Design of Spoke Type CSRR based RF Sensor for Non-Destructive Quality Evaluation of Wood

Apala Banerjee[1], Prakrati Azad[2], M Jaleel Akhtar[1]
[1]Department of Electrical Engineering, Indian Institute of Technology Kanpur, India
[2]Materials Science Programme, Indian Institute of Technology Kanpur, India
apala@iitk.ac.in, prakrati@iitk.ac.in, mjakhtar@iitk.ac.in

***Abstract* — A spoke type novel complementary split ring resonator (CSRR) based RF sensor for non-destructive qualitative assessment of wood is presented. The novelty of the proposed sensor lies in the creation of many capacitive gaps in the sensing region comparable to that of the dimensions of the micro voids and vessels (0.2 mm to 1.2 mm) present in the wood. This kind of novel CSRR geometry basically facilitates maximum electromagnetic interaction between the sensing region and the test specimen suitable for evaluating the quality of wood samples defined in terms of porosity. The wood samples from Indian barks of Neem, Chir, and Sagwan are specially manufactured for testing in the present scenario. The sensor is fabricated on a 0.8 mm thick Taconic substrate, and all the wood samples are measured using the Vector Network Analyzer. In the next step, these samples are heat treated in a microwave oven for 1 min at 350 watts and are measured once again to determine their porosity in terms of the measured resonant frequency and the corresponding transmission coefficient magnitude. The maximum sensitivity achieved corresponds to the Neem sample, which provides a frequency shift of 23.8 MHz for unity percentage change in the porosity.**

***Keywords* — CSRR, microwave, porosity, spoke, wood.**

I. Introduction

Wooden barks in metropolitan cities, owing to exponential urbanization and population boom, are subjected to a secondary process [1] before making woodcraft, wooden furniture, household establishments, etc. Dry woods are most frequently preferred for most of the commercial applications, as the lower moisture content usually improves the quality as well as utility of the wood. In recent years, wooden samples have also been dried using the microwave methods to fasten the overall drying process. However, it is observed that sometimes quite fast heating process damages the internal physical structure of the wood such as cell walls, vessels, micro-voids in the radial and longitudinal plane [2]. This results into degrading the strength and the quality of the wood introducing crack, rots or splits [3], [4], [5], [6], [7]. It is mainly due to this reason that the hybrid heating approach making use of both conventional and microwave methods appears to be more appropriate for the processing of wood without degrading its overall quality. However, for wood samples dried using either the conventional or the microwave method, the quality assessment usually defined in terms of the moisture content or the porosity, is a major challenge. In the past, conventional microwave methods using free space and antenna has been reported to detect wood quality [8], [9]. However, a detailed systematic study including the quality degradation of wood due to heating of various types of wood samples in a controlled microwave environment has not yet been reported. Microwave response of dielectric samples such as wood may be correlated with various useful properties such as the moisture content, porosity, etc., defining the quality of the end product [10], [11], [12]. The metamaterial-inspired RF planar sensors such as those using Split Ring Resonators (SRR) [13], [14] and CSRR structures have recently been used for a number of applications due to their several advantages such as the improved sensitivity, accuracy, and compact geometry. The CSRR-based structures enhance the sensitivity owing to the higher confinement of the electric field within the sensor region [15], [16], [17], [18], [19]. However, to the best of authors' knowledge, these types of planar CSRR based structures have not been employed for quality assessment of wood structures.

One major challenge in using the CSRR-based RF sensor for testing wood samples is the effective interaction between the sensing region and the fine structures including micro-vessels of wood. In this work, a novel spoke type CSRR sensor, with its sensing area containing several capacitive etchings of the dimensions comparable to those of the wood vessels, is proposed. The fine capacitive gaps introduced in the proposed spoke sensor facilitates penetration of the electric field deep insider the wooden vessels, thereby providing significant change in the measured microwave parameter for even small change in the porosity of moisture content of the wood samples. The determination of porosity of wood samples using the proposed spoke CSRR sensor possessing high sensitivity finally helps in assessing the quality of wood using a fully non-destructive approach, as the actual sample is not damaged or destructed during the testing procedures [20].

II. Sensor Design And Analysis

A novel spoke sensor based on the CSRR structure is designed and simulated using the numerical EM simulator Computer Simulation Technology-Microwave Studio (CST MWS) under loaded and unloaded condition to record the microwave parameters at the designated frequency of 4.5 GHz. The schematic of the proposed sensing system is shown in Fig. 1 showing the sample placement and field distribution. The detailed schematic of the sensor structure is illustrated in Fig. 2. The host microstrip line at the top layer (Fig. 2(a)) is modified to have a high impedance at the middle region above the sensing area to confine a higher amount of electric field to

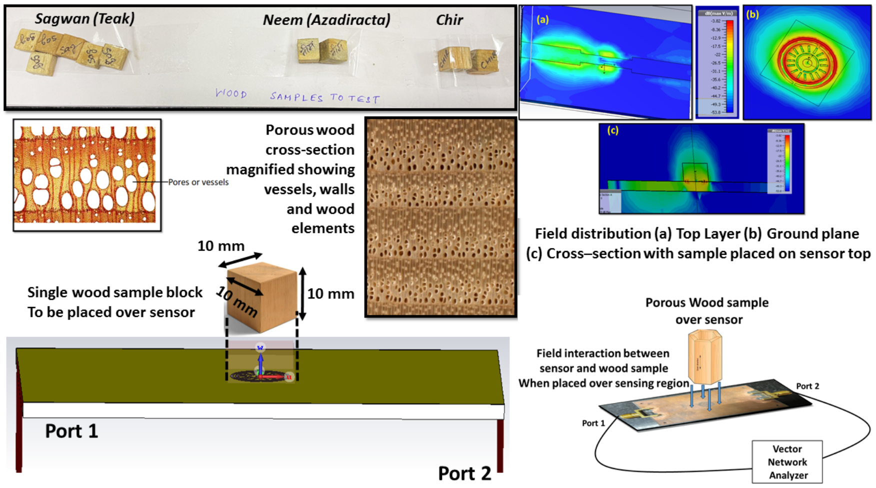

Fig. 1. Schematic for the proposed sensor to evaluate wood quality.

the etched sensing region. From Fig. 1, the field is observed to be concentrating in the microstrip line both near the transition as well as on the high impedance line.

The ground plane (Fig. 2(b)) is etched to design a special type of spoke type CSRR sensing region to possess a higher effective capacitance by etching capacitive gaps having dimensions from 0.2 mm to 0.4 mm effective for the interaction with the porous structure. The dimensions of various physical parameters are tabulated in Table. 1. The S-parameter plots under unloaded and loaded condition for the sensor are shown in the Fig. 2 showing the variation in resonant frequency for two typical dielectric constant values ($\varepsilon_r = 1$ and 2). It can be observed, there occurs a shift of 500 MHz (absolute sensitivity) in its resonant frequency with a fractional sensitivity of 12 with a Q of 450. Fig. 2 then plots the variation of S-parameters against frequency for dielectric range from 2 to 6 which demonstrates the electromagnetic behaviour of wood, as wood dielectric typically varies between this range in the C-band.

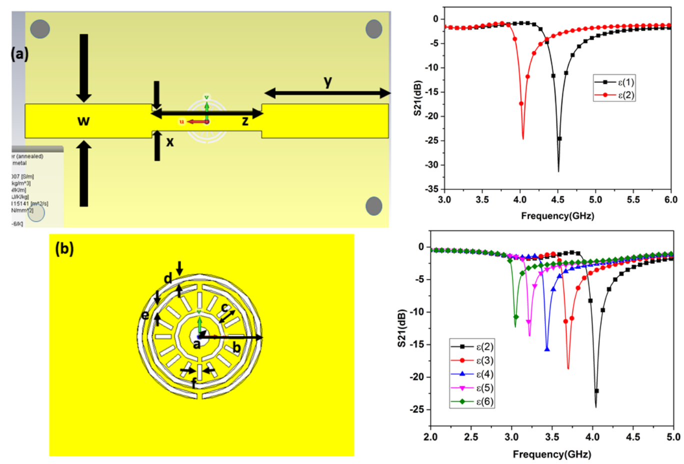

Fig. 2. Schematic of the proposed spoke sensor prototype showing the (a) top view (b) bottom view along with simulation results for different dielectric loading with w = 4.75, x = 2.75, z = 15.10, y = 17.45, a = 0.5, b = 2.85, c = 0.67, d = e = 0.25, and f = 0.2 (in mm).

A. Theory

Dielectric properties of wood samples may be usually defined in three different axes i.e., longitudinal (L), radial (R) and tangential directions (T) as shown in Fig. 3 [2].

The value of dielectric constant at any arbitrary direction is given by

$$\varepsilon' = \varepsilon'_L cos^2\alpha_1 + \varepsilon'_R cos^2\alpha_2 + \varepsilon'_T cos^3\alpha_3 \tag{1}$$

where α_1, α_2, and α_3 are the angles that the E-field makes with the axes L, R, and T respectively.

However, wood contains a number of elements and substances like cellulose, lignin, salt, water etc. Moist wood consists of three components cell wall, air, and bound water where as oven dry wood consists of only cell wall and air. Wood components affect the dielectric properties of wood, which, as per Trapp and Pungs is given by [2]:

$$(\varepsilon'_m)^k = V_1(\varepsilon'_1)^k + V_2(\varepsilon'_2)^k + V_3(\varepsilon'_3)^k + V_4(\varepsilon'_4)^k \tag{2}$$

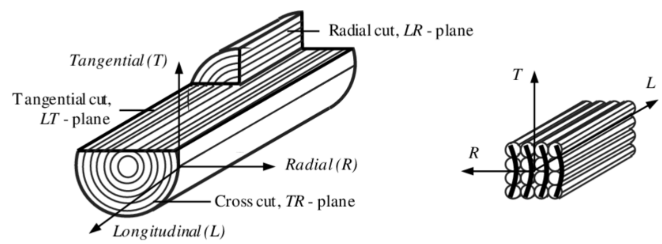

Fig. 3. Wooden cross section showing longitudinal and radial elements in coordinates.

Where k =coefficient determined experimentally V_1, V_2, V_3, and V_4 are the volumes of cell wall, air, bound water, and free water, respectively. The sensitivity in the present scenario has been developed to explain the microwave resonant parameters in terms of the wood porosity as follows:

$$S = \frac{\Delta f}{\Delta Porosity(\%)} = \frac{\Delta S_{21}(dB)}{\Delta Porosity(\%)} \tag{3}$$

Every wood type/specimen will consist of different void structure/internal physical arrangement for cell walls, lignin space, etc. These voids will have different moisture retaining capacity based on their geometry. When microwave heating will take place, these void structures will weaken in a unique way and will give a distinct porosity measurement with the help of the resonant parameters of the Spoke type sensor. So for random number of voids in a wooden structure, a change in resonant parameters will take place because with microwave heating the dielectric property deteriorates giving rise to a shift in the resonant frequency [1].

III. Equivalent Circuit Analysis

The equivalent circuit model for the proposed sensor is developed in the software Advanced Design System (ADS) as shown in Fig. 4 with its optimized lumped parameters. L1 and L2 are inductances of the top host microstrip line. Cc is the coupling capacitance between the top layer and bottom CSRR due to dielectric gap. Cs and Ls are the LC circuit of the resonator designed on the ground plane. R is the resistance that accounts for dielectric and conductor loss in the structure.

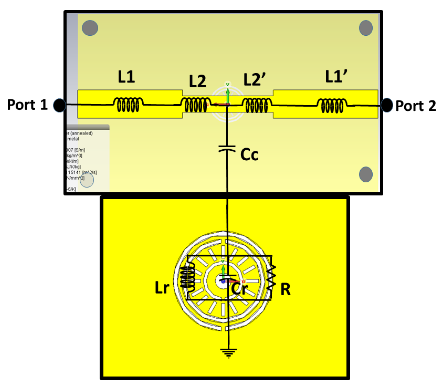

Fig. 4. Schematic of the Equivalent Circuit with the following lumped parameter values as L1 = L1'= 4.1 nH, L2 = L2' = 1.2397 nH, Cc = 0.4811 pF, Lr = 1.239 nH, Cr = 0.55 pF, Rr = 1.265 kΩ.

IV. Measurements And Discussions

A. Measurement Set-up and Fabricated Sensor Prototype

The proposed structure is fabricated in Taconic substrate having a thickness of 0.8 mm as shown in Fig. 5. Measurement is carried out under two situations. The initial measurement is carried out for the untreated (reference) samples in VNA. In the next step, the samples are microwave treated and their conventional porosity is determined. Finally, the measurement for the treated samples are again carried out in VNA to establish the effect of microwave heat on the dielectric nature of the wooden samples under test.

B. Sample Preparation and Microwave optimization

Wooden samples from Indian barks of Chir (Indian Chir pine), Neem (Azadiracta), and Sagwan (teak) trees are prepared in small cuboidal shapes modified into dimensions 10 mm x 10 mm x 10 mm as shown in Fig. 1. The samples after their initial measurement in VNA are microwave treated

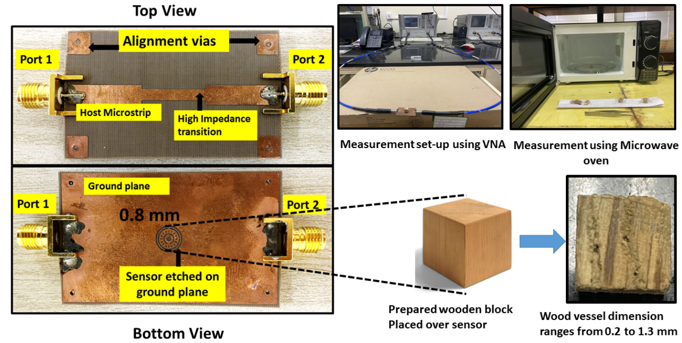

Fig. 5. Fabricated prototype of Spoked sensor (a) Top view (b) Bottom view along with measurement set-up.

at 350 W for 1 min (Fig. 5) individually to observe the effect of microwave heating on the samples.

C. Measurement Analysis of the Treated Wood Samples

At first, the percentage porosity of the wooden samples is obtained using the formula:

$$Porosity(\%) = \frac{W_t.Wood_{ref} - W_t.Wood_{\mu wave}}{W_t.Wood_{ref}} \times 100(\%) \tag{4}$$

Table 1. Measurement results for the microwave treated samples

Sample	Ref. weight (gm)	Microwave treated weight (gm)	Difference (△w)(g)	Δf (MHz)	S_{21} (dB)	Porosity (%)
Neem	0.6915	0.6277	0.0638	150	9	6.38
Sagwan	0.3622	0.3316	0.084	65	6	8.14
Chir	0.5094	0.4559	0.1381	140	3.5	13.81

The measured data are tabulated in Table. 1. In the next step, measurement for the reference wood samples and the microwave treated samples are carried out using VNA (Fig. 6).

From the obtained frequency shift, two responses are plotted against the porosity which are the shift in frequency and the transmission notch magnitude, respectively, as shown in Fig. 7.

Fig. 7(a) demonstrates that Neem exhibits a sensitivity of 23.8 MHz/% variation of porosity. From Fig. 7(b) it can be concluded that as the porosity increases the transmission magnitude decreases, with Neem having the highest percentage. The change in S_{21}(dB) is about 9 dB/% whilst Chir having the minimum (11.53 MHz/% porosity and 0.5 dB/% porosity) of all three. The analysis shows that Neem or Azadiracta is more sensitive to microwave treatment as compared to the rest and can give information regarding the dielectric nature and the qualitative assessment of its wood type. It can be observed that with the increase in the porosity the sensitivity in terms of the transmission notch level is most impacted, as porosity (%) increases, the S_{21} dB level goes on decreasing. A comparison with the conventional structure

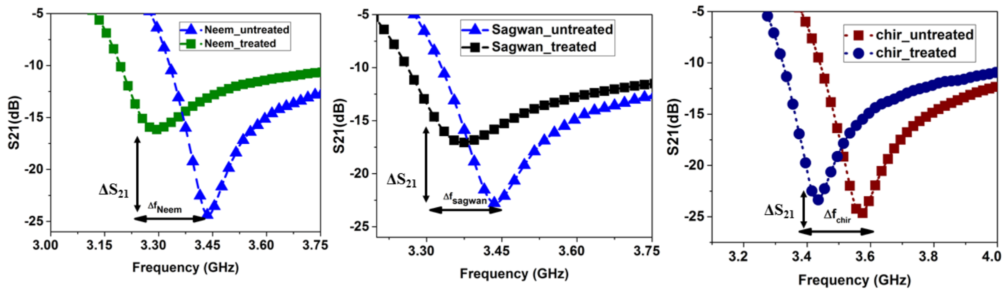

Fig. 6. Measurement results of the wooden samples before and after microwave treatment to determine the resonant frequency shift.

[19] is shown in Table. 2 to demonstrate the performance improvement of the proposed prototype.

Table 2. Comparison between Conventional and Spoke Type CSRR

Type	E-field (V/m)	Fractional Sensitivity(%)	Effective capacitance
Conventional Type	48004	9.5	Low
Modified Spoke type	125000	12	High

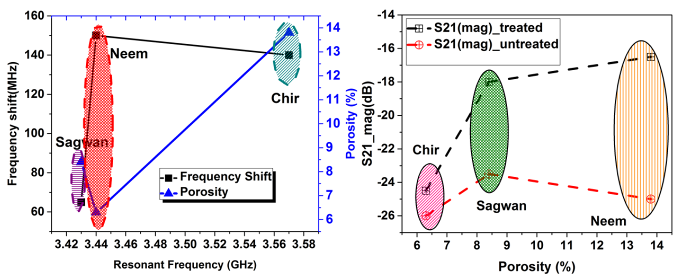

Fig. 7. (a) Frequency response vs porosity (b) Transmission magnitude vs porosity response.

V. Conclusion

A spoke type CSRR RF sensor operating at 4.5 GHz has been developed, fabricated, and tested for non-destructive evaluation of wood. Wooden barks of Chir, Sagwan, and Neem have been tested using the proposed RF sensor. The samples are initially tested under ordinary conditions of room temperature (reference). Afterwards, these samples have been heat treated in a controlled environment using the microwave oven to observe the change in the porosity of each sample by observing the corresponding change in their scattering parameters near the resonant frequency. The maximum sensitivity achieved is for the Neem sample, which basically provides a frequency shift of 23.8 MHz for unity percentage change in the porosity.

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