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Study of wood samples positioning on two microwave planar coupled ring resonators for water content measurements

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***Abstract* – Microwave resonance-based techniques have become increasingly popular for the non-destructive testing of wood materials, as they enable the measurement of moisture content without causing damage. This paper presents a preliminary study focusing on the most suitable way of placing wood samples on two microwave planar coupled ring resonators, specifically the capacitive and inductive configurations, for water content measurements. The study aims to assess the impact of sample positioning on measurement accuracy, considering two different positions corresponding to the coupling points: between the ring gap and the feed line and the inner gap. Results indicate that, for capacitive coupling (c.c.), placing the sample in proximity of the inner gap is more suitable for detecting variations in permittivity, as evidenced by the regression analysis with a R^2 value exceeding 0.98 for the two peaks. Instead, for the inductive coupling (i.c.) configuration, both positions present a good response. The regression analysis reveals a R^2 value greater than 0.98 for the two peaks in proximity of the outer gap, and a R^2 value of 0.9 for the inner one .**

I. INTRODUCTION

Wood is widely used in cultural heritage objects such as historical buildings, sculptures, furniture, musical instruments, and artwork [1]. Measuring water content in wooden-made artifacts plays an essential role in preserving structural integrity, preventing deterioration processes, and controlling mold growth [2], [3]. Due to the fact that wood objects are susceptible to damage caused by changes in moisture content which can lead to dimensional changes, warping, cracking, and even structural failure, water content measurement can be helpful to assess the risk of damage and implement appropriate conservation strategies to preserve the structural integrity of the artifacts [4], [5]. Similarly, high moisture levels in wood can promote both the growth of fungi, insects, and other organisms that cause decay and deterioration and lead to mold growth, compromising the aesthetic value and posing risks to human health. [6].

In this context, Non-Destructive Testing (NDT) techniques play a vital role in assessing the moisture content of cultural heritage objects without causing any damage to the artifacts. In fact, NDT can be adapted to different object types, materials, and sizes, making them versatile tools for moisture content assessment in a wide range of cultural heritage objects [7], [8]. Moreover, non-destructive techniques are typically non-intrusive, requiring minimal or no physical contact with the object, ensuring its preservation. Nowadays, exists a widespread range of NDT technics widely used for their versatility and low intrusiveness [9], like infrared thermography [10], electrical impedance [11], or microwave-based methods [12].

In the last years, microwave, resonance-based methods have been highly used for measuring moisture content in various cultural heritage materials, including stone [13]–[16] and wood [17]. These methods exploit the fact that the dielectric properties of materials, including the presence of moisture in the objects, affect the propagation of microwaves. Resonance characteristics such as resonance frequency f_r and its shift, scattering parameters $|S_{ij}|$, and quality factor Q are analyzed to infer moisture content. These methods offer advantages such as non-invasiveness, being basically contactless measurements, quick testing and data analysis , wide moisture range detection, and high sensitivity and accuracy [18].

The functioning of these methods is based on the measurement of the dielectric properties of the material under test, including permittivity (ε) and loss factor (tan δ). Water, with a relatively high permittivity (ε=78) compared to dry wood (ε=2), is suitable for moisture content measurement using microwave resonance-based techniques. When microwaves pass through a material, their electric field induces polarization in its molecules. This polarization arises from the alignment of water molecules with the applied electric field. As a result, the microwaves experience absorption and phase shift, which can be quantified through the material's complex permittivity (ε*). The resonators (planar structures, cavity resonators, open-ended coaxial probes, or ring resonators) are opportunely configurated to support resonant electromagnetic waves at specific frequencies which correspond to the point of maximum energy absorption by the material.

This paper aims to design and evaluate two configurations of coupled split-ring resonators (CSRR), capacitive coupling (c.c.) and inductive coupling (i.c.), to assess water content in small wood samples and determine the optimal position over the sensing elements.

II. EXPERIMENTAL SETUP

A. Coupled Ring functioning and design

A coupled structure is a type of microwave resonator configuration consisting of two or more ring-shaped structures that are coupled to create a resonant system. This coupling creates a combined resonant structure with unique resonance characteristics. The coupling strength can be adjusted by modifying the distance, or rings' distance, orientation, or geometry, a compact design compared to other resonator configurations, such as cavity resonators or planar patch resonators; the small size of the rings allows for easy integration into measurement systems, facilitates measurements in small samples, and elevates measurement accuracy and repeatability.

The proposed CRRS configurations consist of two coupled planar microstrip ring-resonators in capacitive and inductive configurations as described by *Zarifi et al.* [19]. Figure 1 reports the layout of the two designed sensors, while Table 1 reports the design specifications. In particular, figure 1 (a) reports the capacitive CRRS where the inner rings are electrically coupled and powered by inductive coupling between the feed lines and the outer side of the ring. Dually, figure 1 (b) reports the inductive configuration, where a capacitive coupling between the power lines and the outer side of the rings generates an inductive coupling between the rings themselves.

Table 1. Design specifications in mm.

Parameter	Symbol	Dimension (mm)
Feed line depth	*pf*	2.8
Ring width	*wr*	14
Ring length	*lr*	21
Ring gap	*gr*	0.6
Split distance	*d*	2
Feed gap	*gp*	0.8

The following equation 1 can be used to evaluate the resonant frequency for each ring structure

$$f_r = \frac{c}{2L\sqrt{\varepsilon_{eff}}} \quad (1)$$

where *c* is light speed, *L* the effective length of the ring and, and ε_{eff} the effective permittivity of the resonator, evaluated as a combination of the permittivity of the air and the medium under test.

Both configurations were designed and analyzed with CST studio software.

B. Wood sample dimensions and position

In the study conducted in CST Studio, a wood sample with dimensions of 22 x 11 x 8 mm^3 was designed. The permittivity of the model was varied from 2 to 10 to simulate different water content levels.

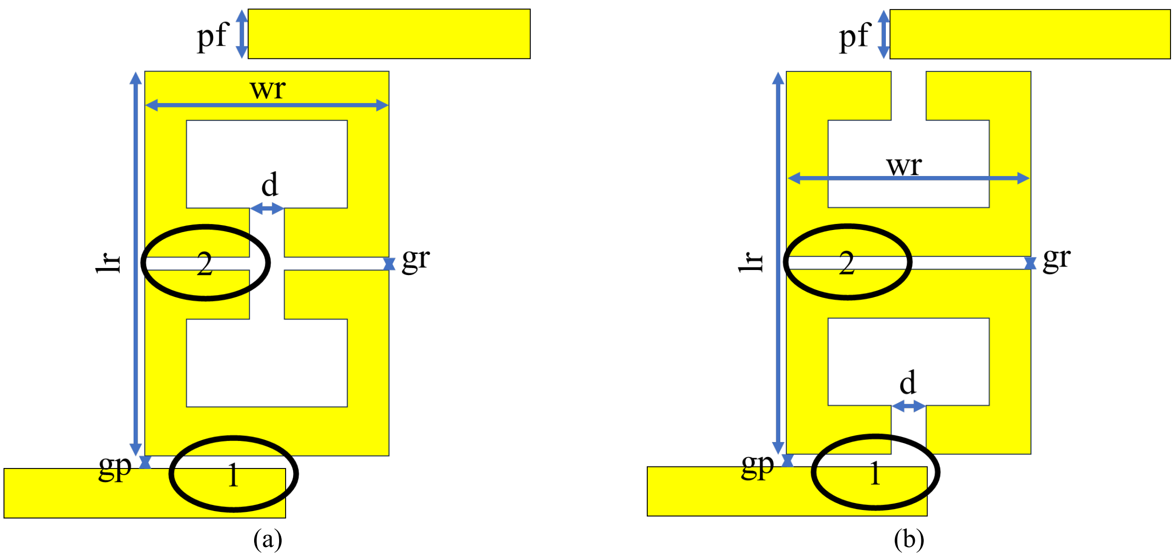

Fig. 1. Coupled split ring: (a) capacitive coupling (b) inductive coupling, with highlighted the dimensional parameters, and the sample positioning

Furthermore, the wood sample was positioned in two distinct positions, near the two main gaps (*gp* = position 1 and *gr* = position 2), for each of the two configurations, as reported in Figure 1. This positioning allows for the evaluation of the influence of sample placement on the resonance characteristics and water content measurements.

C. Post-processing analysis

By analyzing the insertion loss, the resonance frequencies can be identified, and the distances Δf between the resonance peaks are also considered, providing information about the distribution of energy and the resonant behavior of the system. This analysis helps establish a quantitative relationship between the measured resonance frequencies and the varying permittivity of the wood sample. Fitting regression lines to the data makes it possible to determine the trend and correlation between the permittivity values and the corresponding resonance frequencies. This information aids in developing calibration models and facilitates the accurate determination of water content based on the measured resonance frequencies once the physical device is built.

III. RESULTS AND DISCUSSION

Figures 2 and 3 display the results of the two investigated positions, illustrating the outcomes for the two CSRR configurations: capacitive coupling (c.c.) and inductive coupling (i.c.).

Specifically, Figures 2(a) and (b) show the insertion loss for the two positions, emphasizing that when the sample is placed in position 2, a more pronounced frequency shift to the low frequencies occurs with increasing permittivity. This observation is further supported by Figures 2(c) and (d), which display the regression lines between the resonance frequencies associated with the two peaks (f_l and f_h) for the two positions. In Figure 2(c), the resonance frequency f_l demonstrates a total frequency shift of 24 MHz and a R^2=0.6, while the resonance frequency f_h shows a total frequency shift of 9 MHz and an R^2=0.5 within the 1-9 permittivity range.It is worth noting that the relative

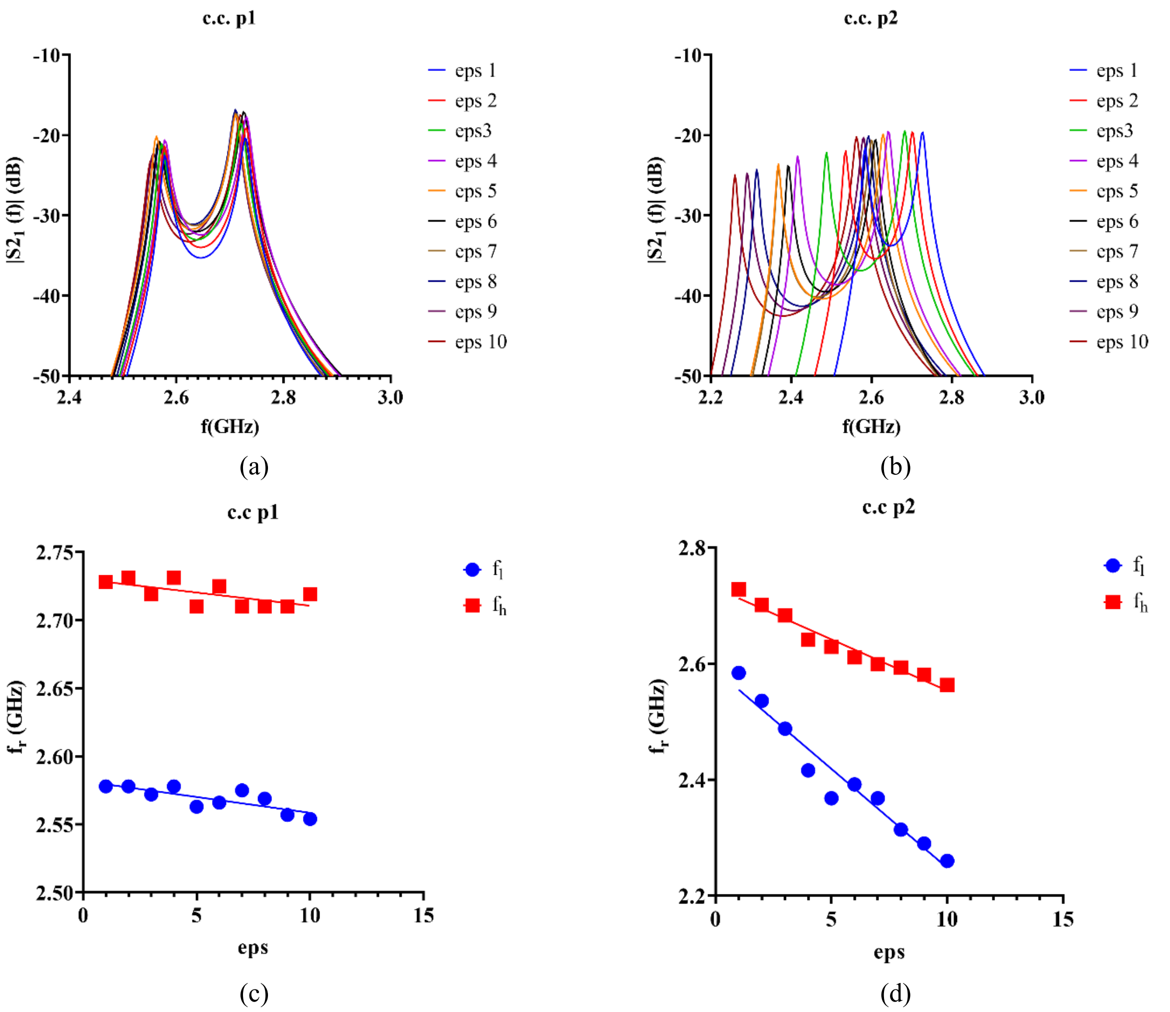

Fig. 2. c.c CSRR: (a) insertion loss for position 1, (b) insertion loss for position 2, (c) and (d) regression curve between $f_{l/h}$ and permittivity, respectively, for position 1 and 2.

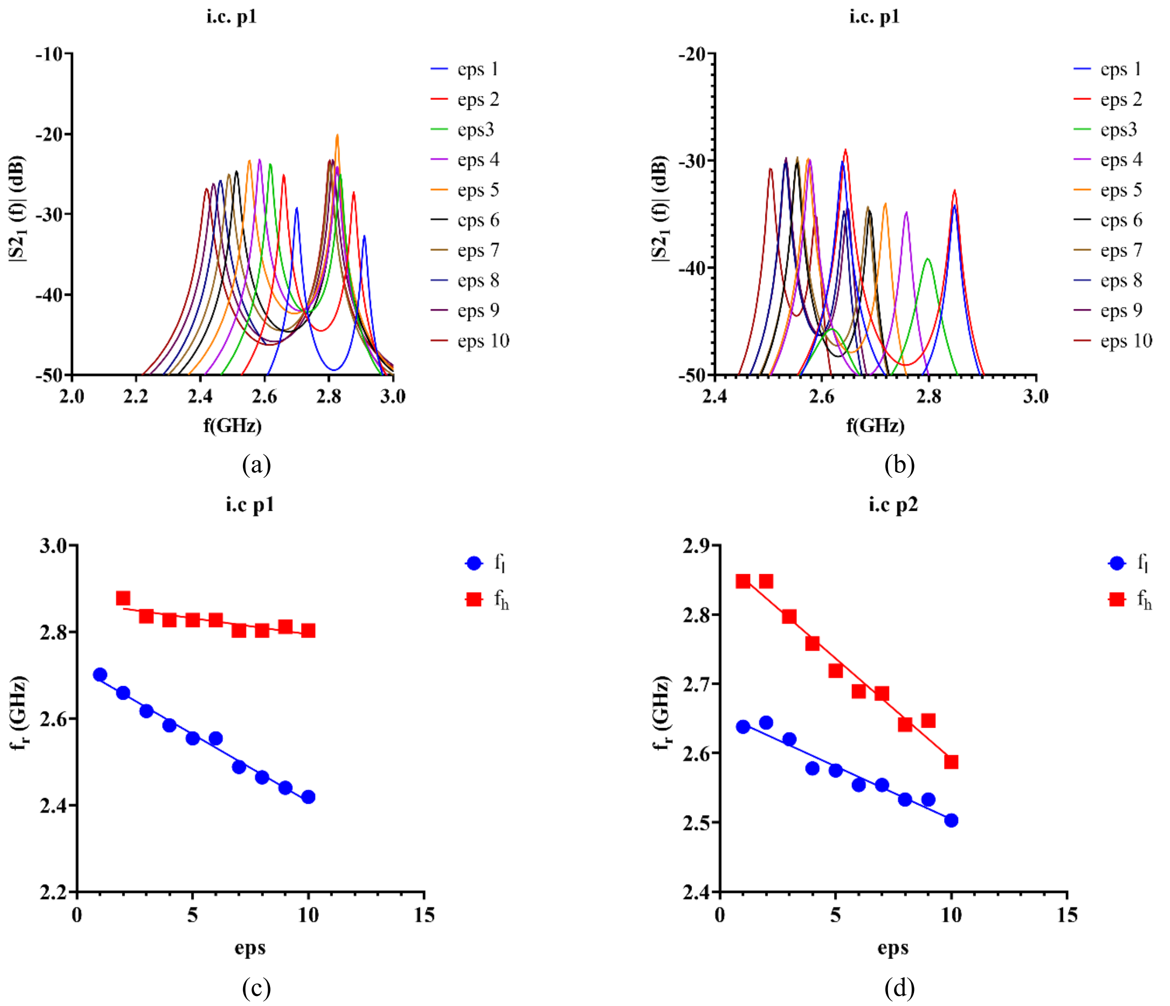

Fig. 3. i.c. CSRR : (a) insertion loss for position 1, (b) insertion loss for position 2, (c) and (d) regression curve between $f_{l/h}$ and permittivity, respectively, for position 1 and 2.

distance (*Δf*) between the two peaks remains constant at approximately 150±8 MHz throughout the entire range of permittivity values considered in the study. This indicates that the separation between the resonance frequencies of the two peaks remains consistent, regardless of the specific permittivity value within the given range.

In Figure 2(d), the resonance frequency f_l demonstrates a total frequency shift of 324 MHz and an R^2=0.9; in contrast, the resonance frequency f_h shows a total frequency shift of 165 MHz R^2=0.96, indicating a considerable resonance frequency change as the permittivity (ε) varies within the range of 1 to 9. Of note, the relative distance (*Δf*) between the two peaks increases with the increasing of permittivity value by *Δf*=144 MHz for ε = 1 to *Δf*=303 MHz for ε = 10.

Figures 3(a) and (b) illustrate the insertion loss for two positions of the i.c. CSRR. When the sample is placed in position one, an increase in permittivity results in a more noticeable shift towards lower frequencies than in position two. This finding is further supported by Figures 3(c) and (d), which exhibit regression lines representing the resonance frequencies associated with the two peaks (f_l and f_h) for the respective positions.

In Figure 3(c), the resonance frequency f_l undergoes a total frequency shift of 282 MHz with an R^2 value of 0.98. In comparison, the resonance frequency f_h experiences a total frequency shift of 108 MHz with a R2 value of 0.80 within the permittivity range of 1 to 10. Moreover, the relative distance (*Δf*) between the two peaks increases as the permittivity value rises, ranging from *Δf* = 210 MHz for *ε* = 1 to *Δf* = 384 MHz for *ε* = 10. This observation highlights a correlation between the increment of *Δf* and the increase in permittivity.

In Figure 3(d), the resonance frequency f_l demonstrates a total frequency shift of 135 MHz with an R^2 value of 0.94, while the resonance frequency f_h shows a total frequency shift of 261 MHz with an R^2 value of 0.97. These results indicate a significant change in resonance frequencies as the permittivity varies from 1 to 10. Furthermore, the relative distance (*Δf*) between the two peaks decreases as the permittivity value increases, ranging from Δf = 202 MHz for ε = 1 to Δf = 8 MHz for ε = 10.

IV. CONLUSIONS

Measuring water content in wooden cultural heritage objects is vital for their preservation, as it helps maintaing their structural integrity, prevent deterioration, control mold growth, monitor environmental conditions, and guide conservation treatments. In this study, the focus was on analyzing two different positions of a capacitive/inductive coupled split-ring resonator (c.c./i.c. CSRR) and their response to changing permittivity (ε) in relation to resonance frequencies and the relative distance between the two peaks. Results indicate that the position of the sample has a low influence in the inductive CSRR, as both configurations exhibit a significant frequency shift in the resonance peaks. In contrast, the capacitive CSRR shows a more favorable response in proximity of the inner gap since presents a wider frequency shift.

For future developments, further analysis and measurements using different wood species and varying levels of water content will be conducted evaluating also the loss tangent variation. This will enhance our understanding of the behavior and performance of the two sensors in different scenarios and contribute to the advancement of water content measurement techniques in wooden cultural heritage conservation.

Moreover recent studies in the field have highlighted the potential for wireless sensing of permittivity in cultural heritage monitoring. Building upon these advancements, our proposed sensor technology possesses the inherent capability to serve as a versatile sensing probe. This innovation paves the way for convenient and efficient "on-site" moisture level monitoring, eliminating the need for physical access to measurement points and ushering in a new era of accessibility and ease in heritage preservation efforts.

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