Evaluation of Surface Roughness of Copper Foils for 5G Applications Using Novel mmWave Resonators

Malgorzata Celuch[1], Marzena Olszewska–Placha[1], Lukasz Nowicki[1], Pawel Kopyt[2], Jerzy Cuper[2]
[1]QWED Sp. z o. o.
[2]Institute of Radioelectronics and Multimedia Technology, Warsaw University of Technology
Warsaw, Poland

Abstract
At millimeter-wave frequencies, considerations of electrical performance and PCB durability may often lead to contradictory requirements with respect to copper foil materials and chemical pre-bond treatments. For example, decreased surface roughness will typically decrease conductor loss but may compromise PCB durability. These issues are being investigated by the iNEMI consortium performing a rigorous study, based on copper foils from different manufacturers, where surface roughness and loss properties of the foils are independently evaluated. An original contribution from the authors of this paper resides in providing easy-to-use instruments, based on mmWave resonator heads, for measuring the effective conductivity of copper foil samples. Such techniques alleviate the need for manufacturing a test vehicle (such as a strip-line segment) and naturally deliver the loss due to the copper, separated from any substrate losses, as no substrate is involved in the measurement.

This paper and conference talk will explain the physical fundamentals of the developed methods, illustrated with the results of copper foil measurements in the 13- 40 GHz range.

We shall focus on Sapphire Dielectric Resonators (SaDR) and plano-concave Fabry-Perot Open Resonator (pc-FPOR), developed with the use of full-wave electromagnetic modeling. Conformal FDTD method is applied for both instrument design and physical insights into the measurement process. Extensions to higher frequencies are underway and will be signaled.

The presented testing methods will help copper foil manufacturers improve manufactured products quality and accelerate new product development. New and better foils will contribute to advancements in PCB manufacturing and overall 5G technologies.

Introduction
In the rapidly evolving landscape of millimeter-wave (mmWave) technologies, the quest for enhanced electrical performance in printed circuit boards (PCBs) encounters a complex interplay with the durability of copper foil materials. These considerations often give rise to conflicting requirements, where improvements in electrical conductivity may compromise the structural integrity of PCBs. The iNEMI consortium has undertaken a comprehensive investigation into this dilemma, meticulously scrutinizing copper foils from various manufacturers. A primary focus of the conducted study lies in independently evaluating surface roughness and loss properties, recognizing the pivotal role these factors play in the overall performance of mmWave applications [1].

This paper presents an original contribution by the authors, addressing the challenges posed by the contradictory requirements of electrical performance and PCB durability. The authors introduce user-friendly instruments based on mmWave resonator heads, offering a novel approach to measuring the effective conductivity or surface resistance of copper foil samples. This technique eliminates the need for manufacturing complex test circuits, such as strip-line segments, providing a direct assessment of copper losses without substrate interference. Leveraging over 25 years of experience in material characterization for various microwave applications, as evidenced in previous works [2] and expert reviews [3], the authors bring forth novel methodologies that promise to revolutionize the evaluation of copper foil materials.

The forthcoming sections of this paper and the accompanying conference talk delve into the physical fundamentals underlying the considered test methods and their application to newly developed copper foils materials. Through an exploration of results obtained in the 13-40 GHz frequency range, the authors shed light on the efficacy of Sapphire Dielectric Resonators (SaDR) and plano-concave Fabry-Perot Open Resonators (pc-FPOR). Employing state-of-the-art full-wave electromagnetic modeling, the authors utilize the conformal FDTD in the bodies-of-Revolution formulation [4][5] for both instrument design and a deeper understanding of the measurement process. Moreover, ongoing efforts to extend these methodologies to higher frequencies will be discussed, signaling a continual commitment to advancing the field.

Beyond their technical complexities, the presented testing methods hold significant implications for the copper foil manufacturing industry. By providing manufacturers with tools to enhance the quality of their products and expedite new product development, the authors aim to contribute to the evolution of PCB manufacturing and the broader landscape of 5G technologies. This paper unfolds as a testament to the fusion of scientific rigor and practical innovation, offering a roadmap for future advancements in the intricate realm of mmWave applications.

Experimental Methodology

SaDR and pc-FPOR resonators provide a versatile and efficient solution for direct measurements of effective conductivity of copper foils, offering several advantages over traditional methods. Both SaDR and pc-FPOR resonators eliminate the requirement for fabricating a dedicated test circuit. This simplifies the measurement process, saving time and resources associated with circuit production. Another significant advantage is the ability to separate the loss from the copper foil itself from any dielectric losses. This separation allows for more precise measurement of the copper foil's properties without interference from other materials. Moreover, the presented resonators enable the separate measurement of both sides of the copper foil. This capability is crucial for understanding and characterizing any potential asymmetry or variations in the properties of the foil on each side.

Sapphire Dielectric Resonator measurement setup

The SaDR is dedicated to characterization of electrically thick conductive layers, meaning satisfying $h_s>3\delta$ condition, where δ denotes skin depth and h_s is thickness of the foil. The SaDR is composed of a sapphire resonator (dielectric head) embedded in the metal cavity, where top and bottom walls are replaceable and composed of conductor layers under test. The device is a multimode structure. In this work, it is used at TE011 and TE021 modes, resulting in a dual-frequency measurement at 13.8 GHz and 20.4 GHz.

The measurements setup consist of SaDR connected to a vector network analyzer (VNA) via RF coaxial cables. Each measurement requires two test samples of a copper foil under test, being said to be identical, of a minimum lateral size of 23 mm x 23 mm. Test samples are laid on the dielectric head and pressed down by two weights, as shown in Figure 1, to eliminate any non-uniformities in flatness, which would otherwise increase measurement uncertainty. For such a setup, for each of the operating modes, resonant frequency and Q-factor are measured using VNA options. The extraction of effective conductivity and surface resistance is conducted with the aid of dedicated software based on measured resonant frequency and Q-factor [6].

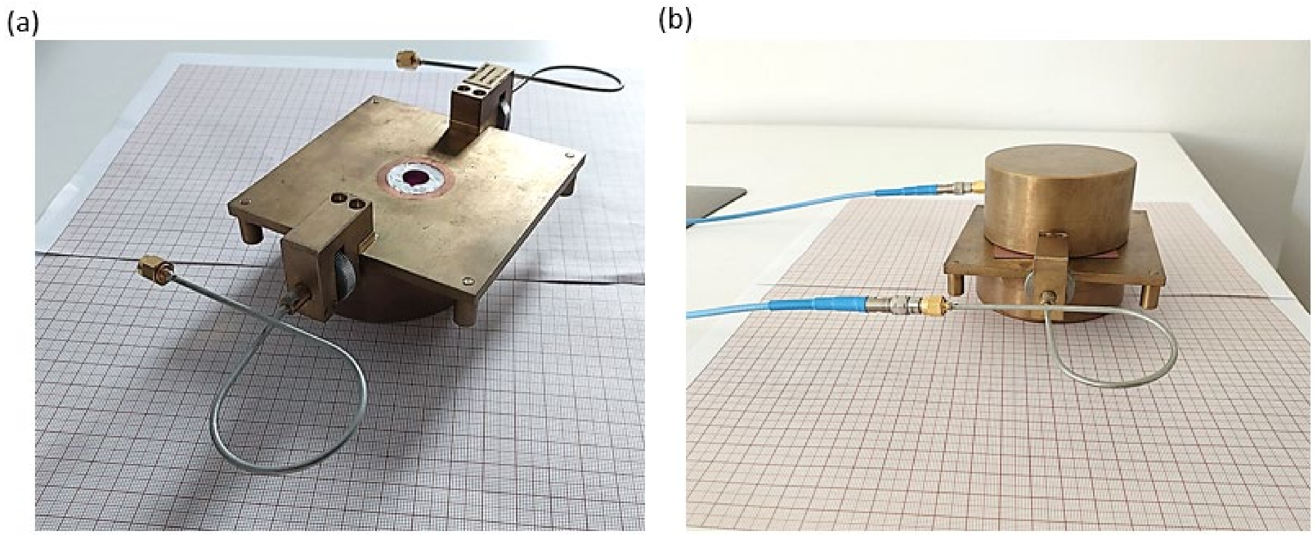

Figure 1. Sapphire Dielectric Resonator (a) without samples and (b) with samples pressed down with metal cylinders.

Plano-Concave Fabry-Perot Open Resonator measurement setup

The set-up consists of a Fabry-Perot Resonator FPOR [7][8] in the plano-concave configuration with one concave mirror being gaussian-shaped and the other mirror flat. The resulting plano-concave pc-FPOR structure employed in this study supports a multiple of resonances in the frequency band starting from 15 GHz and extending to ca. 40 GHz. separated by ca. 1.5 GHz. The properties of the material under test (MUT) are extracted from properties of a test signal passing through the structure and measured via two adjustable couplings installed in the upper, concave mirror. The flat mirror mounted at the bottom of the cavity can be easily replaced by a thin sheet of the MUT, whose diameter has to be at least the same as the diameter of the concave mirror. This geometry facilitates a characterization procedure, which consists of two separate measurements. First, the empty cavity is measured for their resonant frequencies and corresponding Q-factors. Then, a MUT is placed flat on the bottom mirror and the measurements are repeated after the position of the bottom mirror has been corrected so that each new resonant frequency matches the frequency obtained at the reference measurement. This correction is needed to account for the thickness of the sample under test. It also eliminates the risk of selecting a wrong mode (other than the TEM), which facilitates automation of the complete measurement procedure with the role of the operator limited to inserting the samples into the measurement fixture. The MUT's conductivity at each resonant frequency is readily obtained in a data postprocessing procedure based on the ratio of the measured Q-factors.

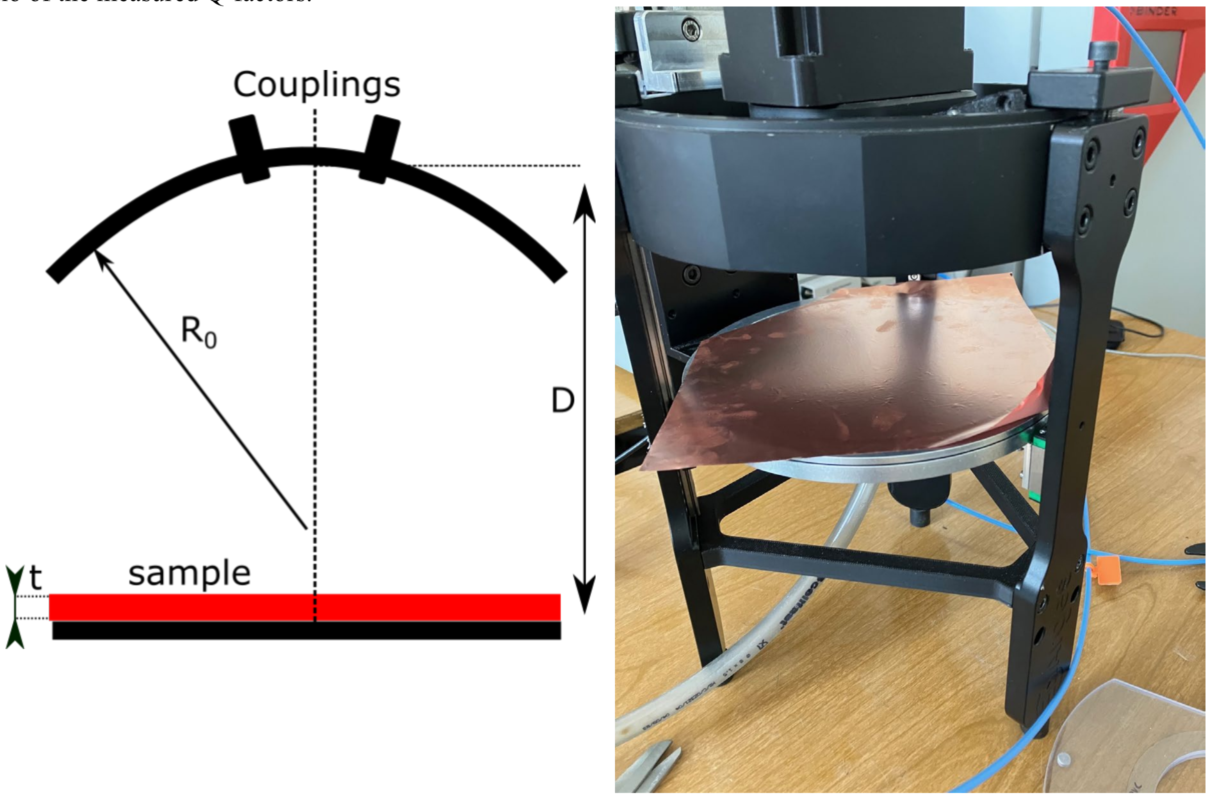

Figure 2. (a) Schematic with marking of dimensions necessary for extraction of material parameters and (b) actual pc-FPOR measurement set-up with MUT

Electromagnetic Insight

The resonance phenomenon, characterized by maximum output signal in response to a fixed input signal, is a crucial concept in physics. Resonance is extensively observed in classical electric circuits, such as the series RLC connection, where the resonant frequency is determined by the interplay of current, inductance, and capacitance (Figure 3).

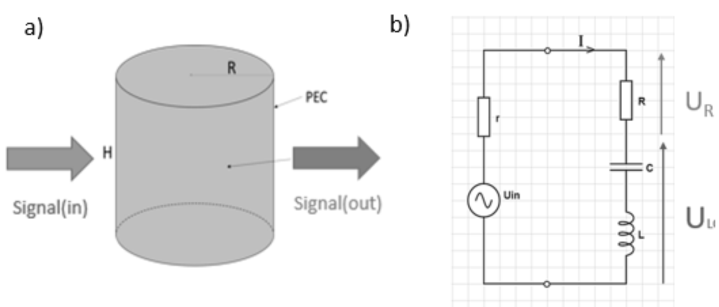

Figure 3. Theoretical model of a) cylindrical resonator and its b) equivalent circuit for one selected resonance.

At the resonant frequency, there is a net zero voltage drop across the series LC components, leading to a maximum voltage detected over the receiver R. The resonant frequency f_r in such circuits is determined by the formula:

$$f_r = \frac{1}{2 \cdot \pi \cdot \sqrt{LC}}, \qquad (1)$$

where f_r – resonance frequency [Hz], L – inductance [H], C – capacitance [F].

Distributed resonant circuits, exemplified by cylindrical cavity resonators, exhibit many resonant frequencies corresponding to different electromagnetic field distributions. For canonical geometries, the resonant frequencies can be determined analytically by solving the Maxwellian eigenvalue problem. For example, in the case of a cylindrical resonator filled with a lossless non-magnetic dielectric, the resonant frequencies are:

$$f_{r,mnp} = \frac{c}{\sqrt{D_k}}\sqrt{(\frac{k_{mn}^{(,)}}{\pi R})^2 + (\frac{p}{H})^2}, \tag{2}$$

where *m,n,p* – modal indices in angular, radial and vertical directions; $f_{r,mnp}$ – frequency of mnp mode, *c* – speed of light, k_{mn} - nth root of mth Bessel function (or its derivative, depending on the mode).

A formula for the quality factor (Q) is presented below, connecting the real part of permittivity, conductivity, and the 3dB bandwidth:

$$Q = \frac{2\pi}{T}\frac{\iiint_V \varepsilon\vec{E}\vec{E}^*dv}{\iiint_V \sigma\vec{E}\vec{E}^*dv} \approx \frac{f_{res}}{\Delta f}, \tag{3}$$

where Q – quality factor of the resonator, *V*- integration volume of nonzero electric field in the resonator, ε – real part of permittivity of materials filling the resonator [F/m] equal D_k* ε_0, where ε_0-permittivity of vacuum, E – Electric field [V/m], σ – conductivity [S/m], *T* – period [s] , f_{res} – resonance frequency [Hz], Δf – 3dB bandwidth [Hz].

Classically [2][3], resonators have been used to measure dielectric losses, such that in eq.(3) $\sigma=2\pi f \varepsilon D_f$, where D_f is dielectric loss factor, extracted from the measurements (while cavity losses are minimized by design and/or deducted in the extraction algorithm). Here, an opposite approach is taken: the dielectric losses are minimized (in SaDR – these are losses in the ultra-low-loss sapphire, in pc-FPOR – air between the mirrors) and also deducted in the extraction algorithm; while the losses of interest become those in metallic walls. Copper foils are incorporated as selected walls (in SaDR – two planar walls of the cylinder, in pc-FPOR – the planar mirror), and their impact on the resonator's overall loss is evaluated through meticulous electromagnetic modelling.

The physical properties of copper foils are critical factors influencing the performance of transmission lines. Note that in popular microstrip lines the electric field intensity is higher below the strip than above (Figure 4). In such cases, the contribution of the bottom side of the copper foil to signal losses becomes more pronounced. Therefore, it is desirable to measure the effective conductivities of the two sides of the foil separately.

To validate and enhance the accuracy of predictions based on field patterns, simulations have been conducted on a segment of the transmission line. In these simulations, a dual-side microstrip configuration was employed, wherein conductivities were independently assigned to both the bottom and upper sides of the copper strip. The purpose of this approach was to simulate real measurement conditions more accurately. Notably, differences in conductivities between the bottom and top sides were deliberately exaggerated during the simulations (Figure 5). This exaggeration aimed to capture and highlight disparities in transmission loss over a short segment of the transmission line. The implications of these findings underscore the importance of measuring both sides of the copper foil. By doing so, a comprehensive understanding of the conductivity variations between the top and bottom sides can be obtained. This dual-sided measurement approach is crucial for assessing and mitigating signal losses effectively, especially in areas where the field intensity beneath the strip is higher. Ultimately, this nuanced measurement strategy enables a more precise characterization of the copper foil's behaviour and contributes to the optimization of transmission line performance.

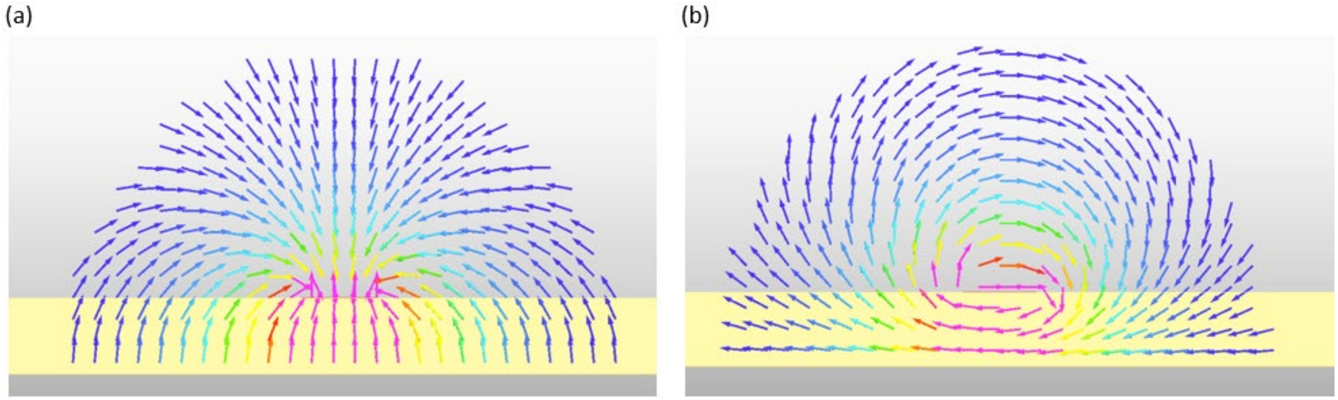

Figure 4. A 50 Ohm microstrip line and the (a) electric field and (b) magnetic field propagating through it.

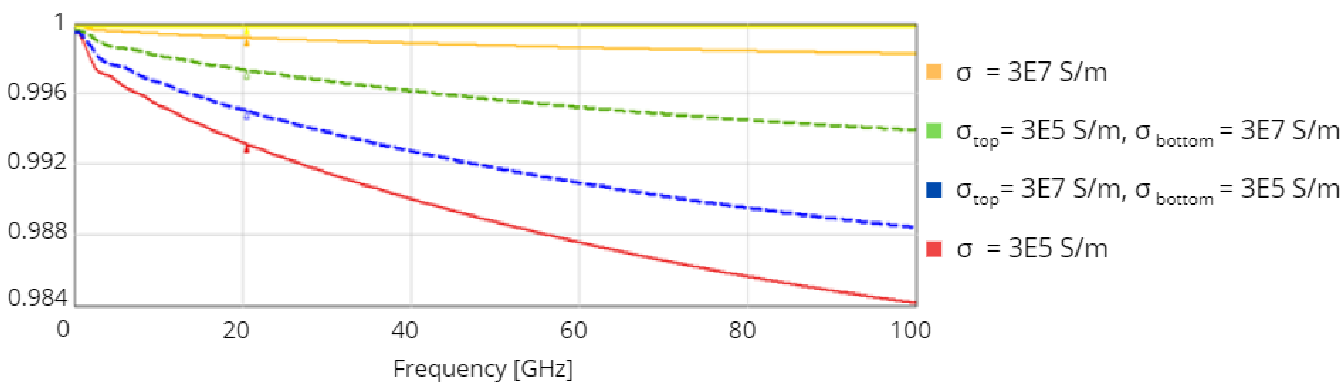

Figure 5. Segment of the line, with a dual-side microstrip - conductivities to the bottom and upper side assigned independently in the model

Results

The measurement procedure involved the use of SaDR and pc-FPOR methods to evaluate two sides, seen as "shiny" and "rough", for copper foils declared by their manufacturers as being “Low Roughness” and “High Roughness”. In characterizing surface roughness, arithmetical mean height (*Sa*) plays a key role [9]. This parameter represents the average of height differences along the mean plane, offering stability in results that are less affected by scratches and measurement noise. For the copper foils tested, *Sa* values above 0.25 µm are considered as “High roughness”, while below 0.25 µm - as “Low roughness”. The samples for the SaDR, measuring 50 mm x50 mm, were carefully prepared to completely cover the resonator cavity, while the pc-FPOR used samples measuring 175 mm x 175 mm with the edges trimmed to fit the resonator. Both sides of the copper foil came from the same sheets. Throughout the process, careful handling of the machined surfaces was a priority to prevent any unintended influences. A vector network analyzer was used to extract frequencies and Q-factors during the measurements for both methods. The collected data were analyzed separately for each side. Quality control measures were implemented to ensure the reliability of the measurements, and a detailed documentation.

First, a summary was created for all received samples. From each 6 sheets of film with the same production parameters, film samples were cut and measured, from which the mean and standard deviation were then calculated. The same procedure was used for all listed production parameters and manufacturers. In doing so, we created a summary from the boxes as below for the 13 GHz frequency (Figure 6). In the center of each box passes a line with a dot in the center indicating the average value of the measurement. The height of this box is equivalent to the standard deviation up and down.

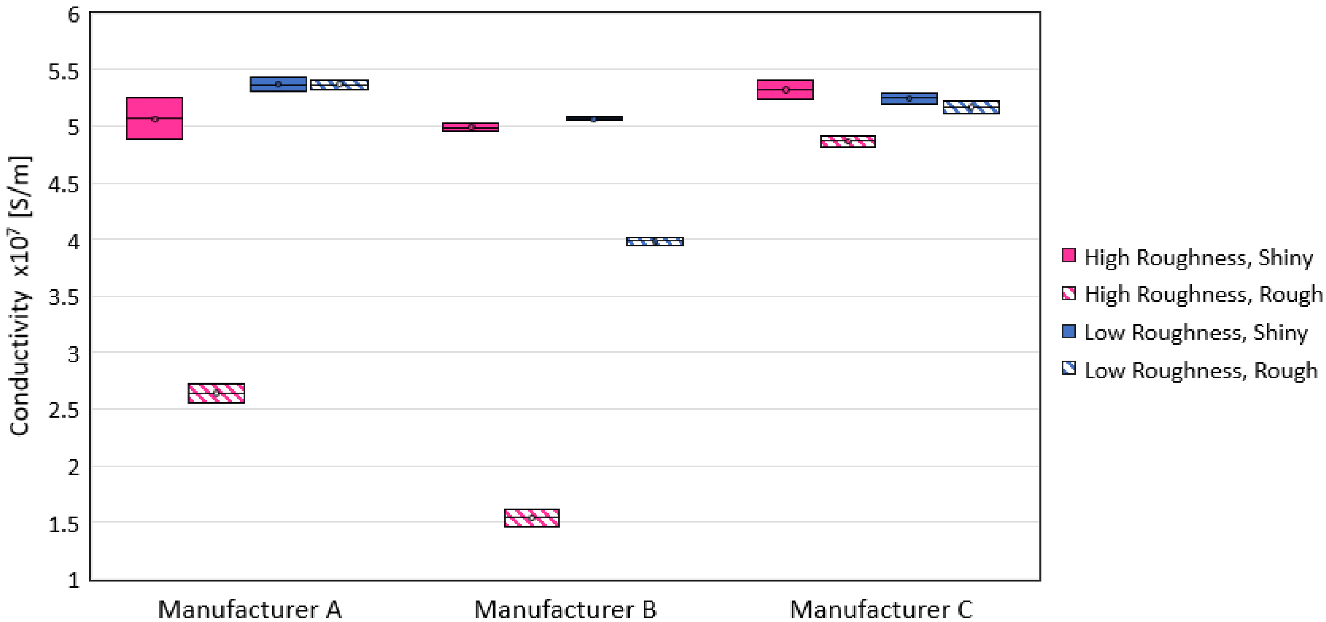

Figure 6. Effective conductivity of copper foil as seen from its two sides (denoted as Shiny and Rough), for two kinds of copper (Low Roughness and High Roughness), from three manufacturers (A,B,C), measured with SaDR at 13 GHz

All the considered copper foils exhibit lower effective conductivity compared to bulk copper. Foil's effective conductivity is affected by factors such as surface roughness and other manufacturing processes. At 13 GHz, copper foils from three different manufacturers, categorized as both High- and Low-Roughness, demonstrate similar effective conductivities when measured on the "shiny" side. The values fall within a 10% range, approximately 5 to 5.5 x 10^7 S/m. This suggests consistency in the performance of copper foils among these manufacturers, at least on the "shiny" side. The "rough" side of high-roughness copper foils shows a lower conductivity compared to the "shiny" side. The conductivity difference can be significant, even by a factor of 2-3, depending on the manufacturer. This indicates that surface roughness plays a crucial role in determining the conductivity of high-roughness copper foils. For low-roughness copper foils, the difference in conductivity between the "shiny" and "rough" sides is less significant compared to high-roughness foils. There is even an anomaly noted for one manufacturer, suggesting that the conductivity difference between the two sides may not follow a consistent pattern for all low-roughness foils.

The same samples were measured at a higher mode using the same measurement procedure. The results have been placed in Figure 7.

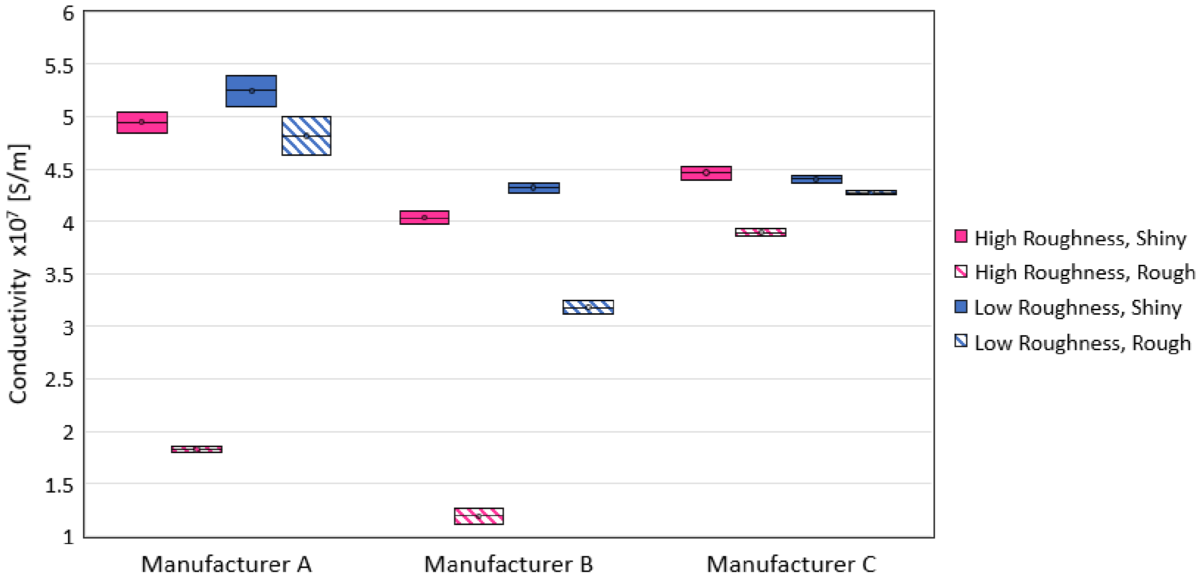

Figure 7. Effective conductivity of copper foil as seen from its two sides (denoted as Shiny and Rough), for two kinds of copper (Low Roughness and High Roughness), from three manufacturers (A,B,C), measured with SaDR at 21 GHz.

At the higher frequency of 21 GHz, all measured effective conductivity values are consistently lower compared to those at 13 GHz. This suggests that as the frequency increases, the effective conductivity of the copper foils tends to decrease. Also, the differences between manufacturers become more significant at 21 GHz. This implies that the performance of copper foils is more varied among different manufacturers at this higher frequency. This may be due to variations in manufacturing processes, material quality, or other factors that influence conductivity. One notable finding is that copper foils from only one manufacturer, of one specific type (High-roughness, shiny side), maintain a relatively higher effective conductivity at the level of 5 x 10^7 S/m. In contrast, copper foils from other manufacturers drop below 4.5 x 10^7 S/m, indicating a decline in conductivity for these materials at the same frequency. The change in conductivity versus frequency for the above results is a great motivation for extensive research into this problem.

Using the SaDR method in combination with pc-FPOR, they give excellent insight into this relationship as shown in Figure 8.

The effective conductivity of the material decreases with increasing frequency, indicating a higher susceptibility to signal loss at elevated frequencies. This frequency-dependent conductivity suggests that signals transmitted at higher frequencies will experience more pronounced attenuation. Moreover, the existence of differences between the two sides of the copper material underscores the importance of accounting for variations in conductivity. These differences may arise from factors such as impurities or variations of thickness, potentially impacting the overall performance of the material in electrical signal transmission. It can also be seen that the roughness of the sample has a significant effect on this relationship. For a sample with high roughness, the conductivity decreases definitely faster with increasing frequency than for a film with low roughness.

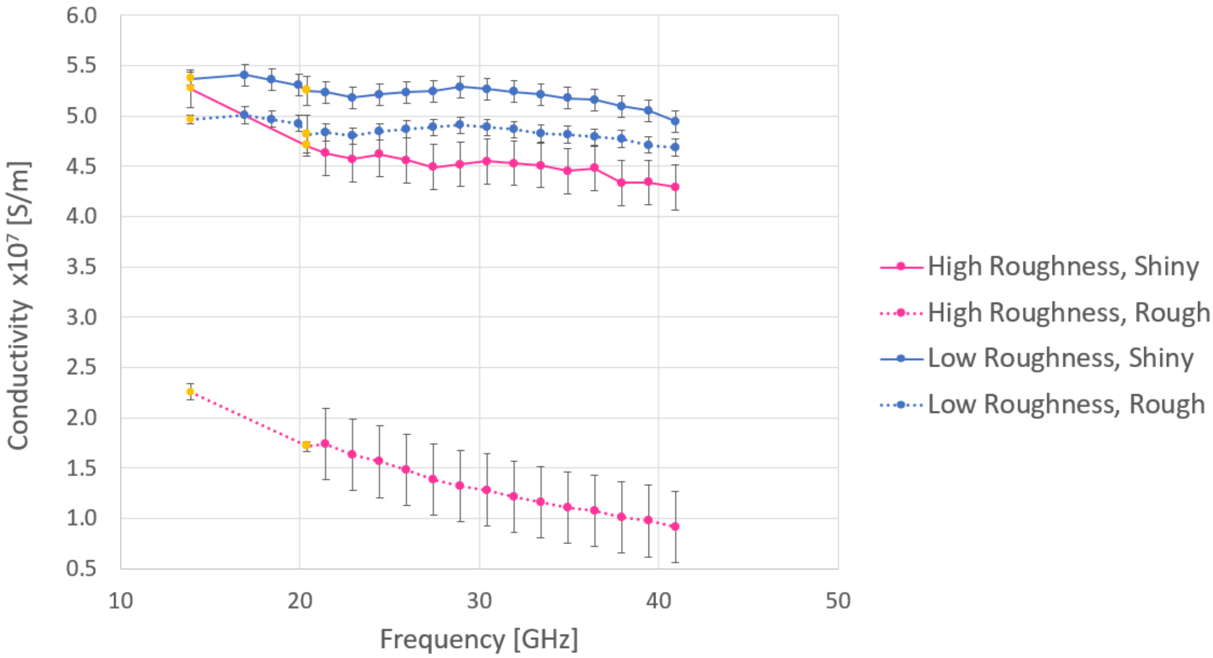

Figure 8. Effective conductivity of copper foil as seen from its two sides (denoted as Shiny and Rough), for two kinds of copper (Low Roughness and High Roughness), from manufacturer A, measured with SaDR (at 13GHz and 21 GHz – yellow dots) and pc-FPOR (20-40 GHz).

Conclusions

In conclusion, this work on exploring the "Reliability & Loss Properties of Copper Foils for 5G Applications," has made significant strides. This task specifically investigates the correlation between the topology of copper foils and copper loss, a critical factor influencing signal loss in 5G circuits.

The authors use two resonator-based instruments—Sapphire Dielectric Resonator and Fabry-Perot Open Resonator. These instruments, operating at frequencies of 13 GHz and 21 GHz and 20-40 GHz, respectively, provide quick and convenient measurements of copper foils. Importantly, these measurements are conducted on the copper foils as delivered by the manufacturer, eliminating the need for constructing a test circuit. Representative sets of copper foils were received from three manufacturers, encompassing both high- and low-roughness variants. Each foil type, measured on both "rough" and "shiny" sides, consists of six sheets, allowing for a comprehensive study of sample and measurement reproducibility with averages and standard deviation calculated. Measurements reveal crucial insights for higher frequencies (mmWave): the effective conductivity of all copper foils decreases, resulting in an increase in electric loss with frequency. Differences in loss attributed to various copper types also become more pronounced. Furthermore, variations in signal loss due to different effective conductivities, as seen by the signal on the two sides of copper, necessitate consideration in circuit design.

Although not shown in this paper, the resonators can also effectively measure foils on laminates. This versatility expands their applicability, making them suitable for a range of scenarios involving composite materials.

Acknowledgements

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