration depth) shows negligible impact, aligning with theoretical expectations. However, the study also demonstrates that while surface roughness is a key factor influencing the foils' electrical performance, there is no simple analytical one-to-one correspondence between conductivity and any of the roughness parameters. The best fit was obtained for the SdR roughness parameter. At 21 GHz we obtain $R^2 = 0.95$, while at 13 GHz it was shown to be $R^2 = 0.97$ [9]. This indicates that while the fit is good, it is not perfect, and other variables such as grain size also play a role and warrant further investigation. Closed-form approximations for foil loss solely as a function of surface roughness, such as those developed in [15][16], are helpful, but should not be expected to provide a better fit than the above given R^2, demonstrated experimentally in this work.

As a practical hint to RF to circuit designers, if the applied CAD software allows only roughness parameters as an input, then Sdr should be used, as being most representative. A recommended approach in terms of modeling the metallic loss, is to measure the actual effective conductivity and use it in the design. It should be noted that the effective conductivity is usually different on the two sides of the foil [8].

The RuDR method offers a practical, scalable approach for the copper foil industry, enabling precise and repeatable evaluations that can guide the development of high-performance foils tailored for 5G and other mmWave technologies. By enhancing the accuracy and efficiency of conductivity σ measurements, this technique supports the advancement of PCB materials, bridging the gap between laboratory research and industrial application. Further work in the 5G_Foil project will provide more insight into the conductivity σ relationship to other process parameters of copper foils' and their manufacturing process.

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